

Using Eye Tracking to Examine a Single Word

Copying Paradigm

Abby Emma Laishley

In Fulfilment of the Requirements for the

Degree of Doctor of Philosophy

Bournemouth University

October, 2016

Copyright statement

This copy of the Thesis has been supplied on condition that anyone who consults it is understood to recognise that its copyright rests with its author and due acknowledgement must always be made of the use of any material contained in, or derived from, this Thesis.

Using Eye Tracking to Examine a Single Word Copying Paradigm

Abby Emma Laishley

Abstract

Classroom learning, the bedrock of school education, relies heavily on written information transfer. The seemingly simple task of copying text from a board is psychologically complex and involves sequential visual and cognitive processes: visual encoding, constructing and maintaining mental representations, and written production. To date, most research in this area has focused on written production. This Thesis aimed to quantify what linguistic units copiers activated during visual encoding; whether similar units were used during encoding and production; and whether copiers whose reading ability was still developing, encoded and produced words in a similar fashion to copiers with fully developed reading ability.

New mobile eyetracking technology enabled recording of eye-movement behaviour as an indicator of cognitive processing over both visual encoding and written production. In two experiments, both adults' and children's eye-movements were recorded as they made handwritten copies of single words presented on a classroom board.

Gaze time measures showed both adults and children encoded whole word and syllable units, though this was not consistent for children processing long words. For all copiers, written production was often based on comparatively smaller units than encoding. Also, children needed more gaze lifts between the written copy and the board than adults, suggesting they relied more on piecemeal linguistic representations of subword units, perhaps because of forgetting.

An additional lexical decision experiment showed how children could encode long words as whole word units, suggesting that piecemeal encoding of subword units might be restricted to a copying task, that includes additional task demands associated with mental representation and written production processes as well as visual encoding.

Word copying relied on systematic linguistic units, but the size of a unit appeared to modulate its functionality differently for encoding and production, even for skilled readers. Findings guided development of a theoretical framework for the copying process.

Publication from this Thesis

Chapter 3 has been published as:

Laishley, A. E., Liversedge, S. P., & Kirkby, J. A. (2015). Lexical processing in children and adults during word copying. *Journal of Cognitive Psychology*, 27(5), 578–593.

List of Contents

Abstract	3
CHAPTER 1	13
1.1 What Information do Readers use to Decode Words?	14
1.2 Encoding Information in a Copying Task	19
1.3 Mentally Representing Information in a Copying Task.....	27
1.4 Producing Information in a Copying Task.....	32
1.5 Overview	44
CHAPTER 2	47
2.1 Introduction to the Copying Paradigm.....	47
2.2 Introduction to Tracking Eye Movements	48
2.3 Tracking Eye Movements	50
2.4 Tracking Eye Movements in a Mobile Copying Paradigm.....	52
2.5 General Methods of the Copying Paradigm.....	55
2.6 Data Handling	62
2.7 Overview	67
CHAPTER 3	68
3.1 The Current Study	68
3.2 Methods.....	71
3.3 Results	72
3.4 Discussion	79
3.5 Overview.....	83
CHAPTER 4	85
4.1 Introduction	85
4.2 The Current Study	92
4.3 Methods.....	96
4.4 Results	98
4.5 Discussion	107
4.6 Overview	115

CHAPTER 5	117
5.1 Introduction.....	117
5.2 Individual Differences in Relation to Sub-Processes during a Copying Task.....	119
5.3 The Current Study.....	129
5.4 Methods.....	131
5.5 Results.....	134
5.6 Discussion.....	139
5.7 Overview.....	150
CHAPTER 6	152
6.1 Introduction.....	152
6.2 Previous Approaches to Gaze Lift Analysis.	161
6.3 The Current Study.....	163
6.4 Methods.....	165
6.5 Results.....	167
6.6 Discussion.....	184
6.7. Overview.....	193
CHAPTER 7	194
7.1 Introduction.....	194
7.2 Methods.....	204
7.3 Results and Discussion.....	206
7.4 General Discussion.....	217
7.5 Overview.....	226
CHAPTER 8	228
8.1 Context of the Research.....	228
8.2 Key Research Findings.....	231
8.3 Proposition of the Basis for a Framework Conceptualising Cognitive Operations during a Single Word Copying Task.....	242
8.4 Challenges in the current research.....	248
8.5 Next Steps for Future Research.....	250
8.6 Final Summary.....	255

REFERENCES.....	258
9.1 References	258
APPENDICES	278
APPENDIX A	278
10.1 Ethical information for Experiment 1: Information sheet for adults..	278
APPENDIX B	279
10.2 Ethical information for Experiment 1: Information sheet for children	279
APPENDIX C	280
10.3 Ethical information for Experiment 1: Consent form for adults	280
APPENDIX D	281
10.4 Ethical information for Experiment 1: Consent form for children	281
APPENDIX E	282
10.5 Ethical information for Experiment 1: Debriefing statement	282
APPENDIX F.....	283
10.6 Ethical information for Experiment 2: Information sheet for children	283
APPENDIX G	284
10.7 Ethical information for Experiment 2: Consent form for children	284
APPENDIX H.....	285
10.8 Ethical information for Experiment 3: Information sheet for adults..	285
APPENDIX I.....	286
10.9 Ethical information for Experiment 3: Information sheet for children	286
APPENDIX J	288
10.10 Ethical information for Experiment 3: Consent form for adults	288
APPENDIX K	289
10.11 Ethical information for Experiment 3: Consent form for parental guardians	289
APPENDIX L	291
10.12 Ethical information for Experiment 3: Consent form for children ..	291
APPENDIX M	292
10.13 Ethical information for Experiment 3: Debriefing statement	292
APPENDIX N	293
10.14 Materials in Experiment 1 for adult participants.....	293
APPENDIX O	294
10.15 Materials in Experiment 1 for child participants.....	294

APPENDIX P.....	295
10.16 Materials in Experiment 2 for child participants	295
APPENDIX Q.....	296
10.17 Structure of linear mixed models for Experiment 2, reported in Chapter 4.....	296
APPENDIX R	299
10.18 Structure of linear mixed models for Experiment 1, reported in Chapter 5.....	299
APPENDIX S.....	302
10.19 Materials in Experiment 3 for adult and child participants.....	302
APPENDIX T	303
10.20 Structure of linear mixed models for Experiment 3, reported in Chapter 6.....	303
APPENDIX U	305
10.21 Structure of linear mixed models for Experiment 3, reported in Chapter 7.....	305

List of Illustrations and Tables

Figure 1. The sequence of components in a copying task.....	48
Figure 2. The Dikablis headmounted eye tracker.....	53
Figure 3. The board display.....	60
Figure 4. The notepaper display.....	61
Figure 5. The revised notepaper display.....	62
Figure 6. An example invalid frame before (left) and after (right) manual pupil detection.....	63
Figure 7. The time-course of events in relation to corresponding measures.....	65
Table 1. Gaze times during encoding (ms) in relation to total encoding, initial encoding, writing onset and secondary encoding for both adults and children on words manipulated for length and frequency in Experiment 1.....	74
Table 2. Gaze lift behaviour for children on words manipulated for length and frequency in Experiment 1.....	77
Table 3. Written production times (ms) in relation to gaze time associated with written production and written production duration for both adults and children on words manipulated for length and frequency in Experiment 1.....	78
Table 4. Children’s response accuracy in percent on words manipulated for length and frequency in Experiment 2.....	99
Table 5. Summary of LMMs for children’s response accuracy on words manipulated for length and frequency and pseudowords manipulated for length in Experiment 2.....	99
Table 6. Gaze times (ms) in relation to first fixation duration, gaze duration, total time, and fixation counts for children on words manipulated for length and frequency, and pseudowords manipulated for length in Experiment 2.....	101
Table 7. Summary of LMMs for first fixation duration for children on words manipulated for length and frequency, and pseudowords manipulated for length in Experiment 2.....	102
Table 8. Summary of LMMs for gaze duration on words manipulated for length and frequency, and pseudowords manipulated for length in Experiment 2.....	103
Table 9. Summary of LMMs for total time on words manipulated for length and frequency, and pseudowords manipulated for length in Experiment 2.....	104
Table 10. Summary of LMMs for first pass fixation count on words manipulated for length and frequency, and pseudowords manipulated for length in Experiment 2.....	105

Table 11. Summary of LMMs for total fixation count on words manipulated for length and frequency, and pseudowords manipulated for length in Experiment 2.	106
Figure 8. Demonstration of shapes in the spatial recall assessment.	133
Table 12. Summary of LMMs for encoding times and number of gaze lifts on words manipulated for length and frequency in Experiment 1 in relation to children’s reading abilities and working memory capacities.	135
Table 13. Summary of LMMs for children’s written production behaviour on words manipulated for length and frequency in Experiment 1 in relation to children’s reading abilities and working memory capacities.	138
Table 14. Characteristics of the 6-7 letter words presented to adults and children in Experiment 3, manipulated for the number of syllables.	166
Table 15. Summary of statistical differences between the stimuli presented to adults and children in Experiment 3, in relation to word frequency, bigram frequency and age of acquisition.	166
Table 16. Gaze times during encoding (ms) in relation to total encoding, initial encoding and writing onset on words manipulated for number of syllables in Experiment 3.	170
Table 17. Summary of LMMs for total encoding, initial encoding and writing onset times on words manipulated for number of syllables in Experiment 3, for both adults and children.	171
Table 18. Children’s secondary encoding times (ms) on cumulative and individual secondary encoding episodes on words manipulated for number of syllables in Experiment 3.	174
Table 19. Summary of LMMs for children’s secondary encoding times on cumulative and individual secondary encoding episodes on words manipulated for number of syllables in Experiment 3.	175
Table 20. Written production behaviour in relation to gaze times and written production duration (ms) for adults and children on words manipulated for number of syllables in Experiment 3.	177
Table 21. Summary of LMMs for written production behaviour in relation to gaze times and written production duration for adults and children on words manipulated for number of syllables in Experiment 3.	178
Table 22. Measures of children’s gaze lift behaviour in relation to the likelihood, number and location of gaze lifts, for words manipulated for the number of syllables in Experiment 3.	181

Table 23. Summary of LMMs for children’s gaze lift behaviour in relation to the likelihood, number and location of gaze lifts, for words manipulated for the number of syllables in Experiment 3.....	183
Table 24. Summary of LMM model for children’s total secondary encoding times in relation to reading ability and verbal memory capacity on words manipulated for number of syllables in Experiment 3.....	207
Table 25. Summary of LMM model for individual differences in children in relation to the number gaze lifts for secondary encoding episodes on words manipulated for number of syllables in Experiment 3.....	209
Table 26. Summary of LMM model for individual differences in children in relation to the amount of secondary encoding time spent on the first return encoding visit on words manipulated for number of syllables in Experiment 3.....	211
Table 27. Summary of LMM model for individual differences in children in relation to the amount of secondary encoding time spent on the second return encoding visit on words manipulated for number of syllables in Experiment 3.....	212
Table 28. Summary of LMM model for individual differences in children in relation to the amount of secondary encoding time spent on the third return encoding visit on words manipulated for number of syllables in Experiment 3.....	213
Table 29. Summary of LMM model for individual differences in children in relation to children’s gaze time associated with written production on words manipulated for number of syllables in Experiment 3.....	214
Table 30. Summary of LMM model for individual differences in children in relation to children’s written production duration on words manipulated for number of syllables in Experiment 3.....	215
Table 31. Summary of LMM model for individual differences in children in relation to the proportion of gaze lifts that occurred at syllable boundaries on words manipulated for number of syllables in Experiment 3.....	216
Figure 9. The Simple View of Writing, adapted from Berninger and Amtmann (2003).	238
Figure 10. The basis of the framework for a single word copying task.....	245

Acknowledgements

First, to Julie Kirkby; it was an honour to be your first PhD student. Your enthusiasm and dedication to your work were inspiring. Thank you for your support and encouragement over the past four years.

Second, to Simon Liversedge; not to overload on “mushy stuff”, but I simply would not be here without you. Thank you for putting me on this path, then sharing your precious time and extensive wisdom to guide me through.

Next, to my fantastic colleagues. I would like to thank Bernhard Angele for his endless patience and seemingly just as endless statistical knowledge. To all the wonderful PhD students in P104, thank you so much for your continuous friendship and reinforcement. Ania, Simon, Nabil and Michele will understand that the cake and wine were relatively inconsequential, obviously.

For giving me several pairs of hands at once, I turn to Alicia, Jess, Lucy and Holly. Thank you for the kind donations of your weekends; your help and optimism were much appreciated. To the parents and children who came to take part, I am sincerely thankful for your willingness and valuable time.

Finally, my gratitude goes to my close family: Frances Clayton, Roger Laishley and Faye Laishley, for their unwavering support (not biased in the least, of course) and love. To my mother, Alex, who held me together through the entire adventure, when you said I would always end up writing a book, I am not sure this was what you had in mind.

Alas, here we are.

CHAPTER 1

A REVIEW OF THE LITERATURE

Children spend their first few years at school developing literacy skills, primarily the abilities to decode, comprehend and produce printed text (Kennedy et al., 2012). In relation to how children learn to read and write, developmental research has specified how children learn to decode (Ehri, 1991; Frith, 1985) and construct (Hayes & Flower, 1980; Mccutchen, 2011) printed text. As such, classroom literacy tasks often focus on either reading or writing activities in isolation, and the course of typical progress in developing reading and writing abilities (Abbott, Berninger, & Fayol, 2010; Share, 1995) has been well documented.

Yet, classroom activities often require children to co-ordinate reading and writing activities within the same task, such as copying from the classroom board. There is theoretical uncertainty about whether reading and writing processes occur similarly when they are co-ordinated (during copying) as when they are carried out in isolation. When co-ordination is required, there is an additional sub-process of mental representation.

Although much is known about reading, mental representation and written production, surprisingly, an understanding of how children co-ordinate these three cognitive sub-processes (with the output of one task becoming the input for the sequential task) is less developed. A word copying paradigm presents an ideal opportunity to investigate how these three constituent sub-processes of a copying task are co-ordinated.

What will become clear is that there is not a lack of understanding altogether, but studies investigating the cognitive processes in word copying have primarily focused on either an encoding or production sub-process, not how encoding and production operate in co-ordination. The descriptions of behavioural events in these studies have informed key terminology in relation to a word copying task that will be used throughout this Thesis. In a word copying task, the *copier*, the individual performing the task, performs a cycle of behavioural events. Within a single *cycle*, the *reference model*, the word to be copied, is visually encoded. Hence, the initial question within this Thesis concerned the nature and the amount of the information encoded. After encoding, the information is mentally represented. Accordingly, another topic within this Thesis concerns the role of verbal and spatial working memory during the copying task. Next, the copier must programme writing events to produce the *copy*, the

written replica of the reference model. Therefore, another theme within this Thesis concerned the extent to which the nature of the information in encoding is the same as in production. It might be that one cycle of encoding, representation and production is not sufficient to produce a complete written copy. In this case, another cycle might be initiated by a *gaze lift*, moving the eyes from the copy to the reference model to begin an additional copying cycle, starting again with encoding.

The next section of this Chapter provides a brief initial review of studies outlining what linguistic information readers use to decode printed text. This is important to frame an understanding of how copiers might encode information during copying. Then, potential similarities and differences between decoding during reading and encoding during copying will be considered. After that, studies that have investigated a word copying task will be reviewed in detail. These studies will be presented in relation to each sub-process of the copying task: encoding, mental representation and then written production.

1.1 What Information do Readers use to Decode Words?

A key concept of learning to decode words is *alphabetic mapping*, associating letter sounds with specific letters (Ehri, 1991). In English, there can be a range of particular phonemes that can be associated with specific graphemes. This is *feed-forward* inconsistency, from spelling to sound for reading (Ziegler, Stone, & Jacobs, 1997). Even worse, there is also *feed-back* inconsistency from sound to spelling for writing (Ziegler et al., 1997).

In order to decode words, children need to learn a range of phoneme and grapheme relationships, and the linguistic rules that determine which association is correct in that single case. To correctly decode word units, children must use the string of letters which, taken together, represent the most unambiguous pronunciation. The larger the letter string needed, the deeper the orthographic *grain size* of the language (Ziegler & Goswami, 2005), and the more beginning readers struggle to decode words (Goswami, Ziegler, Dalton, & Schneider, 2003). Letter strings smaller than a word, *subword units*, can form defined linguistic units, such as a phoneme or a syllable. Even though skilled readers no longer need a phonologically mediated route to recognise words, they still activate a range of different size subword units. This includes morphemes (Taft & Forster, 1975; Alvarez, Carreiras, & Taft, 2001), syllables (Drewnowski & Healy, 1980; Carreiras & Perea, 2002), and phonological sub syllable components such as word onsets (Bowey, 1996), rimes (Bowey, 1990; Treiman,

Mullennix, Bijeljac-Babic, & Richmond-Welty, 1995), graphemes (Rey, Ziegler, & Jacobs, 2000) and the smallest units of individual letters (Rastle & Coltheart, 1998). In reading tasks, all of these units have been suggested to still play a role in visual word recognition.

Like adults, children use subword units to decode words, but because children are still developing their linguistic knowledge, the age of the child determines what linguistic information is used. Potential linguistic information that children might use to decode words will now be considered in three categories: *orthography*, information about the individual letters and letter patterns; *phonology*, information about the sound patterns; and *etymology*, information about the word origins, or how the word form was developed in relation to other linguistic units in the language.

1.1.1 Orthographic information.

The first step in decoding words is encoding orthography, namely letter identity and position within the letter string. Each letter form is recognised by particular feature contours in a fast feature analysis process (Smith, 1973). At the beginning of reading acquisition, children read letter-by-letter to extract sound information, reading by serial phonological decoding. Grainger and Ziegler (2011) suggested that children shift towards parallel letter recognition in order to efficiently map letters onto orthographic representations of words rather than phonetic representations of corresponding letter sounds. According to Ehri's theory of how children learn to read, children begin to consolidate letter sequences like "ed" and "ing" in the alphabetic phase of reading. This starts to mark a transition from decoding words in single letter-sound units to developing sight word reading (Ehri, 2010). By the age of 6, children who are better at recognising letter identities can encode more letters in parallel (Reilhac, Jucla, Iannuzzi, Valdois, & Demonet, 2012). Then, the ability to recognise a greater amount of letters in parallel contributes towards better reading performance throughout primary school (Bosse & Valdois, 2009). Children have still not finished fully developing letter recognition skills by the age of 10, and even age 12, children still vary in how many letters they can identify from a rapidly presented trigram (Kwon, Legge, & Dubbels, 2007). By the age of 12, children are still developing efficiency of letter identification, and have still not yet developed adult-like speed of parallel letter identification.

As well as letter identity, the letter positions determine global word shape and fine detailed letter order which differentiates similar words. Theories of how skilled readers cognitively represent a sequence of letters have been much debated. The split

fovea model (Shillcock, Ellison, & Monaghan, 2000) is unique in that retinopic coordinates play a role in distinguishing letter order. Otherwise, models describe methods of binding letter identities with position irrespective of where the images fall on the retina. Position coding systems can be split into position-specific coding and context schemes. Position-specific coding bases specified letter location on the distance between each letter and particular locations within the word, such as the word beginning (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001); the word centre (Caramazza & Hillis, 1990); or by using both initial and final letters as anchor points (Fischer-Baum, Charny, & McCloskey, 2011). Context location models determine the location of each letter not in terms of a numbered letter position, but in relation to surrounding letters. One suggestion is that sets of letter clusters provide information about relative letter position in the context of surrounding letters (Seidenberg & McClelland, 1989). The Open Bigram model suggests pairs of letters, both adjacent and non-adjacent, provide information (Schoonbaert & Grainger, 2004). The Overlap Model distributes letter positions so that a letter is also associated to some extent with the letter position before and after it (Gomez, Ratcliff, & Perea, 2008). In the SERIOL model, some bigrams receive more activation than others, with bigrams further towards the word end receiving sequentially less activation (Whitney, 2001). Alternatively, spatial coding is used in the SOLAR model, where each individual letter receives a certain amount of activation, and the relative activation of each letter determines the word match (Davis, 2010).

However, these models aim to explain skilled letter encoding rather than directly address how developing readers might encode letter positions. In 7-11 year old children, the word recognition operation is not as selective as in skilled adults, because similar but not necessarily identical inputs can be matched with word representations (Castles, Davis, & Letcher, 1999). Castles, Davis, Cavalot and Forster (2007) described a developmental process of *lexical tuning*, during which letter identity and position encoding starts off as flexible, with near-match input helping word recognition. Then, encoding letter identities and positions becomes more specified with age. For example, the transposed letter primes (*lpay*) and substituted letter primes (*rlay*) facilitated the word recognition (*play*) of 8 year old English children, though the same children at age 10 showed smaller transposed letter facilitation and no substituted letter priming. In this case, the younger children's recognition was helped by primes of both the right letters in the wrong order, and a prime with most correct letter identities, in the right order. By the time those children were two years older, they were slower to accept the right letters

in the wrong order because letter position coding had become more specific. Castles et al. (2007) suggested that word recognition processes are initially broad with limited specificity, but become more refined in order to distinguish between similar words in order to accommodate a growing lexicon. Even between orthographically opaque languages, the speed of lexical tuning depends on the characteristics of the language children are learning. For example, both transposed and substituted letter primes still facilitated word recognition in French children at 10 years old (Lete & Fayol, 2013), suggesting that the tuning process developed at a comparatively slower rate than the English children, who had become more selective in processing letter identities and positions by the same age.

Overall, the exact method children use to code letter identities in certain positions is not well clarified, but the important point is that the specificity of letter position coding is less particular in children than in adults, even by the age of 10 years old.

1.1.2 Phonetic information.

One core part of word decoding lessons is understanding phonology (Department of Education, 2014), finding regularities in how letters represent sounds. Working out how letters and sounds correspond to each other enables children to break down letter strings into decodable segments through *articulatory phonological recoding*, generating letter-sound associations. In English schools, this begins in the first year, when children are 4 or 5 years old (Department of Education, 2014). Phonological recoding can be done either by *synthesising*: sequentially blending all phonemes together in the letter string; or *analysing*: identifying and pronouncing each segmented phoneme individually, though typically children learn phoneme synthesis before phoneme analysis (Pufpaff, 2009). With 4 year old children, synthesising was easier than analysis, and the more phonemes in the word, the harder the task (Goldstein, 1976). Three years later, children preferred to use more sophisticated linguistic units for analysis. Rather than analysing words into individual phonemes, Fox and Routh (1975) showed that children were better at analysing words into individual syllables, with ceiling accuracy by the age of 7. Ability to analyse words into increasingly larger phonetic units developed between the ages of 3-6, but levelled off between 6 and 7 years.

Although syllables are considered to be “the primary linguistic unit” (Goswami, 2008), the characteristics of the syllable itself also determine whether or not syllables are a useful unit for word decoding. For example, 6 and 8 year old French children only consistently used syllables to decode 7 letter bisyllabic words if those syllables were high frequency, preferring to use smaller grapheme-phoneme relationships for low frequency syllables (Maïonchi-Pino, Magnan, & Écalle, 2010). Only by the age of 10 years were children consistently using both high and low frequency syllable units to decode words.

At 6 years old, reading ability impacted the size of the phonetic unit children used for decoding. Colé, Magnan and Grainger (1994) created two pseudoword lists made up of the same graphemes, but either containing high (*vess*, *fi**p*) or low frequency (*fiss*, *ve**p*) rimes – the vowel and consonant ending of the syllable. They found that lower ability children only used individual phonemes, performing equally well on both lists. Mid ability children relied on rimes to some extent, but the higher ability readers were better at decoding the higher frequency rime list, demonstrating that these rimes were a functional unit of information for decoding. In addition, phonetic rime information was most helpful when it overlapped with orthographic rimes. For instance,

in both words and nonwords, 6 year olds made more accurate analogies between letter strings sharing both orthographic and phonological rimes (*mail* to *hail*) compared to only shared phonological rimes (*mail* to *veil*), (Savage, Deault, Daki, & Aouad, 2011; Wood & Farrington-Flint, 2001).

These studies show that phonological information is important for word decoding, and children can use a range of different sized phonetic units. By the age of 7, children are capable of using phoneme, rime and syllable units to decode words, but phonological information is not used in isolation from orthographic information. In addition, reading ability development is important for word decoding, as children have more linguistic knowledge to draw on when working out a range of phonetic units.

1.1.3 Etymological information.

Particularly in orthographically deep languages, phonetic information may not be the most useful, accurate cue in word decoding. Knowing how the word has been formed may be useful in order to work out how the words might be “built” from a base unit. Even children of 5-7 years can be taught to identify a word’s morphology, how the word is structured, in order to overcome inconsistent grapheme-phoneme relationships. For example, children were able to learn how base word forms (*magic*) are used to build derived words (*magician*). They were using morphological information in order to decode the derived word, even though newly added letters changed the phonetic pronunciation of the base form (Devonshire, Morris, & Fluck, 2013). When small phonetic units are unhelpful for accurate decoding, bigger units like morphemes can contribute towards identifying words.

To review the information presented about how children decode words, between the ages of 7 and 10 years old, children are still developing the efficiency with which they visually encode letter identities and letter positions. After visual encoding, children go beyond the literal representation of the orthographic forms of printed text and cognitively process information associated with the phonology and morphology of a range of linguistic units.

1.2 Encoding Information in a Copying Task

Next, discussion will consider how adults and children might draw on linguistic knowledge, specifically in relation to a copying task. First, tasks of reading and copying will briefly be compared. Then, having outlined above the linguistic units used in decoding during reading, the literature review will consider functional word and

subword units during copying. Each section is divided into the three constituent sub-processes of a word copying task. These sub-processes are encoding, mental representation, and production, and will be addressed in turn.

1.2.1 How is encoding different from reading?

Even in adults, the task goals can change the extent to which people need to linguistically process stimuli to complete the task (Nelson, Cottrell, Movellan, & Sereno, 2004). Whilst word encoding is essential during reading for comprehension, there is a difference between reading and encoding. The goal of *reading* is to construct meaning from printed text, and this emphasis on understanding words is explicit, not just implied (Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001). The goal of *encoding* is to visually capture and mentally represent the text; it does not necessarily follow that text must be represented or recognised as individual words. This is evidenced by the way in which 5 year old children behaved when they successfully made a handwritten copy of words containing letter identities they had not yet learned, and words that they had not yet acquired. Even though the children would not have been able to identify all the letters, or access a semantic representation of the letter string, they could accurately make a written copy of the letters and words (Rieben & Saada-Robert, 1997; Rieben, Saada-Robert, & Moro, 1997). Therefore, printed text can be copied without letter or word recognition. That is not to say that linguistic information plays no role in facilitating copying. Copying meaningless characters is a more effortful, laborious process when there are no stored familiar representations of those characters, or unfamiliar letters from unknown languages (McBride-Chang, Chung, & Tong, 2011). Even when copying familiar letters, children can copy more letters in the same amount of time if the letters are arranged into meaningful words than unpronounceable consonant strings (Grabowski, Weinzierl, & Schmitt, 2010).

In encoding, copiers may rely more on orthographic and phonetic characteristics than semantic meaning. In sentence reading, syntactic structure contributes towards good comprehension. In “garden path” sentences which contain an ambiguous syntactic structure, reading times and regressions increase (Frazier & Rayner, 1982; Rayner, Carlson, & Frazier, 1983). Therefore, parsing sentences with meaning is integral for reading. In a copying task, there is no similar support for units larger than individual words, such as phrases or sentences. When adults made copies of sentences by typing on a keyboard, neither typing speed nor accuracy were decreased when typing sentences with a random word order compared to typing the same sentence with the

grammatically correct word order (Shaffer & Hardwick, 1968). In addition, while readers were quicker to process a predictable than unpredictable word based on sentence context (Inhoff, 1984), even with exactly the same sentences, there was no predictability effect when copytyping (Inhoff, Morris, & Calabrese, 1986). Unlike reading, in a copying task, understanding meaning may not be necessary for task completion.

In addition, when adults copied single passages, the mode of production changed speed of task completion, in that it took more copying time when handwriting compared to typing (Brown, 1988). There are at least two possible explanations for this. One may be that only the physical motor movements constrained copying speed. The second might be that the mode of production changed the way in which words were processed. If the cognitive demands of copying by hand involved repetitive cycles of encoding and producing in smaller units than copytyping, the copying time would also have increased. In this case, during copying task in which production occurred by handwriting, semantic units may be even less important than in a copying task in which production occurred by typing, from now on referred to as *copytyping*.

Within the theoretical context of copytyping, Salthouse (1984, 1986) combined dominant contemporary frameworks into a four-component exploratory model. His model is specific to skilled adult performance, and very particular in its consideration of typed copying alone. However, Salthouse explicitly stated that perceptual and cognitive processes before written production were not the same as in reading. He divided encoding processes into two serial activities. The first was labelled “input”, in which text was converted into chunks in a manner involving more than just registration or perception, but not necessarily fusing units to determine meaning. This was because Salthouse theorised that the goal of copying was to decompose characters in an opposite manner to integrating meaning during reading. The second was labelled “parsing”, in which the chunks of text were then further decomposed into ordinal strings of characters.

When applying this theoretical context to a handwritten copying task, several questions emerge. The overarching issue relates to developing an understanding of the units over which encoding and production operate during copying. More specifically, how much can accounts of language processing and copytyping inform an understanding of handwritten copying across both adults and children; how can copying performance be measured in a way that quantifies the units that are functional over both encoding and production; and how does copying behaviour change in relation to reading and memory abilities?

1.2.2 Encoding whole word units during copying.

Adults. Similar to reading-for-meaning (Rayner & Duffy, 1986), adults visually encode and cognitively process whole words during copytyping. Copytyping studies show frequency effects on fixation durations, as adults spend more time looking at low frequency compared to high frequency words in English (Inhoff, Briihl, Bohemier, & Wang, 1992; Inhoff, Morris, & Calabrese, 1986). Similar patterns of gaze duration have been found during handwritten copying in French (Lambert, Alamargot, Larocque, & Caporossi, 2011). Lambert, Kandel, Fayol and Espéret (2008) also found that adults took longer to start writing lower frequency words, suggesting this was because difficulty in activating the word unit increased the time needed for encoding. Despite differences in task demands of copying compared to reading, for adults, a whole word was a functional encoding unit. This idea is supported by findings of a lexicality advantage, in that it took longer for adults to start writing pseudowords compared to real words in French (Lambert, Kandel, Fayol, & Espéret, 2008), replicated in French and Spanish for adults and adolescents (Kandel, Alvarez, & Vallée, 2006), and again in Spanish adults (Afonso, Suárez-Coalla, & Cuetos, 2015).

Children. Similarly, in 8-10 year old children, Kandel and Perret (2015) found that children took less time to start writing higher frequency words, and also for words with higher frequency grapheme-phoneme associations. They suggested that this reflected the ease of accessing word units. Between being presented with the stimuli, and starting written production, children were engaging in cognitive operations sensitive to characteristics of the whole word unit. These operations happened faster for words occurring often within their print experience, and words that obeyed dominant phonetic rules. If children were activating word units just like adults, this would be the expected pattern of results. This would mean that children were capable of encoding 5-8 letter whole words.

However, Kandel and Perret did not report two key details. First, how many words were copied with only one encoding episode, without needing repeated cycles of encoding and production. Second, whether word frequency affected short and long words to the same extent. In relation to the first point, it may be that even if word units were initially encoded, children may not be able to efficiently maintain a complete word representation throughout production. Kandel and Valdois (2006) found that 8-10 year old children still needed more than one encoding episode on 4-7 letter, highly frequent, regular words (though they do not report the probability of needing more than one encoding episode). This may mean that although whole word units may be encoded

initially, they may not be consistently functional over every encoding episode, when part of the word has already been written. In relation to the second point, there may be a limit on the maximum number of letters children can encode. With words ranging from 5-8 letters, it may be that only the shorter words were driving the frequency effects. Even if children are capable of encoding whole words, word encoding may not be consistent, especially for longer words.

Is word encoding automatic? The idea that word recognition is not automatic is controversial. After discussing a large bank of evidence for automatic word recognition in young readers, Stanovich (2000) concluded that word recognition is automatized to adult levels by the age of 8 years old. In an array of classical paradigms in which successful performance relies on ignoring a word's meaning, if word recognition was automatic, children's performance would suffer from the presence of a distracting word. This was the case, suggesting that children could not control word recognition. For instance, Bub, Masson and Lalonde (2006) observed Stroop interference with children aged 7-11 years. When presented with the names of colours, and asked to name the colour in which the word was written, children were more accurate, and quicker to respond when the word matched (*red* written in red ink), compared to conflicted with (*red* written in green ink), the ink colour. These findings indicated that children could not suppress word recognition, even though word recognition interfered with task goals. This supported the idea that word reading occurred automatically.

Yet, the story is more complicated, because Bub et al. go beyond looking at the traditional measures of accuracy and response time in the Stroop paradigm to show the extent to which children engaged in suppression of word recognition. In their distributional analysis of response latencies, the critical comparison was in the Stroop effect on the slower latencies. Their idea was that the more children engaged in suppression of word recognition, the smaller the difference between the response latencies of incongruent trials (in which the coloured characters forms a word that did not match the colour of the ink) and neutral trials (in which the coloured characters were asterisks that could not engage word recognition processes). This difference was smaller for children under the age of 9 than for children over the age of 9, suggesting that younger children engaged in more suppression of word recognition. Bub et al. explained the apparent contradiction of the accuracy data by suggesting that younger children struggled to maintain the correct naming task goal. The important point here is that children did not fail at the task because they could not suppress word recognition. In relation to the idea that word reading is not automatic, Bub et al.'s distributional

analysis of response latencies suggest that young children did not consistently read words irrespective of task demands. This goes against the idea that word reading is always automatic.

Still, the idea that words are automatically recognised also rests on the premise that children visually access all of the letters needed in order to recognise the word. In copying, this may not be the case; the additional tasks of representing and producing the encoded information may modulate the amount and/or nature of the encoded information. If a child's visual attention span was restricted by available cognitive resources to the extent that all of the letters in a word were not visually processed, print recognition may proceed on subword units instead. It may be that in a copying task, children do not automatically read whole words.

How much information can be visually accessed during encoding? When children fixate on a word, not all letters in the fixated word are equally visible (Brysbart & Nazir, 2005). One reason for this is visual acuity; the closer a letter is to the point of fixation, the clearer the visual detail about the letter (Rayner & Bertera, 1979). Another reason is the amount of available cognitive resources; even controlling for acuity, reading speed will still only be as fast as processing capacity allows (Miellet, O'Donnell, & Sereno, 2009). The more difficult the information currently being processed in the fovea, the higher the foveal load; the higher the foveal load, the less information is gained about upcoming parafoveal information and the slower the reading speed (Henderson & Ferreira, 1990).

To demonstrate, McConkie and Rayner (1975) developed a gaze contingent moving window sentence reading paradigm, masking text a prescribed distance away from fixation so that this information was unavailable. The idea being that sentence reading speed would slow down if the amount of text available was less than the amount from which information could be extracted; then, increasing the available characters beyond the maximum that could be used would not increase reading speed. This *perceptual span*, in which useful information can be accessed, extended as far as 4 characters to the left of fixation and 14-16 characters to the right of fixation in skilled readers (see also Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Rayner, Well, & Pollatsek, 1980; Underwood & McConkie, 1985). Compared to adults, children aged 7-11 years have a smaller perceptual span, only needing 8 characters to the right of fixation for maximal reading speed (Rayner, 1986). When reading age-appropriate text, 7 year olds could use information from only one upcoming word, though 9 and 11 year olds reached their normal speed with two upcoming words visible. When Rayner

increased cognitive task demands by asking 9 year old children to read difficult college-level text, their perceptual span decreased. They were only able to use information from one upcoming word, because more of their processing resources were attributed to a smaller selection of letters around fixation. Drawing this research together, when fixating on a word, children access a smaller amount of upcoming linguistic information than adults, and the amount is further decreased when task demands are heightened.

Few studies look at how much parafoveal information individuals can use in a copying task. Inhoff and Wang (1992) adapted McConkie and Rayner's moving window paradigm to a gaze contingent copytyping study in order to test whether there were differences in the perceptual span in copytyping compared to reading. Adult typists were asked to copytype sentences, while only limited information was available beyond the point of fixation. They only needed 7 visible characters to the right of fixation for typing to proceed at normal speed, half the amount of characters needed in reading tasks. Therefore, encoding seems more resource intensive in copying than reading, perhaps because information must be represented and retained in readiness for written production. Furthermore, it may follow that children's perceptual span during a copying task is (as is the case during a reading task) smaller than the adults' perceptual span. It may be that during copying, in a single encoding episode, children do not access all the letters in the fixated word. If children's perceptual span was halved in copying compared to reading, as is the case for adults, children would only be able to visually process about 4 characters in a single fixation.

In a handwritten paragraph copying task, although Bosse, Kandel, Prado and Valdois (2014) did not track fixation locations, they did take a measure of how many letters children wrote during each cycle of encoding and production. Critically, they demonstrated a link between 8-11 year old children's visual attention span and the number of letters children wrote between encoding episodes, about 4-6 letters overall. Then, even controlling for reading ability, a greater visual attention span predicted more letters written between encoding episodes. First, it may be that children are only able to encode a limited amount of information, irrespective of the total amount of information available. Second, it may be that children prefer to copy in unit sizes of between 4 and 6 letters. If this is the case, in a word copying task, the functionality of a word unit might depend on the word length, only being functional in children for relatively short words with about 4 letters.

Overall, adults and children may rely to a different extent on whole word units during encoding information in a copying task. While adults seem to preferentially

encode in whole word units, evidence for a whole word preference in children is less substantial. Although children may be capable of whole word encoding during copying, this may not be the case consistently. It may be that a more restrictive perceptual span encourages encoding of smaller sized units for children.

1.2.3 Encoding subword units during copying.

Adults. The studies discussed in this section approach encoding as a secondary focus. They do report the measure of *writing latency*, the time between stimuli presentation and starting written production, as reflective of encoding (though also including preparatory spelling processes).

Morphemes. The largest subword unit to serve as a processing unit in handwritten production is a morpheme, the smallest grammatical unit of meaning. Kandel, Alvarez and Vallée (2008) explored whether adults activated base root and suffix units. They found that when adults encoded suffixed words (*boulette*; little ball, with the suffix *ette* classifying the size of the ball) and pseudo-suffixed words (*goélette*; a type of boat, with *ette* not relating to the size of the boat), adults took 470ms longer to start writing suffixed than pseudo-suffixed words. This was because when encoding suffixed words, there was an extra time-consuming step of decomposing the word into the component parts of root and suffix, suggesting these units are activated separately during copying. In the pseudo-suffixed words, there was no morphological decomposition, as the letters forming the pseudo-suffix did not form their own grammatical function. The pseudo-suffixed words were encoded as one unit, taking comparatively less time. In another study, Kandel, Spinelli, Tremblay, Guerassimovitch and Alvarez (2012) replicated the findings that adults took more time to start writing suffixed than pseudo-suffixed words. In contrast, prefixed and pseudo-prefixed words were encoded in the same amount of time, suggesting that adults did not decompose words into prefix and root. While adults may not exclusively activate only whole word units, some subword units are more functional than others.

Syllables. Most copying research investigates syllables, the largest subword unit of sound. Lambert, Kandel, Fayol and Espéret (2008) found that lexicality of the stimuli determined whether or not syllables were activated. Adults copied 8 letter words and pseudowords, with 2 or 4 syllables. Writing latencies were 300ms longer for 4 than 2 syllable pseudowords, but this difference was not seen for real words. In a second experiment, irrespective of word frequency, the number of syllables did not affect

writing latencies of 2 or 3 syllable words. Syllable units were not activated if there was a word entry in the lexicon, even if that entry was difficult to access.

Then, Lambert et al. adjusted the copying paradigm in a third experiment to reduce noise in writing latency measures. After encoding, participants were to place their pen in a checkbox on the digitiser, and then program writing events in an adjacent box. In this way, encoding and mental representation were separated from preparatory writing processes like spelling. Despite disassociating encoding from spelling, the number of syllables still only modulated encoding time for pseudowords, not words. This might mean that the syllable was not a functional unit of encoding for adults.

An alternative explanation is that writing latencies were not sensitive enough to detect small effects. Lambert, Sausset and Rigalleau (2015) asked adults to copy 3 syllable (*la.va.bo*) and 2 syllable (*citron; saleté*) words. They considered syllable units (units of pronunciation containing one vowel sound, sometimes but not necessarily accompanied by surrounding consonants) of both phonetic syllables (syllable units in relation to the spoken representation of the word) and orthographic syllables (syllable units in relation to the written representation of the word). Some of their 2 syllable words (*cit.ron*) had the same number of phonetic and orthographic syllables. Other 2 syllable words contained an internal mute e (*sal.e.té*), creating 2 phonetic syllables, but 3 orthographic syllables. There was a numerical difference in that latencies for *citron* were 43ms shorter than *saleté*, which were only 9ms longer than *lavabo*, but these differences were not consistent enough to be significant. Orthographic and phonetic syllables may have a subtle effect on encoding time, but adults may decompose these units too quickly to observe significant differences in measures of writing latency.

Children. While Kandel and colleagues have started to develop an understanding of children's written production during copying, they did not always report measures of writing latency. So far, studies have not addressed whether children activate subword units during encoding, or across both encoding and production. As discussed towards the beginning of the introduction, children are aware of morpheme and syllable sized units, and can employ these units during word decoding tasks. If children do activate subword units during encoding, morpheme and syllable units may be functional linguistic units that facilitate encoding.

1.3 Mentally Representing Information in a Copying Task

Unlike encoding, it is difficult to access time-based measures of representation separate from encoding and production. After encoding, copiers might use working

memory to maintain a mental representation of the encoded information, while programming written production. Only a limited amount of information can be held in working memory. Factors such as resource limitations (Just & Carpenter, 1992), time-based decay eroding representations (Nairne, 1990) or mutual interference between items (Oberauer & Kliegl, 2001) can reduce recall (Baddeley & Hitch, 1974; Baddeley, 1992, 1996, 2003a). If forgetting occurred, copiers may make gaze lifts, moving their eyes from the written copy to the reference model, for an additional encoding episode. It might be that gaze lifts between the copy and the model could be informative about how many letters can be encoded, retained and produced altogether.

Rieben, Meyer and Perregaux, (1989, cited in Kandel & Valdois, 2006) took this approach to show links between working memory and copying, manually observing when children looked back to the reference model during written production. When 5 and 6 year old French children copied individual words and short phrases, even within the 5 year olds, children with less advanced reading, memory and writing abilities were more likely to need encoding episodes between writing individual letters (very small units of encoding) compared to between writing two or more letters (still small, but comparatively larger units of encoding). During copying, remembering and producing words with only one encoding episode may be beyond children's working memory limits. Perhaps the word was not fully encoded, or even if the whole word was encoded, forgetting could occur before finishing written production. These findings suggest that memory capacity may impact on copying, but it is difficult to distinguish whether the impact occurs during encoding, mental representation and/or production.

1.3.1 Representing whole word units throughout production.

Adults. Only one study looked at gaze lifts in adult copying, finding that adults were rarely unable to retain whole words throughout production (Lambert et al., 2011). As such, links between memory and copying in adults are underspecified, partly due to limited gaze lift behaviour.

Children. This is not the case with children, who use more regular gaze lifts when copying. Both children's age and their native language determine how much they rely on gaze lifts.

For young children, 4 or more letters are too many to copy in one cycle of encoding and production, but children copying in a shallower orthography can copy a greater number of letters. When Kandel and Valdois (2006a) asked 6 year olds to copy 4-10 letter words, French children almost always needed gaze lifts, but Spanish children

could retain a whole word half the time. By 7 years old, French and Spanish children could retain whole words more often, 40% and 61% respectively. Even then, it might have been that children were only able to remember the shorter words, as Kandel, Soler, et al. (2006) showed that French 6-7 year olds need gaze lift 85% of the time for 7 letter words.

Between ages 6-8 years, children copied 4-7 letter words with decreasing reliance on gaze lifts, with 9-10 year old children rarely needing lifts (Kandel & Valdois, 2006b). Overall, older children retained whole words more often than younger children, but even the 10 year old children could not retain 7 letters all the time.

So far, it is unclear whether children's copying cycles are based on a critical number of letters. In a paragraph copying task, 8 and 11 year old French children copied all 88 words with 34 and 35 gaze lifts, respectively (Bosse et al., 2014). This might suggest that children were capable of retaining more than one word in a single copying cycle. Overall, children copied 4-5 letters between each gaze lift. However, it is likely that the paragraph contained both content and function words of varying length. Whether or not children can remember less than, exactly, or more than a single word may be due, at least in part, to the number of letters they must represent in memory.

1.3.2 Representing subword units throughout production.

When children do make a mid-word gaze lift, are those gaze lifts located after letters that mark systematic linguistic units?

Syllables. Although research has not clarified whether children activated syllable units during encoding, syllabic structure seems to act as a cue for gaze lifts during written production. Transler, Leybaert and Gombert (1999) found that French 7 and 8 year olds were more likely to make gaze lifts at a syllable boundary than after other letters within a syllable. Kandel and Valdois replicated this pattern in French 6-7 year olds for 4-7 letter (Kandel & Valdois, 2006b) and 4-10 letter words (Kandel & Valdois, 2006a). In contrast, Spanish children did not make systematic gaze lifts at syllable boundaries, suggesting that they used different subword units (Kandel & Valdois, 2006a). In addition, French children's gaze lifts were not exclusively at syllable boundaries. Therefore, syllables were not the only factor determining how much information can be retained.

Humblot, Fayol and Longchamp (1994, cited in Transler et al., 1999) initially found that 6 year olds copied using letter-by-letter strategies, making gaze lifts irrespective of syllable boundaries. But, the 7 year olds showed evidence of using

syllable boundaries. Syllable units were used more often in familiar, regular words, suggesting that difficulty of encoding modulated what subword unit was functional.

Graphemes. Even when predominantly using smaller units than syllables, younger children's gaze lift behaviour was systematic. Rieben, Meyer and Perregaux (1989, cited in Kandel & Valdois, 2006a) found support for use of graphemes. Although 5 year olds were not using syllable boundaries of 3 or more letters, they regularly made gaze lifts between graphemes of 1-2 letters. It might be that a phonetic unit facilitates mental representation, allowing even young children to remember one or more whole letters, not just individual letter strokes. However, these studies did not relate production behaviour to how long participants looked at the to-be-copied word. Hence, it is difficult to distinguish incomplete encoding from forgetting. Even so, gaze lifts have so far been informative about the extent to which a subword unit can be encoded and mentally represented throughout production, in relation to whether mental representation might be on the basis of subword units.

A different approach to specify what happens in the mental representation sub-process is to look at individual differences. In real-world classroom tasks that involve storing some information while processing other information, children rely on working memory. This is evidenced by the way in which children with deficits in working memory show poor achievements in classroom tasks (Alloway, 2006). It may be that working memory skills contribute towards efficient mental representation during a word copying task that is a controlled analogy of a naturalistic classroom task.

The working memory system was first described as quick-access mental workspace for storage and planning (Miller, Galanter, & Pribram, 1960). Since then, the concept has been developed into a multicomponent model of memory (Baddeley & Hitch, 1974) and considered with specific relevance to language processing (Baddeley, 2003). Three core components of the model are the central executive, which controls two subsystems responsible for storage. The visuospatial sketchpad handles visual and spatial information; the phonological loop handles acoustic and verbal information. Each subsystem works by temporarily storing information, but information can only be held for a limited time. To stop the representation decaying, the stored representation must be refreshed by rehearsal. There is also a proposed limit to how much information can be stored, and this limit imposes a restricted capacity for storage of spatial and verbal information in working memory. The term *working memory capacity* refers to how much information individuals are capable of storing. The better an individual's performance on span tasks, designed to assess the maximum amount of information that

can be stored, the higher their working memory capacity. While scarce, there are a few studies that investigate a copying task in relation to working memory; spatial and verbal working memory will be considered in turn.

1.3.3 Spatial working memory.

Even in adults, copiers with a lower working memory capacity made more gaze lifts when copying words and phrases (Alamargot, Caporossi, Chesnet, & Ros, 2011). This might be due to only being able to store a smaller amount of information. However, allocation to either low or high memory capacity group was on the basis of joint low performance on both spatial and verbal memory span tasks, so it is unclear whether group differences were driven by spatial or verbal memory alone.

Grabowski, Weinzierl and Schmitt (2010) differentiated this in children, concluding that difference in copying performance was driven by spatial memory alone. They asked 7 and 9 year olds to copy character strings made up of either meaningful text, numbers or consonants, within 2 minutes. They found that copying speed did not correlate with either word span (as a measure of verbal memory), or listening span (as a measure of central executive functioning). However, in the older children, a greater visuospatial span was correlated with faster copying of numerical and consonant strings, but not meaningful text. One possibility could be that a better spatial memory facilitates targeting the correct area of text after a gaze lift. As children tend to make more gaze lifts than adults, accurate targeting behaviour may have more of a chance to impact on performance.

1.3.4 Verbal working memory.

The role of verbal working memory is even less clear, with no performance deficit in children with lower compared to higher verbal working memory capacity (Grabowski et al., 2010). However, at least in copytyping, prohibiting phonological rehearsal decreased the speed of written production in comparison to normal speed, which indicated that the cognitive processes involved in written production during copytyping relied to some extent on maintaining information in verbal working memory. Service and Turpeinen (2001) used a backwards copytyping task, presenting Finnish adults with one correctly spelled word at a time, asking them to type each word spelled backwards. First, they found that adults typed letter clusters, pausing every two or three letters. This indicated capacity limits in the amount of information that could be stored for planning production events. Importantly, half the participants typed under

conditions of articulatory suppression, which prevented the use of online phonological coding in memory. Service and Turpeinen argued that adults would need phonological memory to rehearse the letter clusters throughout written production, and to keep track of their place in the written copy – which letters had already been written, and which letters were yet to write. They found that articulatory suppression lengthened pause times only for long words over 7 letters, but not short, 5-6 letter words. This suggested that verbal working memory was needed to facilitate efficient written production, but only for long words.

1.4 Producing Information in a Copying Task

Copying studies focusing on production are most numerous, including typing and handwritten copying. One line of copytyping research investigated organisation and execution of skilled motor processing (Grudin, 1983; Ostry, 1983; Shaffer, 1978; Sternberg, Knoll, & Wright, 1978), and age-related changes between adults and older adults (Bosman, 1993; Salthouse, 1984). Similarly in handwritten copying, one line of focus was the physical motor production involved in written copying. For instance, researchers have studied developmental progression in writing ability through comparing speed and legibility of specific letter identities over different age groups of children, also looking for differences between genders and right-or-left handedness (Graham, Berninger, Weintraub, & Schafer, 1998; Graham, Weintraub, & Berninger, 2001).

However, there are also studies approaching writing measures as indicators of cognition associated with spelling and production. In copytyping, studies measured the time-course of key presses; in handwritten copying tasks, studies measure the time-course of writing each letter. These will be considered in turn for adults and, where possible, children.

1.4.1 Programming writing events in whole word units during copytyping.

Adults. In copytyping, one topic is whether or not words are functional units of production, similarly to encoding (Crump & Logan, 2010; Shaffer & Hardwick, 1969; Terzuolo & Viviani, 1980). Recall that encoding gaze times suggested that whole words were recognised (Inhoff, Briihl, Bohemier, & Wang, 1992; Inhoff, Morris, & Calabrese, 1986). After encoding, because the word has already been retrieved and represented in memory, there may not be a process of re-retrieval during production.

In copytyping this is not the case, as word frequency influenced production, as measured by speed of keystroke presses. Specifically, the lower the frequencies with which readers encounter that word, the longer the average pause time between key presses during production, by 10-40ms longer between keystrokes (Inhoff, 1991; Inhoff & Wang, 1992). This suggested that the word was programmed as an entire unit. Findings from West and Sabban (1982) supported this idea, finding that the words per minute typing rates were greater for higher frequency words, suggesting that word units were re-activated during production.

1.4.2 Programming writing events in subword units during copytyping.

Adults. Although word units can be programmed during a copytyping task, it does not necessarily follow that the only unit for programming a writing event is a whole word. In West and Sabban (1982), words (*letter*) were typed faster than nonwords (*rtleet*; composed of the same letters in a random order). Yet, letter clusters that retained the original letter sequences of each word half (*terlet*) were typed faster than the nonwords. Although there was a lexicality advantage, perhaps subword units such as trigrams or syllables could have also been useful units for programming typing events.

Gentner, Larochelle and Grudin (1988) found that the main determinant of the time between keystrokes was the physical difficulty of the keystroke. Subword units organised typed production as well. For the same words, pause time between keys was predicted by word frequency, syllable boundaries and digraph frequency. Even if the word was activated as an entire unit (as indicated by the effects of frequency), multiple programming events maybe have been programed within a word, dependant on subword structure (as indicated by effects of syllable boundaries and digraph frequency). These copytyping studies indicated that both properties of whole words and subword structure could determine written production behaviour during a word copying task.

1.4.3 Programming writing events in whole word units during handwritten copying.

Adults. Unlike copytyping research, in handwritten copying studies, there is a collective focus on what subword units are used in programming writing events, rather than whether or not a whole word is a functional unit. Already, this shift of motivation seems to imply differences in production behaviour based on mode of production. It

could be that the physical act of forming letter strokes rather than pressing a button changes the way in which written production is programmed.

Writing has been theoretically conceptualised as a multi-dimensional task, requiring several interconnecting “modules” controlling cognitive, psychomotor and biophysical processes (Van Galen, 1991). There is a hierarchy of modules, with the output of the higher module forming the input for the lower module. Each module is said to work on progressively smaller unit sizes, starting with large unit sizes in the abstract module, of ideas, concepts, then phrases. Then, the spelling module works with word units, processing orthographic representations related to parts of the word. Next, the motor module uses the smallest units of graphemes, allographs, then individual letter strokes. These motor processes are responsible for controlling the size of letters, and executing the muscular instructions for creating letter strokes. Each module starts to activate representations in a serial way, but representations can continue to be active in parallel. Within the copying literature, studies primarily investigate the spelling module, and examine the word and subword linguistic units used in programming written production.

A few studies speak to the issue of whether or not, in handwritten copying, copiers used whole words as units. Zesiger, Mounoud and Hauert (1993) found that adults took longer to produce pseudo-words compared to real words. This suggested that in adults, the word representation facilitated production. But, most studies suggest that whole word characteristics did not affect production.

In contrast to English copytyping research discussed earlier that found English word frequency influenced typed production, word frequency did not determine the time-course of French handwritten copying. Lambert, Alamargot, Larocque and Caporossi (2011) asked adults to copy four unrelated words (their primary goal was to assess parallel encoding and production), with one target word varying in frequency. Copiers took the same amount of time to produce both high and low frequency words, as measured by writing duration on the digitising tablet. Whether or not word frequency affects written production may depend on language, mode of production and/or extent of parallel processing, but it may be that whole words are not consistent units for programming written production.

In another study first mentioned in the encoding section, Lambert, Kandel, Fayol and Espéret (2008) used a digitising tablet to record production behaviour as French adults made three sequential copies of 8 letter high and low frequency words. Unlike Lambert, Alamargot, Larocque and Caporossi (2011), Lambert, Kandel, Fayol and

Espéret (2008) removed the reference model during copying, to prevent parallel copying. To recall, they found evidence for an effect of frequency in writing latency, indicating word activation before written production. However, effects of frequency were no longer present in the pause time between words that reflected the programming of writing events for the second and third written copies. Therefore, irrespective of parallel or serial copying, there was no support for the idea that French words were programmed for handwritten copying in whole word units.

Overall, while English typing studies find support for the idea that adults programme production events in whole word units during copying, French handwritten studies do not replicate similar findings. But, it is unclear whether this could be due to differences between typing and handwriting, or differences between English and French.

Children. Similar to the studies exploring encoding times, Transler, Leybaert and Gombert (1999) looked for a lexicality advantage, supposedly during written production, but they used a measure of overall copying duration, which also included encoding time. When they timed 7-8 year old French children during copying words and pseudowords, it took longer for children to copy pseudo-words compared to real words, but only for 7-10 letter, not 4 letter items. For the short words, real and pseudo-words took the same time to copy, showing a lack of lexicality advantage. If whole word units underpinned children's copying, a known word would be expected to facilitate copying, whereas a nonword would be more difficult and time-consuming. The authors suggested that lexicality did not affect short items because many short items only needed one copying cycle of encoding and production, but this could be due to noise in the measure of overall copying duration.

Even in longer 6 letter items, Zesiger, Mounoud and Hauert (1993) still did not find a lexicality advantage in 8-12 year old French written production durations as measure by a digitising writing tablet. While children over the age of 10 outperformed younger children, within each age group, children took the same time to write 6 letters irrespective of their lexical status, so lexical representations did not facilitate quicker production durations. This would suggest that whole words were not functional units for programming writing events.

However, approaching the same question using a different manipulation, Kandel and Perret (2015) did find an influence of word frequency on the time-course of writing each letter in 8-10 year old children. If words were programmed as complete units, there would be one programming event before writing the first letter, in which writing

movements for all the letters in that word would be programmed. Then, children would spend a similar amount of time writing each letter, because no online programming would slow down the execution of writing. This was the pattern found for high frequency 5-8 letter words, suggesting that a high frequency word could be programmed as an entire unit. But for low frequency words, children spent more time writing the central letter compared to other letters within the word. Kandel and Perret suggested this extended time on the central letter was needed for a second writing event to be programmed online. This meant that that low frequency words were not programmed in a single writing event. Perhaps short and long words could only be a whole unit of programming writing events if they were easily programmed, as determined in this case by word frequency. So far, writing durations cast doubt on the idea that children consistently programme writing events in terms of whole words during copying. Similarly to the findings with adult populations, French research looking at the way in which children made a handwritten copy of a word does not consistently show support for either a lexicality benefit or word frequency effect on production behaviour. This questions the idea that children programme writing events in whole word units.

It might be that words can be programmed as whole units, depending on their ease of access, as determined by age of acquisition and orthographic regularity (Kandel & Valdois, 2005). For words acquired late within print experience, 6-8 year old French children spent more time writing the critical letter in an irregular word (*façade*), compared to the letter at the same location in a regular word (*farine*). The extended time on the critical letter suggested that a writing event was being programmed online in the irregular word, but not the regular word. For early acquired words, children took a similar time to write letters of regular and irregular words, suggesting no second writing event was programmed. Children may be able to consistently programme a word during written production as a whole word unit if that word is relatively easy to access.

Finally, there may be individual differences between children in relation to the difficulty of programming words during written production. Two English studies looked at how children of different ages copy phrases and sentences, reporting the length of between-word pauses in their analysis. Martlew (1992) found that 8 year old children spent a longer time pausing between words than 10 year old children. She suggested this indicated developmental progression in processing associated with spelling, and that spelling ability constrained written production. The older children were quicker to programme the writing event because processing associated with spelling had become more efficient. In contrast, Sumner, Connelly and Barnett (2014) found that the between

word pause time was similar for both 6 and 9 year old children. It may be that children are still developing efficiency of spelling processes at age 9. Overall, it seems that under certain conditions, children programme writing events in whole word units. However, this was not consistent, and children may preferentially use subword units for programming written production.

1.4.4 Programming writing events in subword units during handwritten copying.

Again, these studies used digitised writing tablets to access online measures of the time-course of written production. There were two measures relating to how the subword units were programmed. One measure is *between-letter pause time*, the duration of the pause between finishing one letter and starting another. If subword representations were programmed for writing as separate units sequentially, there should be greater between-letter pauses between writing of letters at unit boundaries compared to letters within the unit. The other measure is *movement duration*, the time it takes to write one letter from start to finish. If subword representations were programmed for writing as separate units online, there should be longer movement durations on the letter at which the programming event occurs, compared to letters that were not written in parallel with programming events.

Adults. If whole words were not reactivated during written production, it might be that once encoded, words could be decomposed into more convenient smaller spelling units. Inhoff (1991) argued this decomposition could be an unnecessary time-consuming step that increases risk of misremembering letter identities or positions during copytyping. But, it may be that in handwriting, the act of forming varied letter strokes balances the cost in a different way. It may be more efficient to programme multiple smaller writing events than one large event.

Houghton and Zorzi (2003) presented a connectionist model of handwritten spelling, which suggested that during spelling, writers activate information on two representational levels – graphemes and letters. Critically, the spelling system is said to activate syllabically structured graphemes sequentially before unpacking the order and identity of individual letters. Therefore, units smaller than the whole word may be activated during motor programming and used to organise production events. Copying studies aim to clarify which subword units are used to organise programming of written production.

Morphemes. Kandel, Alvarez and Vallée (2008) explored whether a morpheme boundary determined production events in suffixed and pseudo suffixed words. In each pair of words, there was a critical interval between two letters: in the suffixed words, the interval represented a morphological boundary between the root morpheme and the suffix; in the pseudo suffixed words, the interval did not represent a morphological boundary. As described earlier, Kandel et al. found only the suffixed words were decomposed before written production began. In continuation, during production, between-letter critical intervals were 60ms longer for the suffixed compared to the pseudo suffixed words. This suggested that for multi-morphemic words, 2 writing events were programmed one after the other, in terms of morphological units. So, for multi-morphemic words, morphemes and suffixes were treated as separate subword units during written production.

Syllables. Lambert, Kandel, Fayol and Espéret (2008), asked French adults to make three sequential copies of 8 letter words made up of either 2 or 4 syllables. To recall, there was only evidence of activating syllable units during encoding pseudo-words, not words. In contrast, during production, after encoding and writing the first copy, the between-word pauses before the second and third copies (that reflected only production, not encoding) were 20-40ms longer for 4 than 2 syllable words. In a second experiment, they also found that between-word pauses were 15-25ms longer for 3 syllable words than for 2 syllable words. It was later replicated that an increase of even one syllable unit resulted in necessity for longer programming time (Lambert, Sausset, & Rigalleau, 2015). This suggested that French copiers activate subword units of syllables during written production.

Sausset, Lambert, Olive and Larocque (2012) added that the time-course of programming syllable writing events depended on the available cognitive resources. When adults copied 2 and 3 syllable French words in normal lowercase letters, syllables were processed online – there were short between-letter pauses at syllable boundaries, but some of the writing event could be programmed at the same time as writing execution. For more demanding uppercase letters, and even more for enlarged uppercase letters, the between-letter pauses at syllable boundaries were increased. This suggests that when there were less cognitive resources available, adults programmed writing events more sequentially, rather than in parallel with writing execution. However, adding to task demands does not always impact the amount of cognitive resources available. For example, the between-letter intervals needed to programme syllable events stayed the same across copying under conditions with and without time-

pressure (Sausset, Lambert, & Olive, 2013). Hence, written production can only proceed as quickly as cognitive processing allows.

Even across languages, the syllable acts as a strong cue for programming writing events. Similarly, in Spanish, between-letter pauses at syllable boundaries showed that syllables modulated adults' written production (Afonso & Álvarez, 2011). Furthermore, Afonso and Álvarez also found copiers were sensitive to syllabic frequency, in that longer between-letter pauses for lower frequency syllables showed that it was more difficult to programme a writing event for a lower frequency syllable. Not only were syllable units organising motor behaviour, but the difficulty of activating each unit impacted on written production.

Syllable units were activated in terms of their specific language. Kandel, Alvarez and Vallée (2006) asked French-Spanish bilingual adults to copy word cognates, derived from the same root word in each language, with the same letters surrounding the syllable boundaries, but the syllable boundaries (denoted here by the full stop) were between different letters (denoted here in bold), *consi.gner* vs. *consig.nar*. Irrespective of the language, between-letter pauses were longer when those letters were either side of a syllable boundary compared to within a syllable. Even though they were writing the same letters, bilingual adults adopted a flexible strategy of motor programming according to the syllabic structure of the language in which they were writing.

Affixes. Kandel, Spinelli, Tremblay, Guerassimovitch and Alvarez (2012) looked at morphemes (combined with both suffixes and prefixes) together with syllable boundaries. In the first experiment, they compared suffixed words (*pru.neau*), in which the syllable boundary (denoted here by the full stop) did not match the morpheme boundary (suffix denoted here by bold), and pseudo-suffixed single morpheme words (*pin.ceau*), which contained the same end letters as in the suffixed word. They found 10-15ms longer between-letter pauses for suffixed than pseudo-suffixed words, at the syllable boundary, and also marginally at the morpheme boundary. This indicated that multi-morphemic words required more processing than mono-morphemic words, but morpheme and syllable effects can occur independently from each other.

However, a second experiment showed that multi-morphemic words were not always decomposed into their component parts. Using a similar manipulation, this time with prefixes (*inédite*) and pseudo prefixes (*inertie*) instead of suffixes, Kandel, Spinelli, Tremblay, Guerassimovitch and Alvarez (2012) found no significant differences between prefixed and pseudo-prefixed words, at either the morpheme or

syllable boundaries. This suggests that the nature of the morpheme determined whether morphemes or syllables act as cues for programming written production. Perhaps a morpheme is only a useful unit if the boundary is towards the end of the word.

However, the suffixes used were all 3-4 letters, but the number of letters in the prefixes varied to a greater extent. Half of the prefixes had 2 letters, most other prefixes had 3 letters, and only 2 prefixes had 4 letters. Another explanation may be that the size of the linguistic unit determined its functional use, and that some prefixes were too small to be useful.

First, in the prefixed words, the morpheme boundary was earlier within the word compared to the suffixed words. It may be that when programming the same number of letters, copiers preferred to program a large first unit then a small second unit, rather than a small first unit then a large second unit. In this way, less cognitive resources would be taken up with maintaining a larger amount of information for longer, throughout production. Alternatively, these findings could be a product of the nature of the French language. Kandel et al. note that suffixes are more common than prefixes (Cutler, Hawkins, & Gilligan, 1985). It may be that the frequency with which a unit is encountered determines whether or not it is a useful cue for segmenting written production events.

Complex graphemes. Kandel and Spinelli (2010) looked whether simple and complex graphemes act as subword units of production. They created matching word triplets, in which a single phoneme was made up an increasing number of letters. In the first word (*clavier*), the critical phoneme corresponded to a single letter; in the second word (*prairie*), the critical phoneme corresponded to two letters, beginning at the same within word location; in the third word (*plainte*), the critical phoneme corresponded to three letters. They found that as the number of letters in the critical phoneme increased, copiers took longer to write the letters before the critical phoneme. This was because copiers programmed the writing event for the critical phoneme at the same time as carrying out the writing event for the initial letters. As writers programmed a writing event for the critical phoneme, the programming event for the three and two grapheme phonemes were both 5-15ms longer than for the single grapheme phonemes, because writers were programing more letters. This showed that adults used grapheme sized units to modulate written production. Furthermore, grapheme units were useful irrespective of whether those units were simple or complex.

Bigrams. Moreover, Kandel, Peereman, Grosjacques and Fayol (2011) showed that the frequency of bigrams influenced the way in which adults programmed writing

events. In addition, the type of bigram determines the difficulty of programming a writing event in terms of bigrams, as double letter bigrams caused increased cognitive load (Kandel, Peereman, & Ghimenton, 2014). Writing movements were slower when adults were currently programming double letter bigrams (*ss*) compared to bigrams made up of different letters (*st*). This showed that it was cognitively more demanding to programme the double letters.

Phonemes. There are differences overall between the amount of consistency between graphemes and phonemes in French compared to Spanish, but inconsistent phonemes modulate writing events in both languages. Afonso, Alvarez and Kandel (2014) asked adults to copy words containing the same critical letter, but the critical letter corresponded to a different phoneme, one phoneme association more frequent than the other. In Spanish where most grapheme-phoneme relationships are consistent, copiers were facilitated by the regularities in grapheme-phoneme mapping. Between-letter pauses were shorter before the letter corresponding to a dominant phonetic association. Though participants were writing the exact same letter, they took less time to write the letter if it was associated with the dominant phoneme. Even though there are often inconsistencies between graphemes and phonemes in French, the same pattern of behaviour was found. Interestingly, for both French and Spanish, between-letter intervals were increased by about 5ms, and critical letter durations indicating online writing programming were increased by 5-10ms. Even though there are fewer inconsistencies in Spanish, copiers were not more affected by the presence of an infrequency grapheme-phoneme association compared to the French.

So far, research has suggested that adults organise written production events according to a range of different sized units. Support has been found for roles of morphemes, syllables, affixes, complex graphemes, bigrams and individual phonemes.

Children.

Recall that children show awareness of a range of phonological units including syllables and phonemes by the age of 4 years old (Carroll, Snowling, Hulme, & Stevenson, 2003). Like adults, children can use phonological units to organise writing events, but programme different sized writing events depending on age and language.

Syllables. As with the adult studies, researchers measured the letter writing durations and between-letter pauses as indicators of when within a word writing events were being programmed. Kandel and Valdois (2006b) found that for 4-7 letter strings, French children showed systematic increased durations on the first letter of the second syllable (denoted here by **bold**) after the mid-word syllable boundary (denoted here by

the full stop) for both words (*choi.sir*) and pseudowords (*choi.rel*). This effect held over all school grades tested, with children aged from 6-10 years. Kandel et al. interpret these increased durations as reflective of motor programming time, suggesting that children started programming the writing event for the second syllable after writing the last letter of the first syllable, and this programming continued as children started writing the first letter of the second syllable. For instance, in the case of *choisir*, children would start programming the second syllable *sir* after writing *choi*, and finish programming whilst writing the *s*.

This pattern is not consistent across languages. Kandel and Valdois (2006a) asked 6-7 and 7-8 year old French and Spanish children to copy multisyllabic words derived from the same root word. For French, but not Spanish children, the writing durations for the first letter of a syllable boundary were longer than for the letter immediately before or after the first letter. This demonstrated that writing events were programmed in terms of syllables only for the French children, but Spanish children organised writing events in units larger than a syllable. However, when 6-8 year old French-Spanish bilingual children copied the same word, writing movements were consistently programmed in terms of syllable units. Even though trials were blocked, so a child never copied both French and Spanish words in a single session, bilingual children behaved in a similar way to monolingual French children irrespective of whether children were currently writing in French or Spanish. These bilingual children each had both a French and a Spanish native speaking parent, so were learning each language simultaneously; it was not the case that Spanish was learned as a subordinate second language. The authors suggested that rather than adopting a flexible motor programming strategy based on the characteristics of each language, it may be easier for children to only learn one motor programming strategy, based on the characteristics of the most complex language.

Although Kandel and Soler (2010) found that syllabic structure determined the time course of programming writing events for both French and Catalan 6 year olds, children programmed writing events differently. When copying 3 syllable words, French children showed increased letter durations after each of the 2 syllable boundaries within the word, programming the words syllable-by-syllable. But in Catalan children, there was only an increased duration after the second syllable boundary, not the first. This showed that the Catalan children could programme up to two syllables in one writing event. This is in line with some of the findings from Soler and Kandel (2009), showing that when Catalan 6 year olds copied 3 syllable words, Catalan children

programmed the first 2 syllables before starting to write, then programmed the next syllable. Furthermore, Catalan children quickly develop progressively larger units for writing within 5 months, transitioning from a reliance on letter-by-letter units to syllable units at age 5 (Soler & Kandel, 2012).

In contrast, Catalan children do not consistently programme 2 syllables at once. When the copying 2 syllable words, instead of programming 1 writing event for both syllables, they programmed 2 separate writing events (Soler & Kandel, 2009), in the same way as French children (Kandel & Valdois, 2006a, 2006b). As the number of letters in each syllable would be smaller in 3 syllable words compared to 2 syllable words, it may be that Catalan children could only programme 2 relatively small writing events at once.

To draw together this cross-linguistic research, the characteristics of the language impacted on what subword units are used to modulate writing events, and how many units could be programmed at once. In comparison, Spanish is the most orthographically shallow language, and Catalan is deeper than Spanish, but shallower than French; programming writing events was successively more difficult for each language. The Spanish children could programme one writing event for all the letters in a word, but the Catalan and French children needed to programme multiple writing events. Then, both Catalan and French children programmed large-sized syllable units as separate writing events in bisyllabic words. In more difficult trisyllabic words, Catalan children could programme multiple small-sized syllable units in one writing event, but the French children needed to programme even small-sized syllable units in separate events.

To further explore different types of syllabic cues, Kandel, Hérault, Grosjacques, Lambert and Fayol (2009) used French a language convention that a final letter e creates a word that can be segmented into two orthographic syllables, but is pronounced as one syllable (*bar.que*). These words were matched to a word that had two orthographic and phonetic syllables (*bal.con*). Although it took 8 year olds longer to programme writing events than 9 year olds, who were in turn also slower than 10 year olds, Kandel et al. also looked more specifically at the writing durations for the first letter of the second syllable, and the letters immediately before and after. Irrespective of whether the word had one or two phonetic syllables, all children programmed writing events in terms of orthographic syllables, showing longer writing durations on the first letter of the orthographic syllable, than the letters either side. This supported the idea that children

used syllabic structure as a cue for programming writing events, and further suggested that children may privilege orthographic cues over phonetic cues.

Phonemes. That is not to say that children do not use phonetic information during written production. In 8-10 year old Italian children, half of the written mistakes they made involved replacing a letter with a phonologically similar letter (*banchina* for *panchina*), showing that phonological information was activated during copying. Kandel, Soler, Valdois and Gros (2006) also found that production events were modulated by individual phonemes when they asked 6-7 year old children to copy bisyllabic words. In the first syllable of each word, there were always 4 letters, but these letters either made up 4 (*cris.tal*) or 2 phonemes (*chan.son*). Recall that longer writing durations reflected programming of production events. Firstly, irrespective of the first syllable's phoneme structure, there were increased writing durations on the fifth letter, the first letter of the second syllable. The authors suggest this showed that the second syllable was programmed in its own writing event, in line with the research above. Secondly, as children progressed through the first four letters, their writing behaviour changed depending on whether those letters represented 2 or 4 phonemes. Writing duration was similar over all the letters if a single letter corresponded to 1 phoneme (*cris*), showing that these letters were programmed in one writing event at the word beginning. Importantly, if there were 2 phonemes (*chan*), there extra writing time was needed at the second letter, suggesting that the first and second phonemes were programmed in separate writing events. This showed that multi letter graphemes were programmed for writing as a single unit.

Like adults, children organised their written production events in terms of multiple subword units, including orthographic syllables, and individual phonemes. Research suggests that a syllable boundary acts as a strong cue for segmenting written production events, though children copying in different languages differ in the number of syllables they programme in one episode.

1.5 Overview

Looking collectively at the literature, adults and children use a range of linguistic units during visual encoding and written production in a copying task. There seems to be developmental differences in encoding behaviour, whereby adults preferentially relied on whole word units, but children relied to a greater extent on units smaller than a whole word. Comparatively little is understood about how copiers use working memory during specific stages of encoding and production, as it is difficult to

distinguish partial initial encoding from forgetting. Production is the most understood stage, with precise digitised writing measures highlighting the use of subword units of information for both adults and children. Syllable sized units seem to emerge as functional units of information for copiers irrespective of age over 7 years old, but research has yet to confirm whether the same linguistic units are used over encoding, mental representation and production processes for the same word.

Several initial questions emerge. Can more sophisticated measures of encoding clarify the consistency of the extent to which adults and children use whole word units? Even if whole words are not functional units, it seems counterintuitive that a task revolving around speech-based information can be shown to have only tenuous links to verbal working memory. What aspects of verbal and spatial memory do copiers rely on during copying, and do developmental differences in memory abilities predict improved copying performance during encoding and production? Although copying research has developed a firm knowledge base concerning production, there is uncertainty about the subword units of information children are able to activate during encoding. Do children use sound-based subword units in encoding and production?

Most of the copying research has been carried out in French, also identifying differences in comparison to the relatively more grapheme-phoneme consistent Spanish. In particular, English is a very orthographically deep language. This reflects a great deal of irregularity between grapheme-phoneme relationships in the English language, in that on average, each letter contributes towards 4 different phonemes (Borgwaldt, Hellwig, & De Groot, 2005). English words are afflicted by both feed-forward inconsistency from spelling to sound, as used in reading, and feed-back inconsistency from sound to spelling, as used in writing (Ziegler et al., 1997). In contrast, though French is also highly feed-back inconsistent during writing, French is relatively consistent from spelling to sound during reading owing to a variety of phonetic rules (Ziegler, Jacobs, & Stone, 1996). Critically, this may mean differences in the way that French and English children encode information during copying.

In a copying task, the information that is represented and produced is likely to depend on the information that is encoded. It may be that only parts of a difficult word can be encoded at once, which then constrains representation and production in turn. Or, although a difficult word could be entirely encoded, it may be more difficult to maintain a representation of all the information, leading to forgetting or misremembering during production. In a copying task, the first task of encoding is then important as it determines what information is available during production, yet it is not the stage that

has been the focus of most copying research. In addition, there may be differences between languages (French vs. English) or between modes of production (typing vs. handwriting) that modulate the nature of encoding differently.

So far, eye movements have not often been used as a measure in studying a handwritten copying task. In research using skilled adult typists, it was possible to use conventional eye trackers that keep the participant's head immobile. Though participants were not allowed to look at the keyboard, this did not result in disruption to task performance, as touch-typists do not look at the keyboard during typical typing (Inhoff & Wang, 1992). Yet, suppressing visual feedback when writing detrimentally affects task performance during copying tasks (Olive & Piolat, 2002). So, conventional eye trackers would not be appropriate for use in handwritten copy tasks. This Thesis presents a novel paradigm, using mobile eye tracking in a single word copying task, with adult and child participants. Rather than the sequential word copying paradigm of Lambert et al., (2011) to separate encoding and production, the current paradigm aims to use eye movements as a measure of isolated encoding and production in a serial time-course, to investigate each process separately within the copying process as a whole. Next, the copying paradigm will be outlined in Chapter 2, in relation to the decisions made in constructing the paradigm, the behavioural measures considered, and what these measures are suggested to indicate in relation to cognitive processing.

CHAPTER 2

A DESCRIPTION OF THE METHODS APPLIED IN USING EYE MOVEMENTS TO UNDERSTAND COGNITIVE PROCESSING DURING A COPYING TASK

2.1 Introduction to the Copying Paradigm

The research presented in this Thesis aimed to develop understanding of efficient performance in a typical classroom copying task, identifying differences between an adult population with skilled reading and writing abilities, and a developmental child population still honing these abilities. This paradigm was developed to assess the units over which visual encoding and written production operate, in different populations, during a single word handwritten copying task. This chapter introduces the paradigm, draws together the capacities of typical eye trackers in relation to studying print encoding, and describes the eye movement measures used.

First, it may be useful to construct a conceptual framework of the three constituent sub-processes involved in copying a single word from a board, shown in Figure 1. Word copying involves visual encoding, mental representation and written production; all three sub-processes must happen in order to copy a word successfully, in that sequence.

In a single trial, there must be at least one episode of encoding, in which visual uptake of the to-be-copied information occurs, and the copier mentally represents the encoded information in working memory. While the copier stores the representation, writing events must be planned and executed until written production is complete.

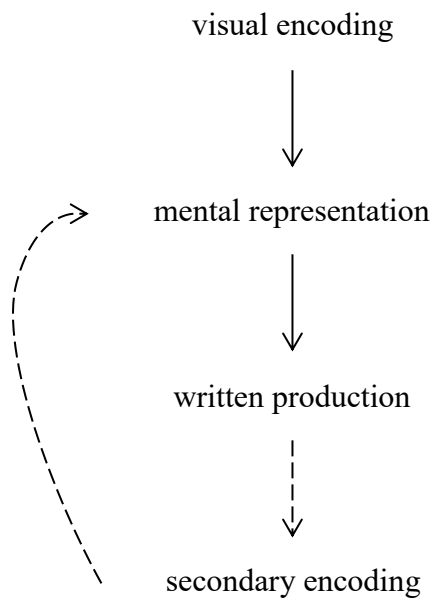


Figure 1. The sequence of components in a copying task.

However, written production may not be necessarily representative of all the information that was initially encoded. For example, the mental representation could break down, so that some of the initially encoded information is forgotten or misremembered. In that case, not all the encoded letters or letter clusters would be written, or the wrong letters would be written. In the event of not encoding all the information, or forgetting the encoded information, copiers would repeat the cycle of encoding, mental representation and production, as many times as needed, until all the letters have been written to the copier's satisfaction.

2.2 Introduction to Tracking Eye Movements

Cognitive psychology focuses on internal mental operations that individuals use to process, interpret and respond to the external environment. Because these mental operations are internal, they are hard to observe directly. To investigate cognitive processing that occurs during a task, researchers need observable behavioural responses that arise from those mental operations.

The study of eye movements is a valuable tool for researchers interested in aspects of cognitive processing (Kirkby, Webster, Blythe, & Liversedge, 2008). Within research on written language processing, sequential movements of the eyes provide a powerful online indication of ongoing cognition during a linguistic task, such as reading (Liversedge & Findlay, 2000). Measuring eye movements is not a new idea, researchers first characterised eye movements during reading as a series of jerks and pauses during passage reading in the late 1800s (Huey, 1898). Miles Tinker (1936, 1946, 1958)

expanded on perception and measuring eye movements, systematically describing how eye movements were controlled during reading and beginning research into children's reading as well as adults'. George McConkie began to look at flexibility of reading strategies (for understanding or speed) and how much upcoming visual and linguistic information readers use during a fixation (McConkie & Rayner, 1975; McConkie, Rayner, & Wilson, 1973). Then, the popularity of tracking eye movements to explore the nature and time course of cognitive processes in reading exploded, and the pioneering work of Keith Rayner solidified eye movements as a gold standard approach in the study of cognitive language processing (Rayner, 1978; see also Clifton et al., 2015). Now, the cognitive processes in reading are well understood, with well-developed models that can account for what happens, cognitively, when people read, such as the E-Z Reader model (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2006) and SWIFT (Engbert, Longtin, & Kliegl, 2002; Richter, Engbert, & Kliegl, 2006). This is important, because while aspects of this Thesis depart from convention, the new paradigm presented is derived from an understanding of eye movements during reading, adapting methods and assumptions from an exceptionally robust field of work to another language processing task.

2.2.1 Types of eye movements.

During the course of interpreting the visual environment, 6 extraocular muscles rotate the eyeball such that light from a point in the visual environment (the point that the person wants to fixate) falls directly onto the centre of the fovea. Light, reflected from an object in the visual environment, passes through the lens and into the eye. The light strikes the retina, the light-sensitive layer at the back of the eye containing the visual receptors, rods and cones, which fire neural signals in response to light stimulation (Duchowski, 2007). The small foveal area is the part of the retina that has the most cones, which means that the image is perceived with the highest acuity. When this important foveal vision is masked such that foveal information is unavailable to the reader, reading becomes an extremely difficult task; even masking one character in foveal vision halves reading speed (Rayner & Bertera, 1979).

Typically, reading researchers focus on one type of eye movement, a *saccade*. During saccades, both eyes move in the same direction to bring an area of the visual environment into high acuity vision. The size of saccades in reading is primarily determined by the number of character spaces between fixation points, rather than visual angle (Morrison & Rayner, 1981). During reading, the majority of saccades are

made in the direction of reading, approximately 8-9 characters in length (Rayner, 1978). Similar saccadic eye movements have been observed during copytyping, although the saccades are much shorter in length, about 3-5 characters (Inhoff et al., 1992).

During a copying task in which participants look between different areas in the visual environment, they may also make *vergence eye movements*. These movements are needed when moving from the currently fixated object to a target object if, compared to the currently fixated object, the target object is either closer or further away from the individual. Vergence movements are about four times slower than saccades, and the eyes are rotated in opposite horizontal directions, taking around 160ms to move from the currently fixated object to a target object at a different depth (Leigh & Zee, 1991). In a copying task, copiers may look between two areas of the visual environment, the paper notebook on the copier's desk, and the wall-mounted board at a relatively greater distance from the copier. When copiers looked from the board to the paper, their eyes would move from the further object to the nearer object, and converge towards each other. When copiers looked from the paper to the board, their eyes would move from the nearer object to the further object, and diverge away from each other.

Eye movements also help to keep the target image still on the retina (Leigh & Zee, 1991), compensating for the movement of the target, *pursuit movements*, and the movement of the head, *vestibulo-ocular reflex movements*. When people make head movements, semi-circular canals in the ear sense the motion and the vestibular system directs quick, counteractive eye movements in order to stabilise the targeted image on the retina. For instance, if a copier were to look at the board, and tilt their head while encoding, their eyes would make reflexive corrective movements in the opposite direction to the angle of the head tilt.

2.3 Tracking Eye Movements

Modern eye trackers are non-invasive, using reflected light to track the specific location of the pupil. Popular eye trackers used in reading research such as the SR Research Eyelink 1000 work by shining an undetectable, harmless beam of infra-red light towards either one eye, in *monocular* eye tracking, or each eye, in *binocular* eye tracking. The light reflects off the front surface of the cornea, then the reflected light is detected by an infrared camera and used to calculate the position and centre of the pupil. This provides a relatively easy and reliable way to collect clean eye movement data,

providing exceptionally detailed recordings every millisecond, sensitive to with a spatial accuracy of up to 0.1 degree of visual angle.

Eye trackers enable a range of measures that quantify reading behaviour, derived from the two staple components that make up a pattern of eye movements during static reading: saccades and fixations. Readers may perceptually experience reading a line of text as a smooth sliding transition along the sentence in the direction of reading. In contrast to the perception of a continuous flow of visual information, visual samples could be likened to a sequence of quick snapshots of small portions of the text. This is because a sequence of eye movements while reading is made up of jerky *saccades*, ballistic 20-40ms movements between the current location and the targeted location; and relatively still *fixations*, pauses of 100-500ms during which visual uptake of information takes place (Staub & Rayner, 2007). The duration of each saccade depends on the distance between the *launch site*, from where the saccade starts, to the *landing site*, to where the saccade finishes. Shorter saccades covering about 2 degrees take 25-30ms, whilst longer saccades covering about 5 degrees take 35-40ms (Rayner, 1978). Many variables influence the duration of fixations, though for the purposes of this methods-focused brief introduction, these variables can be brought together under 3 umbrella categories. First, the stimuli – the visual nature and linguistic properties of the printed text. Second, the reader – the reading abilities and oculomotor capabilities of the person performing the task. Third, the task – what the reader is asked to do with the text. The material point is that through recording the patterns and time-course of a reader's eye gaze, researchers can infer the online cognitive processing required during recognising, parsing and comprehending written text (Liversedge & Findlay, 2000).

A drawback of static eye trackers is that it is difficult to distinguish head movements from eye movements, so participants are required to keep quite still during the reading task for accurate recordings. For reading studies, this is not a high cost for temporal and spatial detail. Participants can comfortably place their head against a padded chin and forehead rest to keep still. Then, researchers display stimuli on a computer screen in front of the participant, for relatively natural reading. However, this means that the static eye trackers of traditional reading research would not be appropriate for studying a task in which participants need to move their heads between different areas of a visual environment, such as copying from a wall-mounted board or display screen.

2.3.2 What measurements have been gained from eye tracking during reading?

It is important to briefly discuss how other researchers have related eye movements to processing, and what they have suggested their measures indicate. While this project does not use identical measures, the ideas are drawn from the same field, with vocabulary embedded from research investigating linguistic processing in reading. The understanding behind traditional measures has then, in the new paradigm, driven ideas about what cognitive operations the available measures could potentially reflect.

Reading research distinguished 2 main components of eye movement control: the decisions of where and when to move the eyes (Kennedy, Radach, Heller, & Pynte, 2000). The where decision concerns where the eyes will be targeted on the next fixation. The when decision concerns when to move the eyes to the next target.

Standard time-based measures are further divided into *early measures* of first pass reading time, considering the fixations on a given interest area before leaving the area for the first time, and *late measures* of second pass and total time, that consider the fixations on an area that has already been fixated before (Rayner, Sereno, Morris, Schmauder, & Clifton, 1989). Already, the current paradigm is driven from the idea that when encoding text, readers may return to a word, this return processing may be more likely in some situations than in others, and that return second pass processing may be of a different nature to first pass processing.

This is important because when, within the time-course of the task, the effect of a linguistic manipulation occurs, can be informative about the nature of the underlying cognitive processes that are happening at that stage of processing (Clifton, Staub, & Rayner, 2007).

2.4 Tracking Eye Movements in a Mobile Copying Paradigm

In the copying paradigm presented here, there are 2 areas of interest in the visual environment – the wall-mounted board and the paper notebook. Both are placed in front of the participant, but it would be difficult to copy information from the board to the paper without making an eye movement between the two areas. This is what participants typically do – they spontaneously move their head to look between the board and the paper. This necessitates the use of an eye tracker that can provide accurate eye movement recordings even when the head is moved between different positions. The Ergoneers Dikablis Essential Eye tracker is head mounted and can accommodate head movements while recording eye movements (see Figure 2). Instead of the eye

tracker being mounted on a table in front of the participant, the tracker is mounted on a frame resembling a pair of spectacles which is then worn by the participant.

Because the camera recording eye movements is attached to the frame, when the copier makes a head movement, the camera also moves, usually remaining in a position that is constant in relation to head and eye position. The fixed relationship between the head and eye camera ensures that the eye remains within camera range, and so the pupil position is trackable irrespective of head movements.

Similarly to the Eyelink 1000, the eye camera is used to record images of the pupil, with reflected infra-red light enabling calculations of the pupil position and centre. There is a second camera in the Dikablis eye tracker – the field camera. This operates as a video camera recording the visual environment directly in front of the copier. The field and eye cameras are synchronised; by overlaying the position of the pupil centre with the visual environment, the Dikablis calculates where gaze is located within the current visual environment. In this paradigm, tracking with head movements was essential. The Dikablis eye tracker can accommodate these movements, but this required compromise in other aspects of the data.

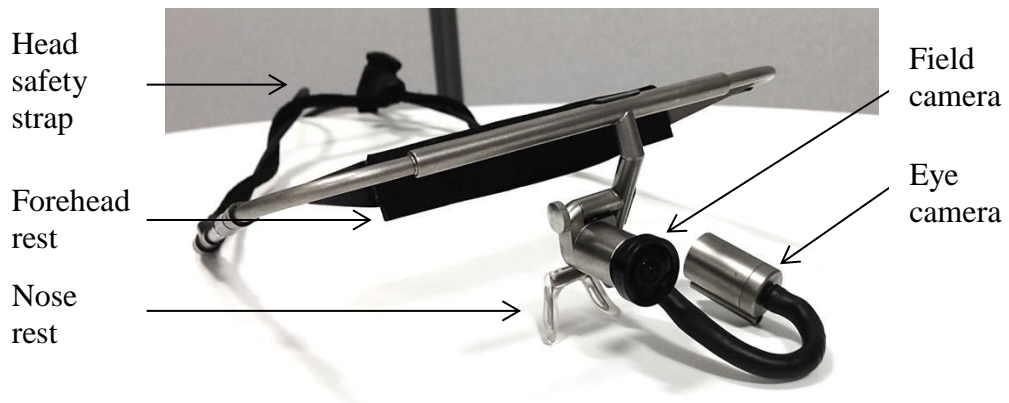


Figure 2. The Dikablis headmounted eye tracker.

The first compromise was that the capability of coping with head movements comes at a cost of both temporal and spatial accuracy. While the Eyelink 1000 can record pupil location once every millisecond, the Dikablis has less temporal and spatial detail, recording pupil location once every 40 milliseconds, within 0.5 degrees visual angle¹. Importantly, although the reduction in sample rate results in less temporal detail, the sample rate is high enough to provide valuable data in investigating the research questions. Inhoff, Morris and Calabrese (1986) suggested that manipulations of word frequency affected the length of gaze durations in a copytyping task by at least 110ms, and even up to 405ms. The Dikablis eye tracker records 25 frames per second. Adapting the time-scale of eye movement behaviour during copying proposed by Inhoff et al. as a baseline, a difference of 110-405ms would correspond to a difference of 3-10 frames recorded by the Dikablis eye tracker. Additionally, Inhoff and Wang (1992) suggested that manipulations of word frequency affected the duration of production events by adding 25ms pause time between each letter of a lower frequency word. Adapting this time-scale as a baseline for written production, for 4-8 letter words, a potential difference could be expected to correspond to 2-5 frames for written production duration. Therefore, it is reasonable to suggest the recording rate is sufficiently high to be potentially sensitive to linguistic manipulations during encoding and perhaps written production.

The second compromise was that the most detailed dependent measure of the time-course of eye movement behaviour was gaze duration, the summed duration of all fixations within an area, not fixation duration, the individual durations of each fixation within an area. Until the technology develops to the point that individual fixations can be measured by a mobile eye tracker, detailed investigation about the time-course of word processing during encoding will be limited. Importantly, gaze duration is still an informative measure sensitive to linguistic manipulations in children's reading. For instance, Joseph, Nation and Liversedge (2013) asked 8 year old children to read sentences containing high and low frequency target words. They found the expected word frequency effect, as children spent less time looking at higher frequency words. Critically, the effect was significant in the measure of gaze duration, but not first fixation duration. Even though the Dikablis cannot provide fixation durations, the

¹ Officially, the Ergoneers company report "Glance direction accuracy" (p.2) within 0.5 degrees visual angle accuracy, though there is no numerical report of calibration or validation accuracy in the recording software (Ergoneers, 2014).

dependent measure of gaze duration is not so limited as to be unable to provide valuable data in relation to the research investigation.

The third and final compromise was a limited amount of automaticity in data analysis. The Dikablis did analyse interest areas automatically. With electronically recognisable markers (examples in the upcoming section) physically placed in the visual environment around each area of interest, the software can automatically recognise whether or not gaze is located within each area of interest, but the Dikablis did not automatically calculate eye movement behaviour in relation to each sub-process of the copying task. This required hand-coding for each trial, recording the beginning and end time points of each encoding and production event in order to relate gaze duration in each area of interest to each sub-process of the copying task. Taking automatic interest area calculation and hand-coded records of encoding and production events together, the recordings generated a measure of the length of a copier's gaze durations on the board during the encoding sub-process and on the paper during the production sub-process.

2.5 General Methods of the Copying Paradigm

This section sets out the general methodology and data-handling procedures adopted in the studies, though details particular to each experiment are described in an individual methods section associated with each experiment.

Viewing was binocular, but monocular left eye movements were tracked, recording gaze location every 40ms using the Ergoneers Dikablis cable eye-tracking system, D Lab version 2.5. A video projector was used to centrally present individual words, one at a time, in a random order, on a wall-mounted board. A fixation cross preceded each target word, which was copied using a pen and a separate sheet of paper. Participants were given unlimited encoding and production time, but were instructed to copy each item as quickly, but as accurately as possible.

In the current paradigm, a single word was presented and copied, one at a time. This is in contrast to the parallel copying paradigm of Lambert et al. (2011), in which each trial consisted of copying four unrelated words. These four words were displayed in a sequence, separated by a space, and all the words remained on display throughout the entire trial. In this way, Lambert et al. could address their aim of examining the time-course of participant's written production operations while participants were also engaged in parallel encoding of a different word simultaneously. However, the aim of the current paradigm was to examine cognitive operations of visual encoding and written production in relation to the same word, occurring in co-ordination with each

other, but in sequence. Recall that in order for eye movement patterns to be an accurate measure of both encoding and production sub-processes, participants would need to engage in encoding and production sequentially. If instead, copiers continued writing the current word while starting to encode an upcoming word in parallel, gaze durations on the board, and gaze durations on the paper would no longer be an accurate, full reflection of all the time spent engaging in cognitive operations of encoding and production. Therefore, due to the decision use eye movement patterns as dependent measures of isolated encoding and production sub-processes, a single word copying paradigm was chosen.

Participants were from two distinct populations based on age as an indicator of either skilled or developing reading ability. Adult participants were students at Bournemouth University, volunteering in exchange for course credit. Child participants were recruited from local schools and received a small gift for volunteering. All adult and child participants spoke English as a first language (in order to minimise differences due to effects of differing reading ability within age groups), and had normal or corrected-to-normal vision (in order to eliminate differences arising from atypical oculomotor behaviour).

Research procedures for participants were approved by The Science, Technology & Health Research Ethics Panel at Bournemouth University. Adults and children, along with their parental guardians, gave informed consent before taking part. Examples of ethical information given to participants can be seen in the appendices, in relation to information sheets, consent forms and written debriefing information. For information in Experiment 1, see Appendices A (information sheet for adults), B (information sheet for children), C (consent form for adults), D (consent form for children) and E (debriefing statement). For information in relation to Experiment 2, see Appendices F (information sheet for children) and G (consent form for children). For information in relation to Experiment 3, see Appendices H (information sheet for adults), I (information sheet for children), J (consent form for adults), K (consent form for parental guardians), L (consent form for children) and M (debriefing statement).

2.5.1 Relative positioning of the reference model and the written copy.

Within the existing literature investigating a word copying task, there has been variation in the relative positioning of the reference model and the written copy. One reason for this might be that the distance between the model and the copy impacts on the likelihood and physical effort of head movements between the model and copy. To

demonstrate this, in a virtual reality setting, Hardiess, Gillner and Mallot (2008) placed participants in front of two cupboards, with four shelves in each cupboard containing geometric blocks. The right cupboard was a near-identical copy of the left cupboard, with some target shapes changed; the task was to identify the changes between the model cupboard and the copied cupboard. Critically, Hardiess et al. varied the horizontal distance between each cupboard. The important point is that as the distance between the model and the copy increased, head movements when looking from one cupboard to another became larger, so more effortful, and were made less often.

In the word copying literature, a similar idea was discussed, though not investigated (Kandel & Valdois, 2006a, 2006b). Kandel and Valdois suggested that programming head movements between the reference model and the written copy would be resource-demanding and physically tiring, so may interfere with programming writing movements and fatigue participants. In order to minimise head movements while allowing eye movements from the reference model to the copy, they asked participants to copy words from a close laptop screen, or a card next to their writing tablet.

Furthermore, Lambert, Alamargot, Larocque, and Caporossi (2011) aimed to minimize both head movements and eye movements between the model and the copy. Their research question specifically concerned how participants encode from a reference model at the same time as executing written production. To examine this, they asked participants to copy words displayed at the top of the writing tablet, creating an even smaller distance between the model and the copy than in the studies by Kandel and Valdois.

In contrast to Lambert et al., the copying paradigm in this Thesis must facilitate eye movements between the model and the copy. In order for eye movements to provide a complete and accurate measure of both encoding and production, encoding and production must happen sequentially, not at the same time.

Similar to Kandel and Valdois, the research questions in this Thesis also concerned how much information could be mentally represented during copying. It could be argued that eye movements between the model and the copy are less effortful than head movements, because a head movement may also require an eye movement as well. If this is the case, copiers may balance the cost of making head and eye movements with the cost of mentally representing as much information as possible. In order to encourage copiers to operate at the limits of their ability to encode and

remember as much information as possible, the cost of returning gaze for an additional encoding episode must not be negligible in the current copying paradigm.

Therefore, in the present work, the reference model was positioned on a wall-mounted board, and the copy was positioned on the writing desk in front of the participant. In this situation, the copiers must make a head movement between the board and the paper when switching between sub-processes of encoding and production. This ensures that eye movements on the board and paper will respectively reflect encoding and production. In addition, gaze lifts returning to the board may be made only when necessary in order to avoid the cost of a head movement. Although Kandel and Valdois suggest that head movements may be fatiguing, this movement between the copy and the model is no more strenuous than would be expected during the course of a natural classroom copying task.

2.5.2 Size of stimuli for the reference model.

Again, the existing literature does not suggest an academic convention for presenting stimuli during a handwritten copying task. This is due insufficient detail in the methods sections, in that the viewing distance, font and text size were not consistently reported. In order to thoroughly conceptualise the way in which stimuli were presented to participants, the font, viewing distance, text size and the number of letters that cover a degree of visual angle are needed. This information is needed because it is informative about the size of the image on the retina and how much visual information is available to the copier. While seemingly trivial, font is important because it determines whether each letter in the stimuli takes up the same amount of space. In proportional fonts, some letters are wider than others; in monospaced fonts, each letter takes up the same amount of horizontal space.

The way in which stimuli have been presented in existing copying studies will briefly be described. Participants in Lambert, Kandel, Fayol, and Espéret (2008) copied from a laptop screen at distance of 80cm, but the font, text size and viewing distance were not reported. Participants in Lambert, Alamargot, Larocque, and Caporossi (2011) copied from a writing tablet screen at an unreported distance, but target words between 6-9 letters long were approximately 4cm (whether 4cm was the mean, lower or upper limit is unclear), font, text size and viewing distance were not reported. On the other hand, participants in Kandel and Valdois (2006a) copied words from a laptop screen displayed in lowercase Times New Roman size 18, though viewing distance was not reported; participants in Kandel and Valdois (2006b) copied words from a 21x15 cm

card, displayed in uppercase Times New Roman size 24, though viewing distance was not reported.

In the present work, the font, viewing distance, text size and the number of letters that cover a degree of visual angle were chosen so that each letter of the stimuli would take up the same amount of horizontal visual space, and that each letter would be legible at the distance of the copier.

The font of Courier New was chosen as it is monospaced. This is important so that controlling word length also controls for word size in visual angle.

The viewing distance of a maximum of 150cm was chosen during informal pilot testing. This distance was great enough so that the head movement required when looking between the board and paper was not physically uncomfortable. Also, the distance was small enough so that a head movement, not only an eye movement, would be required for looking between the paper and the board. Upon collection of data with child participants in the first study, the viewing distance was decreased by 25cm. Due to the differences in height between adults and children, the distance needed to be reduced in order to ensure that when the head was lifted for encoding, eye movements were still fully trackable.

The text size of 24pt was chosen, as when the target word was projected onto the board, letters were clearly legible. Each letter horizontally extended 2.95cm, so was displayed at 1.25 degrees visual angle.

2.5.3 Positioning of items in the visual environment. The eyetracker is most accurate when fixations are made in the centre of the visual environment (captured by the visual field camera) rather than at the extreme upper or lower edges of the environment. This created a three-way relationship between the position of the visual field camera, the stimuli on the board, and the copy on the paper for the most accurate recordings to be taken. The stimuli on the board must be positioned so that during encoding, the stimulus is located in the centre of the visual environment. The written copy on the paper must be positioned so that during production, the copy is located in the centre of the visual environment.

At the set viewing distance, during encoding of the reference model, the centre of the visual environment captured by the field camera was the lower half of the board. This can be seen in Figure 3, in which the outline denotes the position of the entire wall-mounted board, and the fixation cross denotes the position at the centre of the visual environment available to the field camera. This is where a fixation cross was presented before each trial, and replaced by each word stimulus. The electronic markers needed for automatic recognition of the board interest area were placed at each corner of the consistently available visual environment.

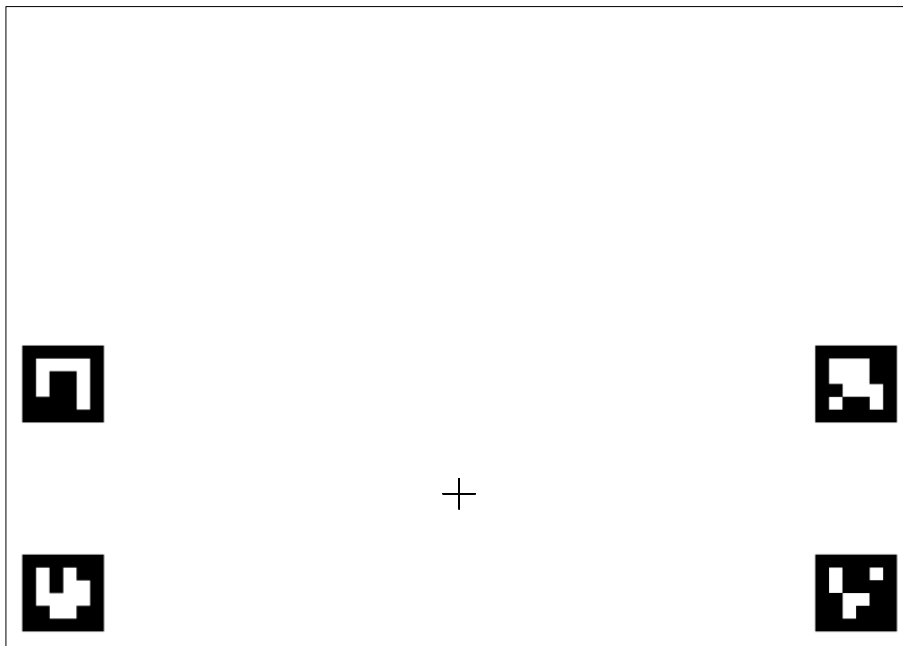


Figure 3. The board display.

During production of the written copy, the centre of the visual environment captured by the field camera was the upper half of the paper. This can be seen in Figure 4, in which the outline denotes the position of the entire paper, and the dotted line denotes the position of the guideline on which the copy was to be written.

At the edge of the paper, copiers checked a box to indicate their copy was complete. This was placed at the lowest edge to encourage copiers to make an eye movement from the written copy to the box. This eye movement produced a definitive moment at which cognitive processing associated with written production was complete. The electronic markers needed for automatic recognition of the paper interest area were placed at each corner of the consistently available visual environment.

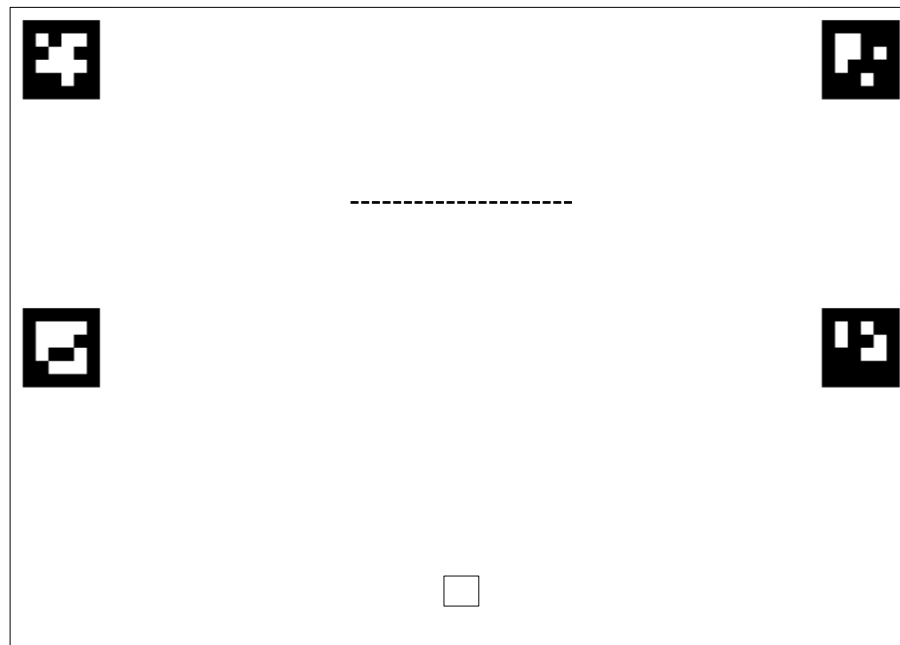


Figure 4. The notepaper display.

To improve upon the eye tracking accuracy on the notepaper, additional markers were added between the first and second experiments. Despite their best efforts to ensure the markers were not covered, children often forgot and placed their non-writing hand over the markers to steady the paper. This steadying action may have arisen out of habit rather than necessity, as the paper notebook was fixed to the desk in order to prevent participants moving or tilting the notebook.

On occasion, children would tilt their heads or physically “zoom in” so close to the paper that the outer markers were no longer in the field camera view consistently. To reduce missing eye tracking data by increasing the amount of markers that consistently remained in the field camera view, two markers were added along the top row, and another two markers were added along the line of writing, seen in Figure 5.

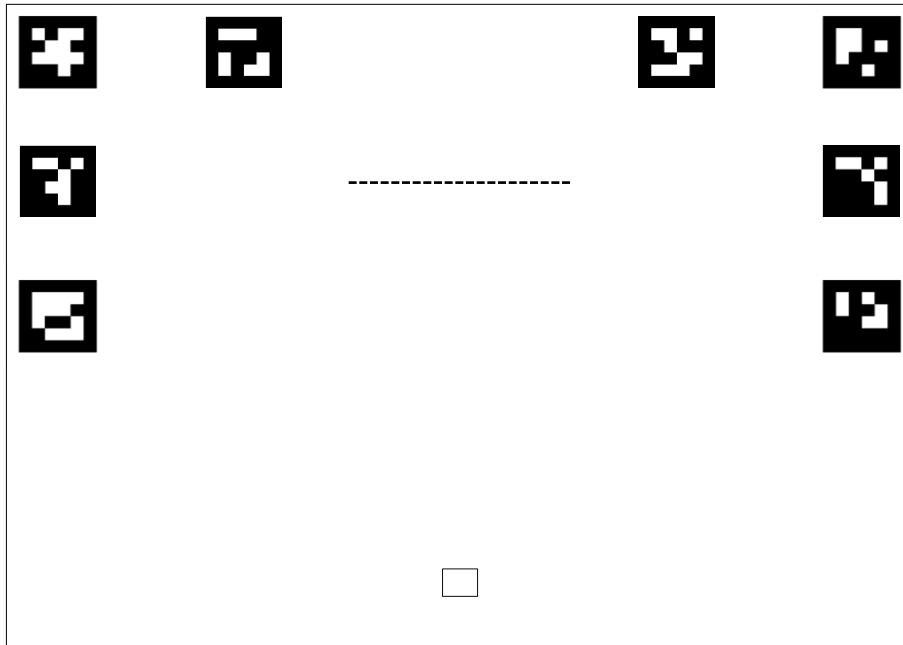


Figure 5. The revised notepaper display.

2.6 Data Handling

After collecting the eye movement data, each participant’s raw data was processed for data coding and analysis.

2.6.1 Data Processing.

Data processing was carried out using Dikablis software programmes.

Dikablis Analysis. The Analysis programme enabled the eye camera recording to be optimised in order to reduce missing eye tracking data, when the automatic pupil detection failed to find the pupil during a minority of recorded frames. Figure 6 demonstrates a typical example of an invalid frame in which the automatic pupil detection failed. After manual pupil detection, the centre of the child’s pupil is shown by the green cross.

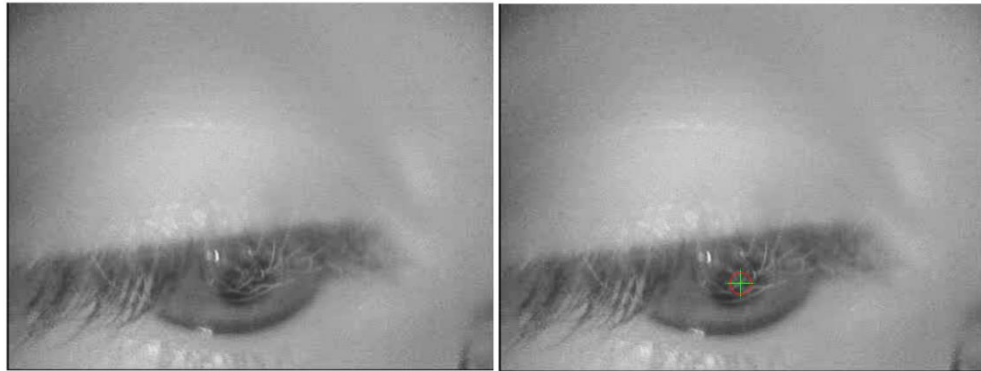


Figure 6. An example invalid frame before (left) and after (right) manual pupil detection.

The Analysis software enabled manual pupil detection on a frame-by-frame basis. Each recorded frame was categorised by the software as either valid or invalid dependent on whether the pupil was detected. For every invalid frame, the software enabled the user to manually identify the observable centre of the pupil.

It is important to note that pupil detection maintained objectivity. While the researcher could identify the pupil centre, this detection was only based on the eye camera recording, not the blended eye camera and field camera recordings. When identifying the centre of the pupil, the researcher did not see the pupil in relation to the visual environment, only the image of the eye in isolation, as seen in Figure 6.

Dikablis Lab. The D-Lab programme enabled the combined eye camera and field camera video recordings to be viewed for trial coding of whether or not gaze was in each interest area for every frame during the experimental session. Viewing the blended eye and field camera videos frame-by-frame in D-Lab, the researcher coded the frame numbers for each trial start and end, encoding periods, writing initiation and completion, number of gaze lifts, and in the second experiment, letter location of each individual gaze lift along with the start frame of each gaze lift.

This enabled assessment of where gaze was during the time-course of the trial, in relation to each encoding and production event, described below.

2.6.2 Data analysis: Measures for encoding.

First, gaze durations on the board where the word was presented formed measures of encoding time; second, there were several measures available that reflected encoding processes over different temporal periods during copying. Figure 7 illustrates the sequence of events within a trial, and how each time-based measure relates to the events, as described below. Measures of encoding are outlined in solid lines; measures of written production are outlined in dotted lines.

Initial encoding. When first presented with a word, there would be an immediate initial encoding period during which copiers would process the word for the first time, similar to early first pass measures of conventional reading studies. This would be defined as the sum of all gaze time on the board before gaze left the board for the first time. During this time, copiers would engage in visual uptake of information, identifying letters and letter positions, perhaps activating word or subword linguistic units.

Writing onset. After encoding, participants would make a head movement to transfer gaze to the paper and start written production of the encoded information. This would be defined as an extended measure of initial encoding, summing the trial time between stimuli presentation onset and writing onset. During this time, copiers would encode the stimuli for the first time and additionally engage in preparatory writing processes such as spelling retrieval.

Secondary encoding. If it was the case that a single encoding episode was not sufficient to produce a complete written copy, copiers might need more than one encoding episode. Secondary encoding during return visits to the board would be defined as the sum of all gaze time on the board after writing onset and before writing completion. During this time, copiers would re-engage in visual encoding, perhaps likened to the late measures of second pass reading, where the previous representation could be reanalysed, or new (previously not encoded) information could be encoded.

Verification encoding. After completing written production, copiers may take an opportunity to verify their copy, checking against the reference model. This period would be defined as the sum of all gaze time on the board after writing completion. During this time, the produced representation would be reanalysed in comparison to the stimuli.

Total encoding. Defined as the sum of all encoding time, total encoding time is most comparable to the global measure of total reading time. Especially for children's reading, effects are sometimes only seen in total reading time rather than the individual

component measures of total reading time (Joseph et al., 2008). In the case that the effects are there in the component measures, but so small as to be trends, if these effects are consistent, the cumulative effect may be significant in the most global measure.

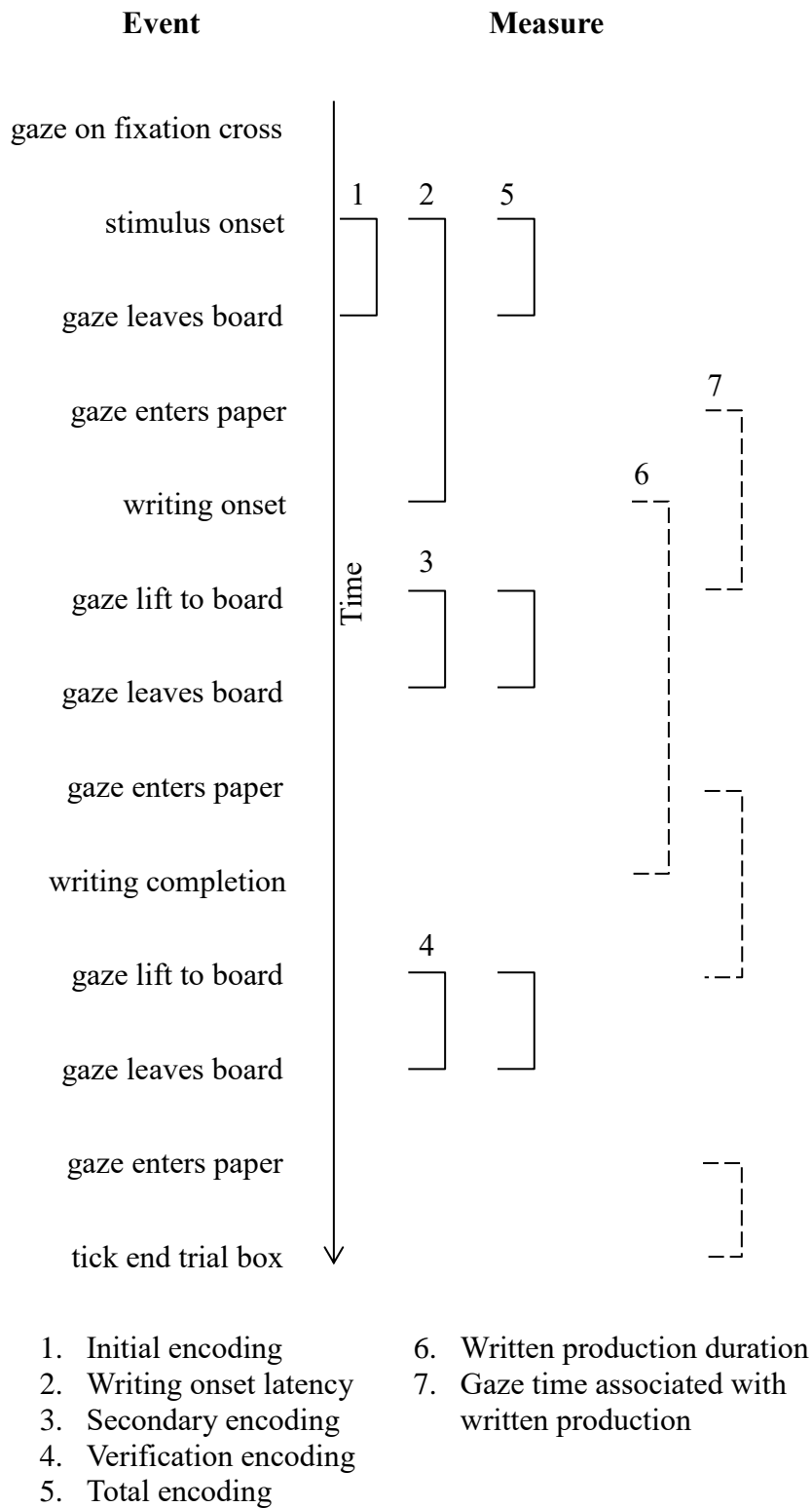


Figure 7. The time-course of events in relation to corresponding measures.

2.6.3 Data analysis: Measures for written production.

The field camera enables a visual record of when the pen movements started and completed written production to gain an indicator of writing time. Also, gaze time on the paper while the pen is not moving would incorporate cognitive processing associated with written production that pen motion alone would not include.

Written production duration. Defined as the time between writing onset and writing completion as measured by the first frame the pen touches the paper, to the frame the pen finishes the final letter, this is a local measure of time associated with executing written production.

Gaze time associated with written production. Defined as the sum of all gaze time in the paper area, this might indicate global cognitive processing associated with written production, including preparatory processing, online planning throughout writing execution, and verification after written completion.

2.6.4 Data analysis: Measures for written production in relation to gaze lifts.

The majority of previous research into handwritten copying tasks approached the topic from an interest in the written production process. But, some studies considered gaze behaviour in terms of gaze lifts between the written copy and the reference model.

Gaze lift analysis. If there are occasions when all the letters of a word could not be written after one encoding episode, copiers may make gaze lifts for additional encoding episodes, as seen in earlier research (Rieben & Saada-Robert, 1997). In the current research, the eye movement footage provided a record of gaze lifts.

Probability of gaze lifts. Defined as the likelihood of making at least one gaze lift to the board for secondary encoding, the probability of gaze lifts might indicate the amount of information that copiers can encode, represent and produce.

Number of gaze lifts. Defined as the number of times gaze returned to the board for secondary encoding, the number of gaze lifts is a measure of the number of encoding-production cycles needed in order to complete written production. The number of cycles could indicate the difficulty of copying that word.

Location of gaze lifts. Defined by the position of the last letter written before a gaze lift, this is a measure of how many letters can be written between gaze lifts, and the units over which written production operates. If the location is systematically after a

particular subword linguistic unit, this would implicate the unit as a cue for organising written production.

2.7 Overview

This chapter has described the copying paradigm used in this Thesis, explaining the rationale behind the methodological decisions. The paradigm was designed to access eye movement behaviour as an observable behavioural response that arises from the mental operations occurring during separate encoding and production sub-processes of a copying task. The Dikablis mobile eye tracker enables such recordings to be taken in a way that provides valuable data that could be potentially sensitive to specific linguistic manipulations relevant to the research questions. Within this Chapter, useful measures of gaze behaviour in relation to specific sub-process of the copying task have been put forward, and described in terms of what these measures may indicate in relation to cognitive processing. In the following Chapter, this copying paradigm will be used in the opening enquiry of the research to investigate how adults and children encode and produce words during a copying task.

CHAPTER 3

THE OPENING EXPERIMENTAL INQUIRY

3.1 The Current Study

Copying research has mostly focused either on skilled or developing readers, rarely contrasting performance in both groups. Using the copying paradigm to investigate differences between skilled and developing readers is important to specify the cognitive processes that occur during copying, and how the nature and time-course of copying changes at different points on a developmental trajectory of reading ability. In this opening enquiry, the aim was to investigate the units over which encoding and production operates during a single word handwritten copying task.

3.1.1 Encoding whole words as complete units.

One way individuals could encode information during copying is by encoding visual information about the letter identities and letter positions, then on the basis of this visual input, engage in a cognitive process of lexical identification in which a mental representation of a whole word unit is activated. (as in Afonso, Suárez-Coalla, & Cuetos, 2015; Inhoff, 1991; Kandel, Alvarez, & Vallée, 2006; Lambert, Kandel, Fayol, & Espéret, 2008). That is to say, copiers may go beyond the literal encoded information of letter forms when they mentally represent the stimulus in readiness for written production. In this case, characteristics of the printed stimulus in relation to linguistic units at a higher level representation than its low level letter forms might be expected to impact on encoding behaviour. Specifically, if copiers did engage in lexical identification of word units, not just encoding of letter units, then characteristics of the word unit that impact on the ease of lexical identification might be expected to modulate encoding behaviour. Time spent looking at the stimulus, as an indicator of time spent encoding and lexically identifying the stimulus, would then vary in relation to the cognitive difficulty an individual experienced during encoding and lexical identification. In this case, it could be expected that factors seen to impact on eye movement behaviour in other tasks that involve visual encoding and lexical identification, such as reading, would also affect eye movement behaviour during copying in a similar manner. In this case, findings in relation to a copying paradigm would be expected to fall in line with established reading research, demonstrating word-based influences on eye movements. During adults' sentence reading, two robust word-based effects are word length, whereby long words attract longer gaze durations

compared to short words (Just & Carpenter, 1980; Rayner, 1998), and word frequency, whereby lower frequency words attract longer gaze durations compared to higher frequency words (Rayner & Duffy, 1986). When word length and frequency were orthogonally manipulated, there was an interaction such that the difference in gaze durations between high- and low frequency long words was greater than the difference between high- and low- frequency short words (Pollatsek, Juhasz, Reichle, Machacek, & Rayner, 2008; Rayner, Sereno, & Raney, 1996). Even though children have only had a few years of print exposure, there has been enough exposure by age 8 years to drive down lexical access times for words that children encountered more often compared to words encountered less frequently. This has been shown in reduction of gaze durations for higher frequency words, even accounting for age of acquisition (Joseph, Nation, & Liversedge, 2013). Across lexical decision tasks and silent or oral sentence reading, children consistently spent more time processing low frequency compared to high frequency words (Ducrot, Pynte, Ghio, & Lété, 2013; Huestegge, Radach, Corbic, & Huestegge, 2009; Hyönä & Olson, 1995), even controlling for word length (Blythe, Liversedge, Joseph, White, & Rayner, 2009). This suggests children consistently engaged in word recognition during reading tasks. Also, similarly to influences of word length in adult eye movement behaviour (Rayner & McConkie, 1976), children spend more time fixating long compared to short words (Blythe, Häikiö, Bertam, Liversedge, & Hyönä, 2011; Huestegge et al., 2009; Hyönä & Olson, 1995), even controlling for word frequency and predictability (Joseph, Liversedge, Blythe, White, & Rayner, 2009).

If encoding was based on retrieved whole words, there may be similar gaze behaviour in copying as in reading: more demanding stimuli would require more extensive cognitive processing. If processing drives eye movement behaviour, because high frequency words would take less time to recognise than low frequency words, gaze times on higher frequency words would be shorter.

3.1.2 Encoding whole and/or partial words in a piecemeal way.

Previous studies have shown that task demands of copying influenced the amount of text that was visually encoded (Inhoff & Wang, 1992) and how much semantic processing influenced eye movements (Inhoff et al., 1986). It might be that lexical processing may not always occur in the same way during copying as in during reading (as in Kandel & Perret, 2015). If this is the case, another way individuals could encode information is by identifying and constructing multiple representations of all the

letter identities in order (separately or in letter clusters). If lexical identification did not complete, word frequency might have less of an influence on encoding time. For longer words, there would still be more letters to encode, so gaze times would be longer.

As working memory is limited (Baddeley & Hitch, 1974), copiers may encode some, but not all, of the letters. In this case, a partial-word representation could be constructed that would not be influenced by word frequency. Copiers would then need at least one secondary encoding episode, copying partial word representations incrementally until production had completed (as in Rieben, Saada-Robert, & Moro, 1997; Rieben & Saada-Robert, 1991, 1997). If copiers encoded a similar number of letters during each encoding episode for long and short words, there would be more successive encoding episodes for longer words. The number of gaze lifts should increase, and total encoding time overall should be longer. Also, there may not be effects of word length on the initial encoding episode, because only the first few letters of either a short or a long word would be encoded (regardless of its entire length).

3.1.3 Forgetting.

Irrespective of the nature of encoding, forgetting might occur, preventing the entire representation being maintained. As word length increases, the likelihood of forgetting should be greater (Baddeley, Thomson, & Buchanan, 1975). So, gaze lifts should be more likely for longer words. In addition, even when individuals know they must remember words, high frequency words were still easier to recall compared to lower frequency words (Balota & Neely, 1980). During copying, if copiers encoded whole words, gaze lifts should be less likely on higher than lower frequency words, as it should be easier to maintain higher frequency word representations. In piecemeal encoding, there should be no influence of frequency on probability of returning for secondary encoding.

3.1.4 Producing whole words as complete units.

If whole word representations are encoded and maintained, the unit used in production could also be an entire word. It has been suggested (Inhoff, 1991) that linguistic knowledge is “consulted” when copiers plan typed production events, and during this motor planning, lexical units are activated so that production is planned directly from a pre-existing, stable, long term representation, rather than one or several constructed representations that could be more vulnerable to errors. If this is the case

during handwritten copying, we should expect production of lower frequency words to take longer and see greater gaze times on the paper during production.

3.1.5 Producing whole and/or partial words as piecemeal units.

Alternatively, production of handwritten words could be planned and written in units smaller than the word (as in Afonso, Alvarez, & Kandel, 2014; Afonso & Álvarez, 2011; Kandel et al., 2006; Kandel, Alvarez, & Vallée, 2008; Kandel, Peereman, Grosjacques, & Fayol, 2011; Kandel, Spinelli, Tremblay, Guerassimovitch, & Alvarez, 2012; Kandel & Spinelli, 2010; Lambert et al., 2008; Sausset, Lambert, & Olive, 2013; Sausset, Lambert, Olive, & Larocque, 2012). In this case, word frequency would not influence production and there should be no influence of frequency on gaze times during production. However, as it would take longer to physically produce more letters, word length should influence production regardless of whether whole-word or piecemeal representations are involved.

3.2 Methods

3.2.1 Participants.

Skilled participants were 14 adults (6 male, 8 female), aged 18–22 (M age = 20 years). Developmental participants were 15 children (8 male, 7 female), aged 7–10 (M age = 9 years, 1 month). Using the Word Reading section of the Wechsler Individual Achievement Test (Wechsler, 2005) to measure reading ability, all children scored a typical, or above-typical reading age (M = 11 years, 3 months, SD = 3 years, 1 month). Children also showed typical IQ scores (M = 105, SD = 10), using the Wechsler Abbreviated Scale of Intelligence (Wechsler, 2011).

3.2.2 Materials and design.

The experiment was a mixed design, comparing between 2 groups (adults vs. children), within factors of word length (short vs. long), and word frequency (high vs. low).

Adults copied 40 target words (see Appendix N): word length was either short (4 letters) or long (8–10 letters); word frequency was either high (M = 773, SD = 122 for short words; M = 835, SD = 113 for long words) or low (M = 1, SD = 0 for short words; M = 1, SD = 0 for long words), assessed using Thorndike-Lorge written frequencies.

A separate stimuli set of 32 target words (see Appendix O) was constructed for children using the Children's Printed Word Database (Masterson et al., 2010); word

frequencies: word length was either short (4 letters) or long (8 letters), word frequency was either high ($M = 119$, $SD = 74$ for short words; $M = 128$ $SD = 63$ for long words) or low ($M = 4$, $SD = 1$ for short words; $M = 3$, $SD = 1$ for long words).

Independent-samples t -tests showed no difference in frequency between short and long high frequency words for adults, $t(18) = 1.17$, $p = .258$, or children, $t(14) = 0.26$, $p = .802$; or between short and long low frequency words for adults, $t(18) = -1.00$, $p = .331$, or children, $t(14) = -0.61$, $p = .554$. All words were single morphemes.

3.2.3 Apparatus.

Monocular left eye movements were tracked with the Dikablis cable eye-tracker, recording gaze location every 40 ms. A video projector presented individual words in a random order on a wall-mounted board. Each letter horizontally extended 1.10° of visual angle for adults, at a distance of 150 cm; and 1.25° of visual angle for children, at a distance of 135 cm².

3.3 Results

Across participants, a 2 (between age group: adults vs. children) \times 2 (within-word length: short vs. long) \times 2 (within-word frequency high vs. low) three-way mixed analysis of variance (ANOVA) was conducted to investigate differences for each dependent measure. Across items, a three-way independent ANOVA was conducted, with word length, word frequency and age group as between items fixed factors. Although data were positively skewed, logarithmic transformations on the data resulted in very similar models in inferential testing, so original models are reported.

Participants were offered breaks throughout to encourage focused attention, but 11% of all trials contained an error or disruption or were incomplete and were excluded from analysis. To ensure writing duration time remained accurate, pen data were excluded when pen tip location was not within visual camera range when participants started or ended written production. In the case of 4 adults, pen data could not be accurately coded due to the individuals' style of holding the pen; for all participants who showed codable pen behaviour, 9% of pen data was excluded.

² Visual angle between adults and children differed as children needed to sit nearer the board in order to ensure that when the head was lifted for encoding, eye movements were still fully trackable. The difference in how effective the eye tracker was at tracking adults compared to children arose due to differences in their height.

3.3.1 Errors.

As this study aimed to examine successful copying, trials containing an uncorrected or corrected error were not included in the same analysis of correct trials. As mistakes and corrections indicate a break down in processing, and were often accompanied by frequent gaze lifts, measures of successful encoding and production time may have been artificially distorted by these trials. Interestingly, all adults copied every word perfectly; only 15% children's trials contained errors.

3.3.2 Encoding measures.

The following eye movement measures were calculated to measure encoding over different temporal periods during copying: total encoding time; initial encoding time; writing onset latency; and secondary encoding time (recall Chapter 2.6 for detailed description). Number of gaze lifts was identified from field camera footage, allowing calculation of gaze lift probability. Table 1 shows mean encoding times for both adults and children. Secondary encoding data are only reported for children, as only 4% of adult trials contained a gaze lift, making meaningful analysis impossible. Gaze lift probability is shown in Table 2.

Table 1. Gaze times during encoding (ms) in relation to total encoding, initial encoding, writing onset and secondary encoding for both adults and children on words manipulated for length and frequency in Experiment 1.

		Short word length		Long word length	
		High frequency	Low frequency	High frequency	Low frequency
Total encoding					
Adults	<i>M</i>	1147	1302	1329	2187
	<i>SD</i>	(576)	(779)	(422)	(892)
Children	<i>M</i>	1160	1347	3337	3070
	<i>SD</i>	(653)	(687)	(2433)	(1838)
Initial encoding					
Adults	<i>M</i>	962	1074	1198	1835
	<i>SD</i>	(222)	(327)	(304)	(526)
Children	<i>M</i>	795	909	1259	1150
	<i>SD</i>	(152)	(253)	(732)	(345)
Writing onset					
Adults	<i>M</i>	2164	2208	2348	2949
	<i>SD</i>	(468)	(625)	(639)	(723)
Children	<i>M</i>	1893	2075	2449	2129
	<i>SD</i>	(411)	(456)	(808)	(468)
Secondary encoding					
Children	<i>M</i>	939	1306	3911	3451
	<i>SD</i>	(564)	(573)	(2555)	(1811)

Total encoding time. As gaze time on the board was indicative of the time course of cognitive processing, total encoding time, which includes both initial and secondary encoding episodes, may only show evidence of frequency effects due to lexical processing if the word is consistently being treated as an entire unit during all encoding episodes. In total encoding time, there were main effects of both length, $F_1(1, 27) = 32.33, p < .001$; $F_2(1, 64) = 147.33, p < .001$, whereby long words were looked at for more time than short words; and frequency, $F_1(1, 27) = 10.11, p < .01$; $F_2(1, 64) = 7.82, p < .01$, whereby total encoding time was shorter on high- compared to low frequency words. There was also a main effect of group, $F_1(1, 27) = 3.51, p = .07$; $F_2(1,$

64) = 45.08, $p < .001$, such that children needed more encoding time than adults, and a three-way interaction between age group, length and frequency, $F_1(1, 27) = 13.26$, $p < .001$; $F_2(1, 64) = 8.21$, $p < .01$.

To explore the three-way interaction, paired (by participants) and independent (by items) t -tests between word frequencies were conducted. Between high- and low frequency short words, there were no consistent influences of frequency across children's total encoding time by participants, $t_1(14) = -1.73$, ns , but across children's items, low frequency short words took more total encoding time than high frequency short words, $t_2(14) = -6.07$, $p < .001$. There were no influences of frequency on children's total encoding time of long words, $t_1(14) = 1.23$, ns ; $t_2(14) = .56$, ns . This suggests that children were capable of encoding whole words, but did not consistently encode long words as a whole unit. For adults, low frequency words had longer total encoding times compared to high frequency words for both short words, $t_1(13) = -2.30$, $p < .05$; $t_2(18) = -1.34$, ns , and long words $t_1(13) = -5.09$, $p < .001$; $t_2(18) = -4.56$, $p < .001$, suggesting that adults consistently encoded whole words.

Initial encoding time. Next, total encoding time was broken down to consider only initial encoding time; similar main effects of length, $F_1(1, 27) = 37.94$, $p < .001$; $F_2(1, 64) = 98.99$, $p < .001$, frequency, $F_1(1, 27) = 16.28$, $p < .001$; $F_2(1, 64) = 22.45$, $p < .001$, and age group $F_1(1, 27) = 4.37$, $p < .05$; $F_2(1, 64) = 39.54$, $p < .001$ remained. Initial encoding time was greater for longer words and greater for lower frequency words, though children spent less time initially encoding a word than adults. This finding suggests adults are doing something different compared to children during initial encoding, and the processing adults engaged in was more demanding.

The three-way interaction between age group, length and frequency was also significant, $F_1(1, 27) = 17.70$, $p < .001$; $F_2(1, 64) = 16.06$, $p < .001$. Children needed less initial encoding time for high compared to low frequency short words, $t_1(14) = -2.87$, $p < .01$; $t_2(14) = -2.37$, $p < .05$. Similar to total encoding, children showed no frequency effects during initial encoding of long words, $t_1(14) = .88$, ns ; $t_2(14) = .45$, ns . This suggested that children used whole word processing for short words, but long word encoding occurred on the basis of units smaller than the whole word. Adults showed a different pattern, as less initial encoding time was needed for high- compared to low frequency words for both short words, $t_1(13) = -2.11$, $p = .055$; $t_2(18) = -2.43$, $p < .05$ and long words, $t_1(13) = -5.46$, $p < .001$; $t_2(18) = -6.70$, $p < .001$, suggesting that adults consistently encoded both short and long words as an entire unit.

Writing onset. Writing onset reflected initial encoding time as well as time associated with planning of production. It seems likely that this may include some form of spelling retrieval, such as phoneme to- grapheme mapping, as well as motor planning. In measures of writing onset, main effects of length remained significant, $F_1(1, 22) = 21.99, p < .001$; $F_2(1, 64) = 50.06, p < .001$, whereby writing onsets were longer for longer words. Main effects of frequency also occurred $F_1(1, 22) = 5.93, p < .05$; $F_2(1, 64) = 10.16, p < .01$, whereby writing onsets were longer for lower frequency words. Main effects of group were significant over items, $F_1(1, 22) = 1.68, ns$; $F_2(1, 64) = 36.13, p < .001$, as children were quicker to start writing compared to adults. Note again, this difference suggests children were performing differently to adults in relation to this aspect of processing.

Exploration of the significant three-way interaction between age group, length and frequency, $F_1(1, 22) = 17.88, p < .001$; $F_2(1, 64) = 19.17, p = .01$, showed that in children, writing onset was shorter for higher frequency than lower frequency short words, $t_1(14) = -2.22, p < .05$; $t_2(14) = -2.60, p < .05$, but for long words, children were quicker to start writing lower frequency words, $t_1(13) = 2.06, p = .06$; $t_2(14) = 1.48, ns$. Again, adults showed a different pattern, as the writing onset latency for higher frequency words was only quicker for long words, $t_1(9) = -4.53, p < .001$; $t_2(18) = -4.47, p < .001$, but not short words $t_1(9) = -.634, ns$; $t_2(18) = -1.29, ns$.

3.3.3 Gaze lifts.

Children needed regular secondary encoding, initiating at least one gaze lift before they finished writing on 46% all their trials. Gaze lift probability indicates whether a trial included a gaze lift (regardless of whether a single lift or multiple lifts occurred within the same trial).

Table 2. Gaze lift behaviour for children on words manipulated for length and frequency in Experiment 1.

	Short word length		Long word length	
	High frequency	Low frequency	High frequency	Low frequency
Probability of making a gaze lift				
<i>M</i>	0.19	0.33	0.71	0.70
<i>SD</i>	(0.34)	(0.39)	(0.32)	(0.36)
Number of gaze lifts per word				
<i>M</i>	1.21	1.58	4.03	3.75
<i>SD</i>	(0.33)	(0.54)	(2.16)	(1.81)

Probability of gaze lifts. Children were more likely to make a gaze lift on longer words, $F_1(1, 14) = 31.95, p < .001$; $F_2(3, 28) = 127.34, p < .001$. Effects of word frequency were significant over items, $F_1(1, 14) = 2.84, p = .114$; $F_2(3, 28) = 4.92, p < .05$, and the interaction was also significant over items, $F_1(1, 14) = 2.57, p = .132$; $F_2(3, 28) = 4.16, p = .051$. Gaze lifts were more probable on a short low frequency word compared to a short high frequency word, $t_1(14) = -2.67, p = .018$; $t_2(14) = -5.18, p < .001$, but gaze lifts on long words occurred just as often regardless of word frequency, $t_1(14) = .13, ns$; $t_2(14) = -.10, ns$.

Number of gaze lifts. The number of gaze lifts showed main effects of length alone, $F_1(1, 5) = 13.70, p < .05$; $F_2(3, 28) = 126.39, p < .001$. There were no main effects of frequency, $F_1(1, 5) = .10, ns$; $F_2(3, 28) = .17, ns$, and no interaction between length and frequency $F_1(1, 5) = 2.66, ns$; $F_2(3, 28) = 1.38, ns$. Compared to short words, children tended to need more than double the amount of gaze lifts for long words, independent of word frequency. This suggested that only the amount of letters constrained how much information children could mentally represent and produce.

Secondary encoding time. The secondary encoding times were computed for trials that contained a gaze lift (approximately half of children's data). While only half of the children made a gaze lift in all conditions, the items analysis is robust, as for those children that made gaze lifts, there was at least one gaze lift on every item. There were main effects of length, $F_1(1, 5) = 13.98, p < .01$; $F_2(3, 28) = 61.98, p < .001$, as long words needed more secondary encoding time compared to short words. Effects of frequency present in initial encoding time were not significant in secondary encoding

time, $F_1(1, 5) = .05, ns$; $F_2(3, 28) = .08, ns$, and the interaction between length and frequency was not significant, $F_1(1, 5) = 3.42, ns$; $F_2(3, 28) = 1.61, ns$.

3.3.4 Written production measures.

Eye movement data enabled calculations of gaze time associated with written production and written production duration was coded from pen location. Times associated with written production and written production duration are displayed in Table 3 for both adults and children.

Table 3. Written production times (ms) in relation to gaze time associated with written production and written production duration for both adults and children on words manipulated for length and frequency in Experiment 1.

		Short word length		Long word length	
		High frequency	Low frequency	High frequency	Low frequency
Gaze time associated with written production					
Adults	<i>M</i>	2635	2628	4432	4389
	<i>SD</i>	(540)	(578)	(840)	(584)
Children	<i>M</i>	4528	4230	7129	7361
	<i>SD</i>	(2109)	(1842)	(3259)	(2930)
Written production duration					
Adults	<i>M</i>	1773	1805	3606	3554
	<i>SD</i>	(269)	(257)	(522)	(471)
Children	<i>M</i>	4124	4255	9591	9611
	<i>SD</i>	(2039)	(2072)	(4388)	(4401)

There were substantial main effects of length for both gaze time associated with written production, $F_1(1, 27) = 108.03, p < .001$; $F_2(1, 64) = 343.47, p < .001$, and written production duration, $F_1(1, 27) = 82.91, p < .001$; $F_2(1, 64) = 556.92, p < .001$. Production measures consistently showed time advantages for shorter words compared to longer words. These differences reflected the extra time needed to manually write more letters for longer words. However, there were no effects of frequency on either measure ($F_1(1, 27) = .03, ns$; $F_2(1, 64) = .61, ns$; $F_1(1, 27) = .15, ns$; $F_2(1, 64) = .02, ns$),

and no three-way interaction ($F_1(1, 27) = 1.53, ns$; $F_2(1, 64) = .03, ns$; $F_1(1, 27) = .01, ns$; $F_2(1, 64) = .87, ns$).

The lack of frequency differences implies that production is independent of word frequency, instead being driven primarily by the amount of content (number of letters) of the string being produced. Also, there were main effects of group for both gaze time associated with written production $F_1(1, 27) = 12.55, p < .001$; $F_2(1, 64) = 359.88, p < .001$; and written production duration $F_1(1, 22) = 17.13, p < .001$; $F_2(1, 64) = 752.31, p < .001$, as children consistently took more time to produce the written words compared to adults.

3.4 Discussion

The current study aimed to explore whether words were treated as whole units during encoding and production during copying. Findings showed that copying draws on linguistic knowledge, and words can be lexically processed in a similar way during copying as in reading. Both a word's length and frequency influenced how much time copiers spent encoding, but influences of word length and frequency were not always the same for children and adults.

Although both adults and children were capable of encoding a whole word, the entire representation could not always be maintained throughout written production. Failure to produce the entire word occurred, but very rarely in adults. Forgetting was more common in children, who returned gaze regularly to the board for secondary encoding, but needed more gaze lifts for some words depending on word length and frequency. During production, findings displayed influences of word length similar to influences in encoding, but effects of word frequency that were present during encoding were not evident in measures of production.

First, results relating to processing associated with encoding will be discussed. Before detailed consideration, it is worth noting a global difference between visual word processing during reading and copying. Cognitive demands associated with copying seem greater than those associated with reading, even for skilled adults. In line with copytyping research showing fixations during copying were longer than during reading (Inhoff & Gordon, 1997; Inhoff et al., 1986), even adult copiers needed at least 1000ms of gaze time during encoding. This is 4 times the typical 250 ms gaze duration during normal reading (Rayner, 1998), suggesting differences between how words are encoded during copying and reading, likely due to differences in task demands.

Similar to visual processing during isolated word recognition and sentence-reading tasks (Hudson & Bergman, 1985; Rayner & Duffy, 1986), adults consistently engaged in word processing during copying. During encoding, adults needed more encoding time for longer, and lower frequency words, with the most difficult words to encode being long, low frequency words. However, whereas lower frequency added about 50 ms to gaze durations during sentence reading (Rayner, 1998), more demanding processing associated with copying (in readiness for written production) required more time than this. As with Inhoff et al. (1986), who showed lower word frequency added at least 100ms to gaze duration during copytyping, we found that even for short words, adults needed at least 150ms more encoding time for lower frequency words.

In contrast to adults, children's encoding indicated different word processing. In total encoding time, children spent more time encoding words than adults, presumably because they found the task more difficult overall. Yet, looking only at initial encoding, adults needed more time than children. This suggests adults initially engaged in more demanding processing, likely associated with retrieving and maintaining stable mental representations for the whole word. Unlike adults who consistently appeared to use whole words as encoding units, the nature of children's encoding was dependent on word length. For short words, children showed similar patterns to adults, with reduced encoding times for higher frequency words, again suggesting children were capable of encoding whole word representations. This is consistent with reading-for-meaning studies showing children's gaze durations on low frequency words were longer than on high frequency words (Blythe et al., 2009; Huestegge et al., 2009; Hyönä & Olson, 1995; Joseph et al., 2013).

However, for long words, the story is more complex. Children did not take longer to encode a lower frequency word if the word length was long, implying children did not purely lexically identify words, then use word representations as the basis for production. Instead they may have encoded only a partial word representation. Interestingly, it took children longer to start writing a higher frequency long word compared to a lower frequency long word, perhaps because more letters were encoded in readiness for written production. One explanation for these findings could be that children were not capable of lexically identifying long words. However, this suggestion seems unlikely given that children's sentence-reading studies demonstrate robust influences of word frequency in mid-length (Blythe et al. 2009; Joseph et al. 2013), and long words (Huestegge et al., 2009), even in words longer than those used in the current

study (Hyönä & Olson, 1995). Thus, it seems likely that children were able to identify long words in the present study.

If children are capable of recognising long words during reading, perhaps task demands associated with copying resulted in children not consistently engaging in whole word processing for long 8 letter words, unlike the shorter 5-6 letter words in Kandel and Perret (2015), and 4 letter words in the current study. Adults' perceptual span during copying is approximately seven characters (Inhoff & Wang, 1992) and it may be that a child's perceptual span is smaller still, as is the case during sentence reading (Rayner, 1986). If this was the case, due to their reduced perceptual span, children may encode units of information that are less than a whole word during copying. Also, children may not have the working memory resources necessary to store the full set of letters in a long word. This may contribute towards not consistently engaging in whole word copying, perhaps because the working memory capacity of children may be smaller compared to adults (Cowan, Aubuchon, Gilchrist, Ricker, & Sauls, 2011). Another reason may be due to the way in which children stored information. Cowan (2001) argued that individuals store information in terms of meaningful units. Because storage capacity is limited, there may only be enough capacity for approximately 4 meaningful items, but the size of a "meaningful unit" can vary. In relation to word copying, if children were encoding information on the basis of letter identities, a single letter may be the size of a meaningful storage unit. If this was the case, then a child could only store about 4 letters after each encoding episode. Then, as was found, children would need at least 2 successive storage episodes in order to encode and produce an 8 letter word, and potentially more storage episodes if less than 4 letters were successfully retained throughout production.

Next, the secondary encoding findings. Both adults and children demonstrated gaze lifts, returning gaze for additional encoding after the initial encoding period. Adults needed so few gaze lifts that their data could not be analysed, suggesting that maintaining a whole word representation did not challenge adults. Adults never demonstrated gaze lifts on short, high frequency words, indicating that these were the easiest to encode and maintain in working memory. Again, children showed a different pattern, needing at least one gaze lift on approximately half of all trials. Gaze lifts could occur for at least 2 possible reasons. If words were initially encoded as a whole, then return lifts could indicate forgetting. Alternatively, if the word was encoded as multiple partial word representations, then gaze lifts would be consistent with incremental encoding.

Children showed occasional gaze lifts on 4 letter words. Recall that encoding behaviour in children was comparable to adults for short words, so these gaze lifts suggest that even when children encoded a whole words, the representation could not always be maintained until production was complete. Research demonstrates that both word length (Baddeley et al., 1975) and frequency (Balota & Neely, 1980) influence the ease with which representations are maintained in memory. Accordingly, gaze lifts were more probable on lower frequency short words, suggesting these representations were harder for children to maintain.

Interestingly, when children returned gaze to the board, there was no influence of word frequency on how long they spent re-encoding, implying that children did not engage in repeated full word identification, but perhaps used gaze lifts to only encode letters yet to be produced. Gaze lifts were most probable on long words irrespective of word frequency, and there was no difference in the number of gaze lifts needed on high and low frequency long words, supporting the idea that these words were incrementally encoded. However, as word length doubled, the number of gaze lifts needed also doubled, suggesting that when children returned for secondary encoding, they encoded a similar number of letters during each return visit irrespective of word length.

Finally, discussion turns to production behaviour. Gaze time and written production duration showed identical patterns in children and adults, namely substantial effects of word length alone. A fundamental constraint on language production is word length. Letters take a comparable amount of time to write, and consequently, when a word contains more letters it takes longer to write. Also, children are less skilled at writing than skilled adult writers. Therefore, it is perhaps unsurprising that children took more time to produce words than did adults. At least some additional processing that children engaged in will have been associated with place-finding behaviour and taking time to resume written production after pausing for secondary encoding. All these suggestions are consistent with the claim that children engaged in partial word encoding.

Importantly, word frequency did not impact written production, suggesting that the ease with which a whole word was encoded did not affect the time it took to write the word. This is inconsistent with earlier copytyping research suggesting that the whole word is a functional unit of planning in relation to written production (Terzuolo & Viviani, 1980). To reiterate, research investigating typing showed that copiers took more time to type low compared to high frequency words (Inhoff, 1991; Inhoff & Wang, 1992). The present results provide no evidence of comparable lexical influences

during handwritten production. The mode of language production (typing vs. handwriting), may change the relative influence of linguistic and motoric influences (Weingarten, Nottbusch, & Will, 2004). If the motoric demands of handwriting (forming letters by multiple varying pen strokes) are more demanding compared to the demands of typing (pressing a single key to produce each letter), then it may be less resource-demanding for a writer to plan several smaller writing events compared to a single larger writing event based on multiple letters. If this was the case, then whole word characteristics such as frequency may be much more influential over the production process during typing. In contrast, handwritten production would be influenced more by subword structure than by whole word characteristics.

The possibility that copiers plan written production in units smaller than the whole word is supported by previous handwritten copying studies, which suggested linguistic influences of subword units on production, like morphemes (Kandel et al., 2008, 2012), syllables (Afonso & Álvarez, 2011; Kandel, Alvarez, et al., 2006; Lambert et al., 2008, 2015; Sausset et al., 2013, 2012), graphemes (Kandel et al., 2011; Kandel, Soler, et al., 2006; Kandel & Spinelli, 2010) and phonemes (Afonso et al., 2014). However, Lambert et al. (2011) found that although there were no main effects of word frequency on written production, word frequency qualified the effects of orthographic regularity. Copiers were slower to write regular compared to irregular low frequency words, suggesting that whole word characteristics of word frequency may have some modulatory influence on written production. It may be that gaze times alone are not sufficiently sensitive to allow for identification of subtle influences during written production. Also, perhaps the frequency of writing a word may be more influential on written production than the frequency of reading a word. These possibilities clearly require further research attention.

3.5 Overview

In summary, the current study demonstrated that head-mounted eye-tracking can provide a valuable method of investigating cognitive processing as adults and children carry out a cognitively complex task, copying, that requires co-ordination of visual encoding, mental representation and written production. In future research, the paradigm could be applied to directly investigate the precise linguistic units that are used when children encode and produce word representations. French studies have suggested that children use syllables (Kandel et al., 2009; Kandel & Soler, 2010; Kandel & Valdois, 2006a, 2006b; Soler & Kandel, 2009, 2012), graphemes (Kandel,

Soler, et al., 2006) and phonemes (Kandel, Soler, et al., 2006; Re & Cornoldi, 2015) during written production in a copying task. Yet, research has not confirmed whether subword segmentation in production reflects similar segmentation during encoding. In addition, English is a morphologically transparent, but phonetically opaque orthography, with less consistency between graphemes and phonemes than French. It may be that cross-linguistic differences in segmentation exist, as between French, Catalan and Spanish (Kandel & Soler, 2010; Soler & Kandel, 2009), resulting in English children relying less on phonological subword units. Alternatively, different segmentation preferences may emerge at different ages, presumably reflecting developmental changes in language processing (as in Soler & Kandel, 2012). The present and future research will contribute to improved understanding of how encoding, representation and production processes are co-ordinated during copying in children with a view to providing insight into the language development more generally.

CHAPTER 4

A LEXICAL DECISION EXPERIMENT TO ASSESS VALIDITY OF CONCLUSIONS DRAWN IN THE FIRST COPYING EXPERIMENT

4.1 Introduction

The opening section of this introduction sets up the motivation for Experiment 2. A key finding from Experiment 1 was that children did not always activate whole word units, as evidenced by inconsistent effects of word frequency when children encoded words during copying. Recall, Experiment 1 showed that children consistently activated whole word units during encoding of short, 4 letter words, but not long, 8 letter words. This was surprising, because researchers have previously shown consistent effects of word frequency when children of a similar age read words during a sentence reading task (Blythe, Liversedge, Joseph, White, & Rayner, 2009; Joseph, Nation, & Liversedge, 2013). As discussed in Chapter 3, one possible explanation for these findings in Experiment 1 is that text processing might proceed in a different way during reading (in which text must be encoded and mentally represented for comprehension) compared to copying (in which text must be encoded and mentally represented for written production). In this case, the nature of text processing may be dependent on the task demands. The task demands of encoding and mentally representing a whole long word throughout production might be beyond children's capabilities. If this was the case, the task demands of encoding and mentally representing a single long word might have been reduced by encoding and mentally representing smaller partial word representations over multiple cycles of encoding and production. Although this explanation can account for the findings in Experiment 1, two alternative explanations will be considered in this Chapter.

First, children may not yet have acquired the long words chosen for the stimuli. As previously described in Rieben and Saada-Robert (1997) children can successfully copy words that they do not yet know, so accurate copying does not depend on successful word recognition. It might have been that in Experiment 1, children did not have a pre-existing lexical entry for all long words. If this was the case, the manipulation of the ease of access of this lexical entry, as determined by word frequency, would not have been effective. Some long words may have been treated as word units, while other long words may have been treated as nonwords. This would have resulted in noise in potential frequency effects in long words.

Second, children's eye movements may not be sufficiently sensitive to differences due to word frequency in long, 8 letter words. Studies have shown that, like adults, children's eye movements were sensitive to word frequency manipulations that moderate word processing during reading. Yet, to date, frequency effects have only been shown in 5-6 letter words in English children. As such, the idea that children's eye movements show sensitivity to word frequency in long, 8 letter English words is an assumption, not directly supported with data. Hyönä and Olson (1995) previously demonstrated that 10 year old children's eye movements during reading were sensitive to word frequency in 9-11 letter Finnish words. However, unlike English, Finnish is an agglutinative language, in which words are often formed by joining multiple words together. It might be that because long words are more common in Finnish than in English, Finnish children may be more used to reading long words than English children. It might be the case that English children find all long words difficult to read, and that their eye movements are not yet sensitive to effects of word frequency by the age of 7 years old in a similar manner as adult eye movements. This would have resulted in an insensitivity to word frequency for encoding gaze times in long words.

The aim of Chapter 4 was to strengthen the argument that the inconsistent frequency effects observed in encoding times in Experiment 1 were due to the upcoming task demands of written production, rather than unknown stimuli or insensitive eye movement measures. To investigate this, Experiment 2, reported in Chapter 4, used a task that involved constituent sub-processes of visual encoding and mental representation, but did not include a third constituent sub-process of written production. Now, an argument for selecting a lexical decision task for Experiment 2 will be outlined. Next, the reasoning for designing an adaptation of the traditional lexical decision task will be presented. Then, a brief review of relevant research investigating children's cognitive processing during lexical decisions will be discussed, followed by a report of the current study.

A lexical decision task was chosen because the dependent measures of response accuracy and response time could address three key questions that concern the extent to which children recognised and consistently encoded whole word units. 1) Whether children accurately recognised the word after encoding; 2) irrespective of whether children activated whole word or subword units during encoding, whether the same units were activated for both short and long words; and 3) whether children activated whole word units during encoding, as evidenced by word frequency effects. A lexical decision paradigm would address all of these points.

In a traditional lexical decision task, participants are typically presented with either a real word, or a pseudoword for which participants have no lexical entry. The task is to decide as quickly as possible whether or not the item is a word, and then press a button to indicate a yes or no response. The response times as measured by the button press are suggested to indicate the extent of cognitive processing involved in the decision.

Yet, in a lexical decision paradigm in which a button press determined response times, the dependent measure would not be directly comparable to the eye movement measures of encoding gaze times used in Experiment 1. Different motor systems responsible for hand movements may not execute responses in the same time as the oculomotor system. In the copying task, to finish visual encoding, children made a saccade away from the word on the board. For the dependent measures of encoding time during copying and response time during lexical decision to be directly comparable, the response method in the lexical decision should also be an eye movement. A similar idea was used in a variant of the traditional lexical decision task that Hoedemaker and Gordon (2014) termed an *ocular lexical decision* task. In their experiment, participants were asked to fixate individual letter strings in a sequence of three strings, moving their eyes from the current to the next string if the current string was a word, but pressing a button instead if the current string was a pseudoword. In this way, Hoedemaker and Gordon were able to access gaze durations on word items, finding that eye movements during a lexical decision task were sensitive to semantic priming. Adults spent less time looking at the second word in the sequence if the meaning of that word was related to the meaning of the first word (e.g., *gold* preceded by *silver*) than an unrelated word. This means that gaze durations in a lexical decision task can demonstrate sensitivity to manipulations that affect processes involved in lexical identification to the point at which a word's meaning becomes available. As such, it could be argued that gaze durations during a lexical decision task may be sensitive to factors of word frequency that modulate processes of lexical access.

However, because Experiment 1 investigated isolated word recognition, the paradigm in Chapter 4 adapted the ocular lexical decision task such that a decision was made on an isolated letter string, rather than decisions on a sequence of multiple strings within a single trial. By having participants fixate a particular area of the screen away from the word to give their decision on whether the presented letter string was a word, such as images of a tick or a cross, gaze durations on a single word could be measured during children's lexical decisions.

To date, developmental research has used a traditional lexical decision paradigm to examine the lexical access process in children. Importantly, the effects of item length (in words and pseudowords) and item accessibility (in words) have been suggested to indicate specific cognitive processes. These two concepts of item length and accessibility in relation to children's lexical decisions will now be addressed in turn.

4.1.1 Item length.

Critically for the current study, Martens and de Jong (2006) suggested that effects of item length on response times during lexical decision can be informative about the linguistic units that children cognitively processed during the decision. Martens and de Jong used the Dual Route Cascaded model of word recognition to explain how item length would differentially affect the lexical and sublexical routes of processing, impacting on the time taken to respond to the time. They suggested that increasing item length should not increase response time if children used the lexical route, but effects of item length should be evident in response time if children used the nonlexical route.

In the lexical route, letters are said to be activated in parallel for every letter position, which then activate corresponding words in the orthographic lexicon with letters in the appropriate positions. The critical point suggested by Martens and de Jong (2006) was that if letters were activated in parallel, lexical decisions would not be influenced by word length because each letter in the word is activated at the same time.

Alternatively, in the nonlexical route, after letters are activated, their phonology is decoded in a serial manner to name the letter string in an assembled manner. The important point suggested by Martens and de Jong was that the decoding process would be sensitive to word length, taking more time with each letter to decode. In relation to lexical decisions, the presence and strength of word length effects might be informative about the linguistic units children used to reach the decision, either word or letter units.

So far, three experiments have manipulated word length of pseudowords and words in different languages, asking children to make a lexical decision. Di Filippo, de Luca, Judica, Spinelli and Zoccolotti (2006) asked 8-9 year old Italian children to decide on 3 or 5 letter items, Martens and de Jong (2006) asked 10 year old Dutch children to decide on 3-6 letter items, and Araújo, Faísca, Bramão, Petersson and Reis (2014) asked 8-10 year old Portuguese children to decide on 4-5 or 6-7 letter items. All three experiments consistently showed the same 2 key findings, which will now be described.

The first finding was that response times on words were quicker than pseudowords. This can be explained by the idea of building activation within the lexical access process until the level of activation is sufficiently high enough for a word to be accessed. The more activation needed, the longer the time needed to achieve lexical access, which is achieved for words but not pseudowords. This *lexicality effect*, a benefit for words over pseudowords, is in line with the idea that children achieved word decisions on the basis of a lexical processing route, engaging in lexical activation based on word units that often activated word items (but not pseudoword items), then disengaged with the decision process after lexical access.

The second finding was that word length did not affect words and pseudowords to the same extent. The difference between long and short items was about five times greater for pseudowords (approximately 120-300ms) than for words (approximately 30-50ms). This might be explained by children persisting with a non-lexical route, continuing with serial decoding of letter units. If the lexical route was consistently unproductive for pseudowords, but only sometimes unproductive for words, word length would modulate response times on pseudowords to a greater extent than words because children would engage in serial letter decoding more often for pseudowords.

Although de Zeeuw, Schreuder and Verhoeven (2014) did not experimentally manipulate word length, they included word length as a predictor in their linear mixed models of response times of 7, 9 and 11 year old Dutch children. They did not report a statistical comparison of words and pseudowords, but did state that word length was a strong predictor of response times for 5-13 letter words. Does it necessarily follow that, unlike the 3 studies above, all words were accessed using letter decoding rather than activating word units? Another possibility might be that not all the letters in a word can always be activated in parallel.

The DRC model (Coltheart et al., 2001) was designed to describe adult lexical access in words with up to 8 letters, and as discussed during the literature review, children are developing parallel letter recognition (Kwon et al., 2007). It might be that children can only recognise a limited number of letters in parallel, and that limit may be smaller than 8 letters. In the 3 studies described collectively above, comparing words differing by 2-3 letters did not result in a large word length effect (Araújo et al., 2014; Di Filippo et al., 2006; Martens & de Jong, 2006). Word length effects might be more evident if the difference between short and long words is more than 3 letters.

Nevertheless, looking collectively at studies investigating effects of item length, research has so far suggested that children primarily engage in text processing based on

word units during lexical decisions, but phonologically decode letter units before rejecting an item as a word. Importantly, these studies also indicate that children are capable of accessing a mental representation of a whole word unit during a lexical decision task.

4.1.2 Item accessibility.

As well as item length, lexical decisions have also been suggested to be sensitive to the ease of lexical access, with more accessible items taking less response time. So far, researchers have investigated several factors determining ease of access, including whole word frequency, frequency of subword units, and neighbourhood size. These factors will now be considered in turn.

In relation to word frequency affecting lexical access, the DRC model (Coltheart et al., 2001) specified that the activation levels of higher frequency words should rise faster than lower frequency words. This results in the prediction that, compared to lower frequency words, lexical access will take less time for higher frequency words, therefore children will respond faster to these words in lexical decisions. Indeed, research supports this. In the study by Araújo et al. (2014), word items were manipulated for frequency, either occurring relatively often or rarely in children's print experience. They found that children were quicker to decide on higher frequency words, showing evidence for a process such as lexical access in which properties of the whole word unit impacted response time.

Similarly, de Zeeuw, Schreuder, and Verhoeven (2014) showed that 7, 9 and 11 year old Dutch children were sensitive to whole word frequency and constituent word frequency in unhyphenated compound words. Children took less time to respond to higher frequency words, and less time for both high and low frequency words with a high frequency first morpheme compared to a low frequency morpheme. As well as whole word units, subword units of morphemes must also be activated, with higher frequency morphemes facilitating lexical decisions.

However, although subword units may be activated, they may not always be facilitative. Another approach to demonstrate lexical access during children's lexical decisions investigated neighbourhood effects from subword units. Luque, López-Zamora, Alvarez and Bordoy (2013) showed that for high frequency 4-6 letter words, higher frequency first syllables facilitated quicker decisions in 7 and 9 year old Spanish children. In contrast, for low frequency words, higher frequency first syllables inhibited reaction times. Again, these findings can be explained by a lexical process, but this time

in relation to inhibitory competition. In order to access the low frequency word, competing syllable neighbours must be inhibited. As activation for higher frequency words rises more quickly than lower frequency words, more inhibition is needed to deactivate higher frequency competitors, taking more time. This supports the idea that children engage in processing word units during lexical decisions, activating word units in the orthographic lexicon.

On the other hand, van den Boer, de Jong and Haentjens-van Meeteren (2012) explained how children could approach the lexical decision task as a naming task, relying on a larger phonological lexicon to a greater extent than their smaller orthographic lexicon. If this was the case, children would show a reduced sensitivity than adults to large neighbourhood effects of whole word units. In adult lexical decisions, larger neighbourhood sizes tend to facilitate decisions for words, but extend decisions for nonwords (Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004). Yet, van den Boer et al. found that 7 and 10 year old Dutch children were sensitive to neighbourhood sizes in a similar manner as adults. Children relied to a greater extent on lexical access rather than phonological recoding, even in nonwords. To strengthen this argument, van de Boer et al. went on to show that preventing the use of phonological recoding did not affect children's response times. Under conditions of articulatory suppression, children would not be able to sequentially decode nonwords through a nonlexical route, and if the nonlexical route was their primary means for performing lexical decisions, their performance should have suffered. This was not the case, as children who were prohibited from phonological recoding by repeating "dubba" every second were no slower than children who could have made decisions through phonological recoding, suggesting that children primarily engaged in lexical access.

Schmalz, Marinus and Castles (2013) explained preferential use of lexical and nonlexical routes by suggesting that children rely on both lexical and nonlexical routes for words, but which route is preferred depends on the orthographic regularity. They asked 8-9 year old Australian children to decide on pseudowords and high or low frequency words. Consistent with findings above, children spent more time deciding on pseudowords than words, and also more time deciding on lower frequency words than high frequency words. Importantly, high and low frequency words were either orthographically regular (*horse*; *spade*) or irregular (*book*; *calf*), and this regularity modulated effects of frequency on decision behaviour. Children were more likely to mis-categorise low frequency irregular (*calf*) compared to regular (*spade*) words, suggesting the use of phonological decoding strategies with unfamiliar orthography. In

contrast, children were just as accurate and fast in responding to both high frequency irregular (*book*) and regular (*horse*) words, suggesting that children relied on direct lexical access in familiar word decisions. This is in line with the idea that if a letter string does not pass a familiarity check, children continue with subword decoding before rejecting the string as a word. Then, irregular words that are likely to be decoded incorrectly are also consequently more likely to not match a lexical representation, and be rejected.

Looking at the studies described above that investigate how ease of access moderated response times in lexical decisions, children consistently demonstrated use of a lexical access process performed on whole word units.

4.2 The Current Study

To reiterate, Experiment 2 aimed to evaluate competitive explanations for the findings in Experiment 1, investigating whether children recognised the majority of words, in particular long words, and whether eye movement behaviour showed sensitivity to word frequency in long words. Critically, Experiment 2 was designed to investigate cognitive processing of the same stimuli as used in Experiment 1, with children of a similar age, but in a task that only included the first 2 constituent processes of a copying task: encoding and mental representation. If it was the case that children recognised and showed sensitivity to word frequency in long words, these findings would strengthen the argument outlined in Experiment 1 that children inconsistently engaged in encoding of whole word units during a copying task due to additional task demands of written production.

In a lexical decision task, there are typically two dependent measures. Response accuracy relates to whether words and pseudowords were categorised correctly. In turn, this can address the first point of whether children recognised the word items. Response time relates to the length of time between word presentation and a decision being made, which in turn has been suggested to reflect the time associated with cognitive processing occurring within that decision process. Measures of response time can be used to address the second point regarding the linguistic units children used when engaging in lexical decisions. The differences due to lexical status and item length, as well as the time-course of effects in relation to word frequency, might inform about whether children cognitively processed letter or word units. To that end, the literature outlined above about children's lexical decisions informed several initial predictions.

It was expected that response accuracy will demonstrate correct categorisation of words and pseudowords at above chance levels of accuracy. If children are capable of recognising the word stimuli, then they should be more likely to accept rather than reject the majority of word items. In turn, it would follow that response times will be sensitive to lexical status, with children needing more time to respond to pseudowords than words. If, as suggested by the studies described above, children engage in lexical access, there should be a time benefit for letter strings that can activate a corresponding entry in the mental lexicon (words), compared to letter strings that have no corresponding entry to activate (pseudowords).

In addition, response times will be sensitive to word length, but word length will affect pseudowords to a greater extent than words. If, as seen in Di Filippo et al. (2006), Martens and de Jong (2006) and Araújo et al. (2014), children persist in a nonlexical route in attempt to lexically access items, they will take more time to respond to longer items when each letter is decoded serially. Because words will be named through the nonlexical route less often, they will require less time-consuming serial phonological decoding, so there will be less opportunity for a word length effect. Critically, response times will be sensitive to word frequency, for both long and short words. If, as seen in Luque et al. (2013), Schmalz et al. (2013) Araújo et al. (2014), and de Zeeuw et al. (2014), children engage in a lexical access process that is modulated by ease of lexical access as determined by word frequency, children should be quicker to reach decisions on high frequent compared to low frequent words.

Yet, as stated at the beginning of Chapter 4, the method by which responses were given was designed to relate to eye movement behaviour rather than a button press. Recall that this enabled gaze duration on the word during a lexical decision task, potentially, to be a comparable measure to encoding time during a word copying task. Both measures indicate the length of time cognitively processing the text for the first time after stimuli presentation, before programming a saccade away from the word. In Experiment 2, this was achieved by asking children to give their response by looking in a specified area of the screen away from the target word, either a tick for word items or a cross for pseudoword items. This meant that rather than a single measure of response time, the eye movement measures provided a more detailed indication of the time-course of word processing while looking at the word.

In studies using sentence reading tasks, children have been shown to be sensitive to word frequency on the initial encounter of that word in a sentence, in measures of gaze duration (Huestegge et al., 2009; Joseph et al., 2013) and even earlier measures of

first fixation duration (Hyönä & Olson, 1995; Blythe et al., 2009). This literature guided a further specification of the effects of word frequency. The time-course of word frequency effects will be informative about whether word recognition has taken place by way of a lexical access process on the basis of whole words, or an assembled letter-by-letter process mediated by phonetic coding. If effects appear in early measures such as first fixation duration (time spent looking at the word on the first fixation) or gaze duration (time spent looking at the word over all fixations before leaving the word for the first time) this would indicate that word frequency influenced a fast acting process such as lexical access (Clifton et al., 2007). If frequency effects only appear in the later measure of total time (time spent looking at the word over all fixations on both initial and return visits to the word), this would indicate that word frequency influenced a more time-consuming process such as phonological coding. On the basis of the studies looking at the time-course of word frequency effects in sentence reading tasks, if children engage in lexical access in a similar manner during lexical decision, effects of word frequency should be seen in early measures such as gaze duration, and possibly also first fixation duration (Hyönä & Olson, 1995; Blythe et al., 2009; Huestegge et al., 2009; Joseph et al., 2013), not just total time. As high frequency words should be accessed faster than low frequency words due to rapidly rising levels of activation (as in the DRC model, Coltheart et al., 2001), children should spend less time looking at higher frequency words.

Apart from longer fixation durations, the number of fixations could also have contributed towards the extended response times seen in the lexical decision literature in relation to item length (Di Filippo et al., 2006; Martens & de Jong, 2006; Araújo et al., 2014) and word frequency (Luque et al., 2013; Schmalz et al., 2013; Araújo et al., 2014; de Zeeuw et al., 2014) could be. As stated by Rayner, Sereno, and Raney (1996), there are two likely reasons for refixating a word. One reason is an initial landing position towards the word beginning or end, at which not all the information about the word can be efficiently obtained. The other reason is a difficulty during the processes of lexical access. In a lexical decision paradigm in which all words are centrally presented, the most likely cause of refixations is the second reason of difficulty in lexical access. It could have been that in the lexical decision studies, children experienced difficulty in lexically accessing pseudowords that did not have a corresponding entry in the mental lexicon, and words that reached activation at a slower rate. If this resulted in more fixations, children may have spent more time deciding on pseudowords than words, and more time on low frequency than high frequency words.

So far, children's fixation counts during lexical decision tasks have not been reported. Still, when Hautala, Hyönä, Aro, and Lyytinen (2011) recorded eye movements as 10 year old children and adults read lists of pseudowords and words aloud, both children and adults needed more fixations on pseudowords than words. Also, in a sentence reading task, Hyönä and Olson (1995) noted that 10 year old children not only spent more time fixating low than high frequency words, children also made more fixations on low than high frequency words. This literature guided the predictions in relation to fixation counts. If children engage in lexical access, fixation counts will be sensitive to lexical status, such that children will make more fixations on pseudowords than words. Also, fixation counts will be sensitive to word frequency, such that children will make more fixations on low frequency than high frequency words.

Even in skilled adults, individuals who perform highly on tests of word knowledge also showed faster and more accurate lexical decisions compared to individuals with lower scores on word knowledge (Lewellen, Goldinger, Pisoni, & Greene, 1993). This is consistent with the idea that lexical decisions are made on the basis of a word recognition process that is sensitive to the ease of accessing lexical information. However, the developmental studies discussed earlier have so far not examined individual differences in lexical decisions of typically developing children. In addition to examining word length and frequency effects, examining the extent to which word reading abilities facilitate children's lexical decisions might provide another way of assessing the extent to which lexical decisions rely on whole word knowledge.

If the cognitive processing that children engage in draws on whole word knowledge, then children with a greater amount of whole word knowledge should perform more efficiently compared to children who are relying on a smaller amount of whole word knowledge. Word reading age should influence the time it takes for lexical access to complete, with higher reading ages predicting quicker lexical access. Compared to children with lower reading ages, children with higher reading ages should need less total time fixating on the word and make fewer fixations on word items due to more efficient lexical access processes. In turn, it may follow that as seen in Lewellen et al. (1993), efficient lexical processing results in accurate lexical decisions. Whilst children are expected to have acquired the majority of word items, there may have been individual differences in the children's mental lexicons. If children have a comparatively larger lexicon, they may be more accurate in categorising both words and pseudowords. Children with higher reading ages should have a higher accuracy rate

than children with lower reading ages in categorising items. Finally, if children rely on decoding letter-sound relationships, then children with more proficient letter-sound decoding abilities should decode items more accurately compared to children with less proficient decoding abilities. Pseudoword decoding age should influence response accuracy, with higher decoding ages predicting more accurate categorisation of items.

4.3 Methods

4.3.1 Participants.

All participants were native English speakers with normal or corrected-to-normal vision and no known reading difficulties. The 22 child participants (11 male) were aged between 7 and 10 years old ($M = 9$ years, 0 months, $SD = 11$ months), and were within typical norms of performance for both word reading age ($M = 10$ years, 4 months, $SD = 2$ years, 11 months) and IQ ($M = 105$, $SD = 12$) as measured respectively by the Wechsler Individual Achievement Test (Wechsler, 2005) and the Wechsler Abbreviated Scale of Intelligence (Wechsler, 2011). The children who participated in the current study using the ocular lexical decision paradigm had not previously participated in the experiment using the copying paradigm, reported as Experiment 1 in Chapter 3.

4.3.2 Materials and Design.

Experimental items. In total, there were 64 experimental items, 32 pronounceable pseudowords and 32 single-morpheme real words (see Appendix P). In addition to the experimental items, 4 practice items were included, 2 pseudowords and 2 real words. The real words were the same as sourced for the items in Experiment 1, sourced from the Children's Printed Word Database (Masterson, Stuart, Dixon, & Lovejoy, 2010), and orthogonally manipulated for word length and word frequency, as described in Experiment 1. The database also provided counts of phonological and orthographic neighbours for post-hoc statistical control.

Pseudowords were sourced from the MCWord orthographic database (Medler & Binder, 2005), and each pseudoword was selected on the basis of matching a real word in number of letters, and having a comparable bigram token frequency to that real word ($Mean\ difference = 3$, $SD = 4$); a paired t -test showed that bigram frequencies did not differ between words and pseudowords ($t(31) = -1.620$, $p = .115$).

Reading ability. Two tests from the reading subsection of the Wechsler Individual Achievement Test (Wechsler, 2005) were used in order to assess individual differences in children's ability to read words and decode pseudowords.

The word reading test required children to read aloud from a progressively challenging word list. This test was designed to assess letter knowledge and phonological awareness in a task where children can use sight-word knowledge, retrieving word-specific knowledge to facilitate reading of the word list. Performance resulted in a measure of reading age, the predicted chronological age at which a typically developing child would have performed to that standard of word reading.

The pseudoword decoding test required children to read aloud a list of orthographically legal, pronounceable nonwords. This test was designed to assess children's ability to apply phonetic decoding skills in a task where they cannot rely only on sight-word knowledge and must decode letter strings. In order to decode nonwords that shared rimes with real words (broan), children must use analogy decoding, applying rules from known words to a new letter string. In order to decode complex nonwords (retashment), children must decode using blending, decoding more than one unit and then blending each unit together to complete the whole pronunciation. This resulted in a measure of pseudoword decoding age, the predicted chronological age at which a typically developing child would have performed to that standard of pseudoword decoding.

4.3.3 Apparatus.

Viewing was binocular, but monocular eye movements were recorded using an EyeLink 1000 eye tracker, taking the right eye position every millisecond. A chin and forehead rest was used to stabilise the child's head in order to minimize head movements. Items were presented in black Courier New size 14 text against a white background, at viewing distance of 66cm. Each letter horizontally extended 0.35 degrees of visual angle.

4.3.4 Procedure.

The eyetracker was calibrated using a 3 point horizontal calibration to less than 0.35 degrees accuracy, and recalibrated as needed in between trials. To familiarise children with the experimental procedure, 4 practice trials were completed before the experimental trials. Participants were instructed to look at a central fixation cross to begin each trial. After stable fixation for 250ms, the experimental item was centrally

presented. Children were asked to decide if the word was real or made-up, then give their answer by looking at a green tick to the left of the word, or a red cross to the right of the word. After gaze continuously stayed on either the tick or cross for 1000ms, a blank screen was presented before the next trial. After practicing, children were encouraged to clarify understanding before experimental trials began. All participants saw all experimental items, presented in a random order.

4.4 Results

4.4.1 Response accuracy.

To examine response accuracy, generalised linear mixed models with a logistic link function were run using the lme4 package (Bates, Maechler, Bolker, & Walker, 2014) in R, version 3.2.0 (RCoreTeam, 2015). There were two models: one model was calculated with the whole dataset specifying lexical status and word length as fixed factors; the other model was calculated with a subset of word data, specifying word length and word frequency as fixed factors. For each dependent measure, the model began with the maximal random effects structure as suggested by (Barr, Levy, Scheepers, & Tily, 2013). If the model with the maximal random effects structure failed to converge, or there were too many parameters to fit the data, as indicated by correlations of 1 or -1 in the random structure, random slopes and correlations between random slopes were removed from the model. Model specifications for the final models resulting from this process can be found in Appendix Q.

For the first model, sum contrasts were used to assess whether the two levels of the lexical status and word length factors influenced dependent measures differently. For the second model, sum contrasts were used to assess whether the two levels of the word length and word frequency factors influenced dependent measures differently.

The percent of accurate responses for words and pseudowords is shown in Table 4.

Table 4. Children’s response accuracy in percent on words manipulated for length and frequency in Experiment 2.

		Short			Long		
		High frequency	Low frequency	Pseudo word	High frequency	Low frequency	Pseudo word
Correct	M	99	59	78	93	82	84
	SD	(3)	(18)	(19)	(14)	(20)	(16)

All children performed above chance levels ($M = 82\%$, $SD = 12\%$), so none were excluded for below chance decision accuracy. Importantly, response accuracy was above chance levels of 50% for all words, indicating children recognised the majority of words. The linear mixed models for response accuracy are summarised in Table 5, with reliable effects shown in bold³.

Table 5. Summary of LMMs for children’s response accuracy on words manipulated for length and frequency and pseudowords manipulated for length in Experiment 2.

		Word and pseudoword data			Word data only		
		<i>b</i>	SE	<i>z</i>	<i>b</i>	SE	<i>z</i>
Word characteristics	Lexicality	-0.27	0.18	-1.45			
	Length	0.27	0.18	1.50	-0.20	0.39	-0.51
	Frequency				-2.07	0.50	-4.13
	Lexicality length interaction	0.03	0.18	0.15			
	Length frequency interaction				1.13	0.37	3.02
Reading abilities	Reading age	0.25	0.08	3.18	0.32	0.09	3.36
	Pseudoword decoding age	0.03	0.06	0.52	0.01	0.07	0.16

³ This convention of denoting significant findings by emboldened text will be used in tables throughout the Thesis.

Looking at the first model calculated over all word and nonword data, lexical status and item length were not reliable predictors. Children were equally accurate at categorising words compared to pseudowords. Importantly, children's accuracy of categorising short words was similar to their accuracy of categorising long words.

Looking at the second model calculated over just the word items, there were differences in response accuracy within the words. The reliability of word length and frequency was qualified by an interaction, such that the difference due to word frequency was greater for the short words than the long words.

Reading ability accounted for variance in both models, such that children with higher reading ages categorised items more accurately than children with lower reading ages.

4.4.2 Response time.

Further analysis of eye movement behaviour was carried out for trials with accurate responses. Trials in which a real word was identified as a pseudoword or vice versa were excluded (18%). As is typical with reaction times, the data were skewed. The quantile quantile plots revealed strong deviations from normality, but applying log transformations reduced the deviation. The transformed models are reported below.

Table 6 summarises the mean for each dependent measure, reporting eye movement behaviour on the word or pseudoword. First pass and total measures are included. As children were instructed to keep their gaze on either the tick or the cross for 1 second to give a "yes" or "no" response, this gave opportunity for children to leave the word, make a fixation on the tick or cross, and return for another visual sample of the word before formalising their answer. This verification behaviour happened on approximately a third of all trials.

Table 6. Gaze times (ms) in relation to first fixation duration, gaze duration, total time, and fixation counts for children on words manipulated for length and frequency, and pseudowords manipulated for length in Experiment 2.

		Short items			Long items		
		High frequency	Low frequency	Pseudo-word	High frequency	Low frequency	Pseudo-word
First fixation duration	<i>M</i>	510	432	533	433	379	422
	<i>SD</i>	(216)	(216)	(168)	(132)	(137)	(118)
Gaze duration	<i>M</i>	1569	1950	2105	1835	1966	2576
	<i>SD</i>	(399)	(652)	(617)	(576)	(475)	(940)
Total time	<i>M</i>	2164	2547	2622	2523	3086	3554
	<i>SD</i>	(1030)	(997)	(955)	(1278)	(2774)	(1742)
First run fixation count	<i>M</i>	2.78	3.47	3.71	4.44	4.97	5.94
	<i>SD</i>	(0.80)	(1.20)	(1.12)	(1.06)	(1.54)	(1.85)
Fixation count	<i>M</i>	4.27	4.94	4.87	6.10	7.90	8.37
	<i>SD</i>	(2.12)	(2.13)	(1.74)	(2.79)	(7.62)	(3.64)

First fixation duration.

The summary of the two linear mixed models for how long children spent first fixating items are shown in Table 7.

Table 7. Summary of LMMs for first fixation duration for children on words manipulated for length and frequency, and pseudowords manipulated for length in Experiment 2.

		Word and pseudoword data			Word data only		
		<i>b</i>	SE	<i>t</i>	<i>b</i>	SE	<i>t</i>
Word characteristics	Lexicality	0.02	0.03	0.64			
	Length	-0.04	0.03	-1.09	-0.02	0.03	-0.65
	Frequency				-0.08	0.03	-2.35
	Lexicality length interaction	-0.01	0.03	-0.26			
	Length frequency interaction				0.02	0.03	0.47
Reading abilities	Reading age	-0.01	0.02	-0.37	0.01	0.02	0.53
	Pseudoword decoding age	-0.01	0.02	-0.44	-0.02	0.02	-1.21

Across the dataset as a whole, there were no reliable predictors of the earliest measure of first fixation duration in relation to lexical status or item length. Children spent a similar amount of time on words compared to pseudowords, and took the same amount of time on short compared to long letter strings.

In the model specifying the subset of word data, only word frequency was a reliable predictor. On the initial fixation, children spent more time on high frequency words compared to low frequency words, irrespective of word length.

Gaze duration.

Two linear mixed models were also calculated in relation to children’s gaze durations, how long children spent on the word over all fixations, before leaving the word for the first time. These models are reported in Table 8.

Table 8. Summary of LMMs for gaze duration on words manipulated for length and frequency, and pseudowords manipulated for length in Experiment 2.

		Word and pseudoword data			Word data only		
		<i>b</i>	SE	<i>t</i>	<i>b</i>	SE	<i>t</i>
Word characteristics	Lexicality	0.11	0.02	4.67			
	Length	0.08	0.02	3.11	0.05	0.03	1.78
	Frequency				0.06	0.03	2.13
	Lexicality length interaction	0.01	0.02	0.70			
	Length frequency interaction				-0.01	0.03	-0.53
Reading abilities	Reading age	-0.04	0.02	-1.70	-0.04	0.02	-1.71
	Pseudoword decoding age	0.00	0.02	0.25	0.00	0.02	0.22

When modelling the dataset as a whole, both lexical status and item length emerged as reliable predictors of gaze duration. Children demonstrated a benefit for words, such that less time was needed for words compared to pseudowords. For item length, less time was taken on short items than long items.

Yet, the reliability of item length as a predictor was marginal in the model of the subset of word data. Children’s gaze durations on short words may have taken marginally less time than on long words. Importantly, word frequency predicted gaze duration, with the pattern of effect in the reverse direction as seen in first fixation duration. Children needed shorter gaze durations on high frequency compared to low frequency words, irrespective of word length.

Total time.

The latest measure of response time of total time reflected the summed duration of all fixations durations on a word throughout the trial. The two models calculated for total time are shown in Table 9.

Table 9. Summary of LMMs for total time on words manipulated for length and frequency, and pseudowords manipulated for length in Experiment 2.

		Word and pseudoword data			Word data only		
		<i>b</i>	SE	<i>t</i>	<i>b</i>	SE	<i>t</i>
Word characteristics	Lexicality	0.11	0.03	3.93			
	Length	0.10	0.03	3.51	0.07	0.03	2.00
	Frequency				0.07	0.03	2.33
	Lexicality length interaction	0.03	0.02	1.38			
	Length frequency interaction				-0.01	0.03	-0.18
Reading abilities	Reading age	-0.05	0.03	-1.91	-0.07	0.03	-2.24
	Pseudoword decoding age	0.00	0.02	0.19	0.01	0.03	0.39

The model calculated over the whole dataset showed identical patterns in measures of total time as for gaze duration. In total time, lexical status was a reliable predictor, such that less time was needed for words than pseudowords. Item length also reliably predicted total time, such that less time was needed for short than long items.

In model of the word data subset, both word length and word frequency reliably predicted total time, and these effects were independent. Children spent less total time on short compared to long words, and also less total time on high frequency compared to low frequency words.

Reading ability also accounted for variance, with trends in the dataset as a whole, and reliable effects in the word data. Children with higher reading ages needed less total time than children with lower reading ages.

First pass fixation count.

Again, two models were calculated for the number of fixations made before the eyes left the word for the first time. These models are shown in Table 10.

Table 10. Summary of LMMs for first pass fixation count on words manipulated for length and frequency, and pseudowords manipulated for length in Experiment 2.

		Word and pseudoword data			Word data only		
		<i>b</i>	SE	<i>t</i>	<i>b</i>	SE	<i>t</i>
Word characteristics	Lexicality	0.10	0.02	4.30			
	Length	0.24	0.03	7.74	0.23	0.03	6.67
	Frequency				0.08	0.03	2.66
	Lexicality length interaction	0.01	0.02	0.32			
	Length frequency interaction				-0.02	0.02	-0.64
Reading abilities	Reading age	-0.03	0.02	-1.55	-0.04	0.02	-1.87
	Pseudoword decoding age	0.00	0.02	0.27	0.01	0.02	0.34

Across the dataset as a whole, both lexical status and item length reliably predicted how many fixations children made on their first visit to the word. More fixations were needed for pseudowords than words, and more fixations were also made on long items than on short items.

In the subset of data of words alone, both word length and word frequency were reliable predictors of the number of fixations. Irrespective of word frequency, children needed more fixations on long words than short words. Children also needed more fixations on low frequency words than high frequency words regardless of word length.

Reading ability was a marginal predictor in the word data, with trends cautiously suggesting that children with lower reading ages may have made more fixations than children with higher reading ages.

Total fixation count.

The final measure is total fixation count, summing the number of fixations children made on an item throughout an entire trial, including any return visits. The two models for total fixation count are shown in Table 11.

Table 11. Summary of LMMs for total fixation count on words manipulated for length and frequency, and pseudowords manipulated for length in Experiment 2.

		Word and pseudoword data			Word data only		
		<i>b</i>	SE	<i>t</i>	<i>b</i>	SE	<i>t</i>
Word characteristics	Lexicality	0.10	0.02	4.04			
	Length	0.25	0.03	7.32	0.22	0.03	6.60
	Frequency				0.09	0.03	2.66
	Lexicality length interaction	0.03	0.02	1.31			
	Length frequency interaction				-0.01	0.03	-0.23
Reading abilities	Reading age	-0.06	0.03	-2.12	-0.08	0.03	-2.68
	Pseudoword decoding age	0.01	0.02	0.41	0.02	0.02	0.75

Near identical patterns were found in total fixation counts as for first pass fixation counts. In the model of the whole dataset, children showed an influence of lexicality, needing more fixations for pseudowords than words. There was also an influence of item length, as long items required more fixations than short items.

In the model using only word data, length was a reliable predictor such that children made more fixations on long words than short words. Frequency was also a reliable predictor such that children also needed more fixations on low frequency than high frequency words, and these influences of length and frequency were independent.

In both models, reading age reliably predicted total number of fixations, such that children with higher reading ages made fewer fixations than children with lower reading ages.

4.5 Discussion

The current study aimed to test whether children could accurately categorise the word stimuli used in Experiment 1, and whether their eye movement patterns were sensitive to whole word properties of length and frequency in a lexical decision task. Findings suggested that children were capable of correctly categorising the majority of real words. Importantly, this was true for both long high frequency and long low frequency words, suggesting that children within the age range of 7-10 had acquired the word items.

Children needed between 1 to 3.5 seconds to categorise words and pseudowords, but the time taken was modulated by the lexical status of the letter string and the characteristics of the word. Eye movements were sensitive to lexical status, as demonstrated by response times and fixation counts. Children needed shorter, and fewer fixations on words than pseudowords, indicating a benefit for words that can be accessed through a lexical route, rather than pseudowords that required phonological coding. Eye movements were also sensitive to item length, with longer items requiring more time and more fixations than shorter items. This effect of length was consistent over a greater number of response time measures for pseudowords than for words.

Response times were also sensitive to word frequency, but the effect of word frequency on response time differed throughout the time-course of the lexical decision. Initially, children needed longer first fixations on higher frequency words compared to low frequency words. Later in the time-course of lexical decision there was facilitation in relation to word frequency, with children needing fewer and shorter fixations for the higher frequency words overall.

Findings largely indicated that children primarily engaged in a whole word lexical access process when categorising real words. Specific findings with regard to response accuracy and response time will now be addressed in turn, in relation to lexical status, item length, and word frequency. Next, individual differences in children's lexical decisions will be discussed. Then, there will be a brief comparison of gaze durations during reading, lexical decision and copying, considering relative task demands. Finally, Chapter 4 will end with a summary detailing how findings related to the specific questions outlined in the introduction.

4.5.1 Response accuracy.

One aim of Experiment 2 was to assess the explanation that inconsistent frequency effects observed in encoding times in Experiment 1 were due to children not

knowing the long words chosen for the stimuli. This was tested in Experiment 2 by investigating whether children could correctly categorise these words and length-matched pseudowords at above chance levels. As predicted, response accuracies indicated that children performed at above chance levels for both words and pseudowords, suggesting that children had acquired the majority of words. There was a surprising interaction between word length and frequency such that the difference in accuracy between high and low frequency words was greater for short than long words. This finding is in contrast to other research that reports an influence of word frequency on children's lexical decision accuracy such that decisions on high frequency words were more accurate than low frequency words (de Zeeuw et al., 2014; Luque et al., 2013; Schmalz et al., 2013). On the other hand, in their study that included manipulations of both word length and frequency, Araújo et al., (2014) found a similar interaction of length and frequency on decision accuracy. As in Experiment 2, children were the least accurate in categorising short, low frequency words, and the difference in accuracy between high and low frequency words was greater in short words than in long words. One explanation for this might be the extent of orthographic regularity, in particular in the low frequency words. Low frequency words may have been less likely to pass a familiarity check compared to high frequency words, and then be accessed through phonological decoding rather than whole word access. As shown in Schmalz et al. (2013), when making lexical decisions, children were more likely to miscategorise low frequency words if they were orthographically irregular than regular. They explained this due to irregular words being decoded phonologically according to dominant letter-sound associations in a way that when the item is named, did not match the irregular pronunciation, so was rejected as a word item. While Schmalz et al., controlled word length in order to manipulate orthographic regularity and word frequency, the current study included a manipulation of both word length and word frequency, and in order to source these appropriate stimuli, orthographic regularity was not controlled. It could have been that a minority of irregular items contributed towards mis-categorisations of low frequent, short word items.

Overall, the response accuracies in Experiment 2 contrasted with the idea that 7-10 year old children had not acquired the majority of word items, in particular the long words.

4.5.2 Response time.

Another aim of Experiment 2 was to assess the explanation that Experiment 1 found inconsistent frequency effects during encoding because children's eye movements may not be sufficiently sensitive to differences due to word frequency in long, 8 letter words rather than children inconsistently engaging in lexical access. This was primarily tested in Experiment 2 by investigating whether children's eye movements demonstrated sensitivity to manipulations of word frequency in a lexical decision task. In addition, the lexical decision task presented extra opportunities to investigate the extent to which children consistently engaged in lexical access, by looking at children's sensitivity to lexical status and item length. In this way, it would be possible to distinguish the possibility of children not engaging in lexical access from the possibility that lexical access in children was not yet sensitive to a word frequency manipulation of the magnitude used in Experiment. Effects in relation to lexical status, word length and word frequency will now be considered.

Lexical status. Consistent with measures of reaction time in lexical decision tasks (Araújo et al., 2014; Di Filippo et al., 2006; Martens & de Jong, 2006), in the current study, lexical status predicted response time. This indicated that categorisation of pseudowords involved a relatively more time-consuming cognitive process than words. In measures of gaze duration and total time, children spent longer looking at pseudowords compared to words, demonstrating a time benefit for items that could be recognised by a lexical access process in comparison to items that could not.

As well as longer fixations, children also needed more fixations on pseudowords than words during lexical decisions in a similar manner as Hautala et al. (2011) found in reading aloud. As suggested by Rayner et al., (1996), one explanation for an increased fixation count may be due to difficulty in lexical processing. As pseudowords would not have been in children's mental lexicons, children would not have been able to successfully access a pseudoword even after an exhaustive search. The increased fixation count for pseudowords over words supports the idea that children engaged in lexical access which was successful for word items, but children encountered difficulty when attempting to access pseudoword items.

In line with previous research (Araújo et al., 2014; Di Filippo et al., 2006; Martens & de Jong, 2006), when categorising words and pseudowords, it could be that children successfully engaged in accessing word units through a lexical route, but continued with relatively more time-consuming phonological coding through a nonlexical route before rejecting a pseudoword as a word.

Item length. Effects of item length were not always consistent across the model calculated on the whole dataset and the model calculated on the word subset, and effects of item length were also not present in the earliest measure of first fixation duration. However, in measures of gaze duration, children tended to spend more time looking at long than short items; this effect was reliable on the model calculated across the whole data, but marginal in the subset of word items. In the most global measure of total time, children consistently took more time fixating long compared to short times, irrespective of whether items were words or pseudowords.

This would suggest that irrespective of whether or not the item was a word or a pseudoword, children needed more time to decide on long compared to short items. These findings did not match Araújo et al. (2014), Di Filippo et al. (2006), or Martens and de Jong (2006), who all found trends of length effects in words that were qualified by an interaction with lexicality. This previous research collectively showed that word length effects were weaker in words than pseudowords, and attributed this to children engaging on phonological decoding on a letter-by-letter basis only in pseudowords. As discussed in the introduction to Experiment 2, the weakness of word length effects could be explained by a Dual Route Cascade model (Coltheart et al., 2001). If parallel letter decoding occurred during lexical processing and serial letter decoding occurred during nonlexical processing, gaze durations should only be extended for longer words if the letters were decoded one-by-one. As item length predicted gaze durations on words and pseudowords, this might suggest that children used a nonlexical route to process all items.

Nevertheless, word length effects were less consistently reliable over word items than over word and pseudoword items in gaze duration, and not evident in the earliest measure of first fixation duration. These findings are more in line with the previous studies (Araújo et al., 2014; Di Filippo et al., 2006; Martens & de Jong, 2006). It might have been that when the analysis was collapsed across word frequency, trends in words were evident enough to support a word length effect that was mainly driven by the pseudowords. If this was the case, this might suggest that children used a lexical route to process words more often than a nonlexical route.

However, the studies by Araújo et al. (2014), Di Filippo et al. (2006) and Martens and de Jong (2006) all used words of less than 8 letters, and some words were less than 4 letters, so shorter words than used in the current study. In a different study that looked at children's lexical decisions, de Zeeuw et al. (2014) used words of up to 13 letters, and they found that word length did modulate response times for words in a

similar way as found in the current study. One reason to explain why stronger word length effects were found in research that investigates comparatively longer words might be that children did not have enough processing resources to distribute over all the letters of long words in parallel. If this was the case, children may still have decoded some letters in parallel in line with a lexical route of processing, but decoded less than all the letters in the word within a single fixation. If this was the case, children might need more fixations to decode all the letters as word length increased. This is exactly what was found, as children needed more fixations on long words than short words.

Taking together the findings about item length in words and pseudowords, children may rely on a lexical access process when deciding on word items, though some word items may have been categorised by way of a nonlexical route.

Word frequency. Perhaps the most important results in the current study involve the comparisons of time spent looking at high and low frequency words, which provided a firm indication of lexical processing. Similarly to the previous studies that investigated the impact of word frequency on children's lexical decisions (Araújo et al., 2014; de Zeeuw et al., 2014; Luque et al., 2013; Schmalz et al., 2013), word frequency modulated response times. If children were relying on lexical routes of processing, higher frequency words would be more accessible, contributing towards quicker lexical decisions. Furthermore, word frequency effects were found for both short and long words; irrespective of a word's length, children needed shorter gaze durations and shorter total times for high compared to low frequency words. This suggested that children did not engage in functionally different processing for short and long words. Unlike in the copying task in Experiment 1, children relied on lexical routes of processing based on whole word units (as described in the Dual Route Cascaded model, Coltheart et al., 2001) for both short and long words in this lexical decision task in Experiment 2.

Interestingly, effects of word frequency were evident in the earliest measure of the time-course of lexical decision. Word frequency predicted first fixation durations such that children spent more time on high than low frequency words, and this direction of the effect was in the opposite direction expected. While word frequency effects have been shown to be unreliable in children (Blythe et al., 2006), Joseph et al. (2009), did show a similar counterintuitive findings in first fixation in relation to a word length manipulation. That is, Joseph et al. found that children spent more time fixating short words than long words on the first fixation duration. Then in gaze duration, the direction of the effect reversed so that as expected, children spent less time fixating

short words than long words. Joseph et al. also reported a higher probability of refixating longer words. In the current study, in a similar manner to that found in Joseph et al., after spending less time on low frequency than high frequency words in first fixation duration, effects in gaze duration are in the expected direction in that more time was needed for lower frequency words. In addition, children also needed more fixations on lower frequency words. It might have been the case that children spent more time on the initial fixation of a higher frequency word if refixations were less likely in order to achieve successful lexical access.

Critically, word frequency facilitated gaze durations and total times, with children taking less time for high than low frequency words. This is perhaps the most important finding of Experiment 2, as it indicated that ease of access, as determined by word frequency based on whole word units, contributed towards quicker lexical decisions. This effect was seen irrespective of word length, so indicated that children engaged in a lexical access process when fixating both short and long words.

4.5.3 Individual differences.

In addition to examining how characteristics of the word modulated children's lexical decisions, the current study also looked at how characteristics of the individual modulated decision behaviour, namely word reading and pseudoword decoding ability. In skilled adults that have been shown to engage in consistent lexical processing during decisions, word knowledge was related to both response time and accuracy (Lewellen et al., 1993). This was thought to be due to efficient lexical access operating more rapidly and successfully in adults with more word knowledge. In the current study, similar effects were found in children's lexical decisions, such that children with higher reading ages needed less total time looking at word items compared to children with lower reading ages. In terms of a lexical access operation such as described in the DRC model (Coltheart et al., 2001), it may have been that lexical activation happened more rapidly in children with a greater amount of word knowledge. That children's lexical decisions are facilitated by efficient word reading skills is an indicator that the cognitive processing occurring during those decisions on word items relied on whole word knowledge. These individual differences supported the idea that children engaged in lexical processing based on word units.

In terms of accuracy of categorising word and nonwords items, word reading age predicted accuracy rate such that compared to children with lower word reading ages, children with higher word reading ages were more accurate at categorising both

words and pseudowords. Again, this is in line with the findings for adults in Lewellen et al., as children with a comparatively larger mental lexicon were better at both accepting word items and rejecting pseudoword items. In relation to the point about whether or not children had acquired the word items, while all children could accurately categorise the majority of word items (and so had acquired the majority of the word stimuli), it may have been that reading age determined the extent of the minority of items that were not recognised.

Against predictions, pseudoword decoding ability did not reliably account for variance in response accuracy. This was surprising, as the findings in relation to lexical status and word length discussed earlier suggested that children were engaging in a phonological decoding operation, processing items, especially nonwords items, through a nonlexical route of processing. If children identified letters and then decoded their corresponding sounds in order to name the word in a nonlexical processing route (Coltheart et al., 2001), then the children with better letter-sound decoding abilities should have decoded items more accurately. However, when theorising how individuals develop proficiency in decoding, (Perfetti & Hart, 2002) suggest that connections between orthography and phonology are established early on in the time-course of reading development. In the current study, it may have been that by the age of 7, children had already established all the necessary connections between letters and sound in order to decode the pseudowords. If this was the case, having a lower pseudoword decoding ability would not result in being unable to decode items, as was found in the current study.

4.5.4 Task comparison.

This final section of the discussion considers the gaze duration findings in the current study to that of similar measures in copying and reading tasks, in order to reflect on relative task demands. Recall that initial encoding time in Experiment 1, gaze duration in Experiment 2, and gaze duration in published sentence reading studies all measured how long children spent looking at a word before leaving the word for the first time in that trial. If longer times reflected higher task demands, comparing these measures might be informative about the relative difficulty of task demands.

Surprisingly, children did not need longer gaze durations during lexical decisions (in a task that only required encoding and mental representation) compared to copying (in a task that required encoding and mental representation in readiness for a third sub-process of written production). In sentence reading, children needed about

400ms overall, with word length effects of about 90ms (Joseph et al., 2009), and word frequency effects of about 60ms (Blythe et al., 2009). In comparison, children took much more initial encoding time during copying, about 800ms overall, with word length effects of about 400ms, and low frequency adding 100ms for short words (as reported in Experiment 1). Yet, even for short words, children needed about twice as much time to process words during lexical decision than during copying. For long words, gaze durations during lexical decision were a third longer than during encoding for copying, though the nature of long word processing may have been different between the two tasks, with lexical decision relying to a greater extent on whole word units than copying.

If children were capable of processing words very quickly in a reading task, why did they take 2-3 times longer during copying, and 4-5 times longer during lexical decisions? One reason might be that children engaged in a more exhaustive familiarity check during lexical decisions in order to avoid rejecting real words. In reading, readers expect to encounter a series of legal words, and eye movements are programmed to move to the next word often before the current word is fully identified (Reichle et al., 1998). Similarly in lexical decisions, Reichle, Tokowicz, Liu and Perfetti (2011) also showed that adults still begin to programme saccades on the basis of a familiarity check rather than full lexical identification. In a novel paradigm, Reichle et al. presented participants with two letter strings, one centrally and one to the right, while using event-related potentials to record electrical activity associated with both language processing and eye movement programming. This allowed measurement of event-related potential waveforms, indicating the time-course of word frequency effects in specific relation to saccade onsets. Word frequency modulated waveforms well before saccade onsets, and accounting for saccade programming time, word frequency effects were present before the start of saccadic programming. This means that adult readers moved their eyes on an early basis of a quick familiarity check in a lexical decision task, not completing word identification before programming a movement away from the word.

So far, it is not clear whether children also make lexical decisions on the basis of a quick familiarity check. Because children's vocabularies are still regularly expanding, they may be more cautious than adults before rejecting a word. This is supported by the idea that children's lexical decisions are conservative in that they laboriously decoded pseudowords letter-by-letter before rejecting them. Also recall that children engaged in verification behaviour about a third of the time, leaving the word to briefly fixate an answer, then returning for another visual sample of the word before confirming their

decision. It might be that children are more thorough than adults when making a lexical decision, basing their lexical decisions on complete identification rather than a familiarity check alone.

4.6 Overview

In summary, the current study demonstrated that eye movements during a single word lexical decision task could be a potential tool for investigating the nature of children's language processing. Eye movements highlighted a lexical status effect in that pseudowords required more time and fixations than words. Word length effects showed that pseudowords were consistently processed using a nonlexical decoding route, but word length effects in the word data were inconsistent, perhaps suggesting flexible reliance on both lexical and nonlexical routes for words, or that children cannot process up to 8 letters at the same time. Importantly, word frequency predicted response times and fixation counts, suggesting that ease of word access as determined by word frequency facilitated quicker decisions. This facilitation would have only been evident if children consistently relied on lexical route to access word units. Both word frequency effects and accuracy performance in long words supported the idea that children processed long words as whole units, and were capable of correctly categorising the words. In addition, individual differences in reading ability also modulated the total time children needed to categorise items, supporting the idea that cognitive processing in lexical decisions relied on word knowledge.

In relation to Experiment 1, findings in Experiment 2 strengthened the argument that the inconsistent frequency effects observed in encoding times in Experiment 1 may have been due to the upcoming task demands of written production. Experiment 2 set out to address 3 key questions that were outlined in the introduction. In answer to these questions, 1) Children accurately recognised the word after encoding. Therefore, findings in Experiment 1 were unlikely to be due to children not knowing the stimuli. 2) Irrespective of whether children activated whole word or subword units during encoding, the same units were activated for both short and long words. As evidenced by findings in relation to lexical status and word frequency that occurred independent of word length, children's processing of both short and long words was based on the same linguistic units. 3) Children activated whole word units during encoding, as evidenced by word frequency effects on measures of fixation time that suggested children engaged in a whole word process of lexical access. Therefore, findings in Experiment 1 were

unlikely to be due to children's eye movements being insensitive to effects of word frequency in long words.

Overall, children's lexical decision behaviour indicated consistent lexical processing based on whole word units for word items in a task that involved encoding and mental representation, but not written production. This allowed a ruling out of a major issue with the stimuli selected for Experiment 1, and showed children's sensitivity to characteristics of the word that modulate ease of lexical access in long words such as word frequency in an eye movement paradigm. It may have been that in Experiment 1, the additional task demands of written production resulted in children inconsistently engaging in lexical processing of word units, and instead relied on subword units, particularly when copying long words.

In addition, in Experiment 2, not only did the characteristics of the word modulate children's behaviour, but characteristics of the individual also impacted on the efficiency of the lexical processes occurring in the task. Although children seemed to consistently engage in the same lexical processes, some children were more efficient than others. The next chapter will reconsider the findings in relation to children's copying behaviour in terms of how the characteristics of the individual may have influenced copying performance.

CHAPTER 5

CHILDREN'S COPYING BEHAVIOUR IN RELATION TO READING ABILITY AND WORKING MEMORY CAPACITY

5.1 Introduction

5.1.1 What motivated the adoption of an individual differences approach?

In the opening research enquiry that investigated how characteristics of the stimuli impacted on copying performance in skilled and beginning readers, Experiment 1 investigated group differences. Recall that participants were asked to make a handwritten copy of a single word in each trial, and words were orthogonally manipulated for word length and word frequency. This manipulation was performed in order to examine the extent to which copiers cognitively processed whole word units during a copying task. Average differences were analysed between two groups of individuals, adults and children, which represented distinct populations, skilled or developing readers. As described by Cronbach (1957) when discussing his disciples of scientific psychology, within experiments examining group differences, an important contributor towards experimental success is control in relation to participants. Any individual variation between participants within each comparison group would contribute towards error variance, and in turn noise in the experimental control. In accordance, participants in each group of adults and children were selected, based on participant age as an indicator of reading ability (as discussed in Blythe & Joseph, 2011), in such a way that variance between participants within a comparison group was likely to be less than variance across participants between comparison groups.

An alternative research perspective is that of individual differences approach, looking at how continuous variation among individuals within a population impacts on behaviour. Rather than attempting to minimise individual differences within comparison groups, Underwood described the individual differences approach to be so important in theory construction as to provide “a critical test of theories as they are being born” (p.130, Underwood, 1975). His argument was that when thinking (theoretically) about a cognitive process, individual differences (within a participant group) in a variable hypothesised to be important for task performance should predict individual differences in the measure of performance. In relation to word copying, when examining a theoretical framework of the sub-process of encoding, individual differences in variables such as reading ability that were hypothesised to be important for encoding should predict encoding efficiency. If not, then the theoretical relationship between the

variable and the task (that the encoding involves cognitive processes that rely on reading ability) would need to be redefined.

Some of the findings in Experiment 1 called into question the idea that children were engaging in word reading during the encoding sub-process of a copying task. Specifically, hallmarks of whole word processing, such as a benefit for higher frequency words, were not consistent in Experiment 1 that involved a word copying task, despite these effects being present in Experiment 2 that involved a lexical decision task. Looking at individual differences of reading ability in relation to copying behaviour might provide an avenue of examining whether children draw on linguistic information used in reading processes, particularly during encoding. Do children engage in cognitive processes that rely on reading ability throughout different sub-process of a copying task?

Another concept outlined in Experiment 1 was that copiers might maintain a mental representation of the encoded information in readiness for written production. One way of measuring forgetting of this mental representation might be quantifying the amount of information lost between encoding and production. However, in Experiment 1, children may not have consistently encoded the entire word unit. Hence, when children did not produce the entire linguistic unit in one episode of production, it was difficult to distinguish whether children had not initially encoded the complete stimulus, or whether children had forgotten all or part of a mental representation of the completely encoded stimulus. The nature of the mental representation that children form after encoding is not well understood, and the nature of that representation may fundamentally influence the nature of the children's production. Looking at individual differences of working memory capacity in relation to copying behaviour might provide an avenue of examining the nature of the mental representation that children form during copying. Do children engage in cognitive processes of mental representation that rely on working memory capacity throughout different sub-process of a copying task?

The following sections will outline how individual differences in reading ability and working memory capacity might functionally constrain a specific sub-process of the copying task (encoding, mental representation or written production), in relation to a relevant theoretical concept. This understanding will be used to inform predictions on how such constraints might impact on children's copying behaviour.

5.2 Individual Differences in Relation to Sub-Processes during a Copying Task

5.2.1 Reading ability in relation to encoding.

Reading ability is a multifaceted concept, but two composite reading abilities that have been suggested to facilitate word encoding are that of word knowledge and decoding skills (Nation & Snowling, 2004). Findings from Experiment 1 indicated that children used a range of linguistic units during encoding, and it might be that children rely on word knowledge and decoding skills during encoding of word and subword units.

One way to explain why individual differences in reading ability should result in differences in word encoding efficiency might be in terms of a connectionist model of word recognition (Plaut, McClelland, & Seidenberg, 1996). The model put forward by Plaut et al. has an integrated learning-mechanism in the way that orthographic, phonetic and semantic units are connected, and reading ability is said to develop through establishing substantial connections between units. Early in the development of reading ability, readers are suggested to be developing connections between orthography and phonology. In comparatively more developed reading, connections between orthography and semantics become stronger, so readers become less reliant on orthographic-phonetic mappings. The more established the connections within the semantic pathway, the faster the processing of word units. The more established the connections within the orthographic-phonetic pathway, the faster the processing of subword units. In relation to word copying, establishing semantic and orthographic-phonetic connections might facilitate the efficiency of encoding word and subword units.

Copying research has so far not examined the extent to which reading ability constrains the efficiency of just the encoding sub-process during copying. However, McBride-Chang, Chung, and Tong (2011) showed that copying skill, as measured by how accurately 7-9 year old children copied unfamiliar print written in Vietnamese, explained variance in children's Chinese reading ability. One of their suggestions was that copying and reading both drew on the ability to identify details about the characters, as the Vietnamese contained diacritical markers, small symbol-like markings that disambiguated letters, and Chinese contained detailed letter strokes in a precise space and relative orientation. In relation to English copying, it might be that word reading ability determines the efficiency with which orthographic letter forms can be identified, which in turn might constrain the accuracy with which orthographic forms can be mapped onto both phonetic and semantic units.

In relation to encoding, reading ability might constrain the efficiency with which letter forms can be visually encoded, and then cognitively mapped onto corresponding sound and word units. This might be expected to impact on the time efficiency of the encoding sub-process.

5.2.2 Reading ability in relation to mental representation.

Reading ability has also been suggested to constrain sub-processes after information encoding, of mental representation. In discussing how individuals mentally represent sound-based information such as words, Kail developed an argument that reading abilities constrain the speed of subvocal articulation during rehearsal in memory (Kail, 1997; Kail & Park, 1994). To break this argument down with relevance to children's copying behaviour, between encoding and completing their written production, children might need to maintain a mental representation of the encoded information, storing the representation at the same time as programming writing events for the stored letters. One mechanism through which this might be achieved is their working memory system.

Baddeley modelled a working memory system that explained how specific types of information could be stored and concurrently processed for a limited period of time (Baddeley & Hitch, 1974; Baddeley, 2003). In relation to verbal information such as letters, a limited amount of information could be stored in the phonological loop by a process of phonological recoding in which visual letter forms were mentally recoded and represented as their corresponding letter sounds. Baddeley explained that there were two subcomponents within the phonological loop, one storage component which holds these memory traces, and another maintenance component that sustains activation of the memory traces. In order to keep the stored representation intact, individuals would periodically rehearse the representation in a similar mental manner as subvocally repeating the letter sounds. Without this rehearsal, the temporary stored memory trace would decay and be forgotten, even within about 1-2 seconds in the case of children (Cowan & Alloway, 2009).

A key concept in relation to Kail's argument is that rehearsal takes time, which is determined in part by the fluency with which verbal representations can be subvocally articulated. This idea is that quicker articulation rates allow for faster rehearsal, which in turn enables a larger amount of information to be rehearsed within the same time frame in comparison to a rehearsal process operating with slower articulation rates. Support for this idea can be drawn from tasks involving oral recall, as even in 5 year old

children, articulation rates have been correlated with verbal memory span (Gathercole & Adams, 1994).

In a copying task, children might rely on their working memory system after encoding the letter information, recoding this orthographic information phonetically in order to construct a mental representation in readiness for written production. In order to efficiently maintain this representation throughout production, children might rehearse the stored letters until they can be programmed in writing events. If the stored letter representation begins to decay between rehearsal and written production programming, children might attempt to reconstruct the decaying memory trace. Applying Kail's argument, faster rehearsal might result in less decay, so less forgetting. As suggested in Experiment 1, one outcome of forgetting information might have been that children paused written production to make a gaze lift back to the board for another encoding episode. If reading ability constrained the efficiency of maintaining a mental representation, it might be the case that fewer gaze lifts arise from forgetting in children that can rely on a higher level of reading ability.

In their study of French children's word copying, Rieben and Saada-Robert (1997) looked at how many letters could be "transported" between episodes of encoding and production. Children encoded information from reference text of a short story written on a classroom board, and wrote their comments about the story in their notebooks. In order to encode words in the story, children were allowed to walk up to the board for an encoding episode, then return to their seat to programme and execute writing events. The researchers recorded how many letters were written between each visit to the board, and inferred the amount of letters that could be mentally retained from each word. Critically, this was a longitudinal study repeated 4 times throughout the school year, and measures of children's reading ability (in relation to their letter and word knowledge) showed an increase over each testing session. Rieben and Saada-Robert showed that children systematically transported larger units of information as the study progressed. Letter-by-letter units were used most often in the first testing session, production of larger units of two or three letters increased over the second and third testing sessions, and children were remembering a higher amount of morpheme and word units by the final testing session. While reading ability may not have been the only ability to develop progressively over the school year, increased letter and word knowledge may have contributed towards children being able to mentally represent a larger amount of information between encoding and production.

In relation to mental representation, reading ability might constrain the efficiency with which the mental representation can be rehearsed, and the accuracy with which decaying mental representations can be reconstructed. This might be expected to impact on the number of gaze lifts that arise from forgetting.

5.2.3 Reading ability in relation to written production.

Reading ability has also been suggested to contribute towards efficient performance in written production by way of a link between reading fluency and spelling processing (Sumner, Connelly, & Barnett, 2014). Edwards-Santoro, Coyne and Simmons (2006) noted that spelling processes rely on the same mapping between letters and sounds as in reading: in reading, sounds are mapped onto letters; in writing, letters are mapped onto sounds. Although reading and spelling abilities are likely to have some unique constituent abilities, they have been described as interrelated and likened to two sides of the same coin, following a similar course of acquisition (Perfetti, 1997; Ehri, 2000).

One way of contextualising the contribution of reading ability to written production might be in terms of Perfetti and Hart's (2001) lexical quality hypothesis. They suggested that within the mental lexicon, each word entry is of a different quality, determined by how much orthographic, phonetic and semantic information is available about the word. The more information about that word, the higher the lexical quality of the representation. The key idea in relation to the lexical quality hypothesis is that one characteristic determining higher quality mental representations of linguistic units is highly specified spelling. That does not mean that skilled readers only have high quality representations specified by precise spelling, but that one characteristic of readers with higher reading ability is a greater number of higher quality representations than relatively readers with lower reading ability. In this case, compared to less skilled readers, the writing events of more skilled readers would be based on relatively more specified representations of spelling.

In relation to a word copying task, it might be that reading ability contributes to the efficiency of spelling processes associated with written production. This idea was investigated in the work of Sumner et al. (2014), who looked at the time-course of written production of a sentence during a copying task in relation to children's reading abilities. They found that reading ability predicted the number of words written per minute, such that 9 year old children with higher reading abilities wrote more words per minute. These findings are in line with the idea that the planning of written production

events may be more efficient when based on a relatively highly specified representation of spelling.

In relation to written production, reading ability might constrain the specification of the spelling representation on which the programming and execution of writing events are based. This might be expected to impact on the time efficiency of the programming and execution of writing events.

5.3.4 Working memory capacity in relation to encoding for mental representation.

In relation to written production during paragraph copying, Grabowski, Weinzierl, and Schmitt (2010) stated that enough information about the to-be-copied word needed to be encoded so as to reproduce a copy that was graphically equivalent to the reference model, but not necessarily identical in terms of size, thickness of letter strokes or colour. Grabowski further outlined the qualities of the stimuli that needed to be retained in the copy, and suggested that this was the information encoded from the stimuli. They said that in the written copy, each symbol must be identifiable, in the correct sequence in relation to the original order of symbols, with symbol groups (such as words) delimited either by other symbols (such as punctuation) or by spaces, maintaining the spatial layout of symbol groups with respect to line breaks. In order to achieve this accurate copy, Grabowski et al. also outlined some of the spatial and verbal characteristics of information that copiers might mentally represent during the course of copying. These spatial and verbal characteristics will now be discussed in turn.

In the isolated word copying task used in this Thesis, two relevant aspects of spatial information that copiers might mentally represent are the graphical forms of the letters and the spatial layout of the word in relation to the visual environment. This spatial information may be needed for place-finding over repeated copying cycles, and maintaining a representation of the correct letter shapes in the correct order. As described above, Grabowski et al. also suggested that verbal information is mentally represented in terms of the phonological forms of the letters. This verbal information may be needed for maintaining the correct letter identities in the correct order. Within the context of Baddeley's model of working memory (Baddeley & Hitch, 1974; Baddeley, 2003), children might use the two of the components within the working memory system to respectively store spatial and verbal information. Recall from the literature review that there are three core components within Baddeley's model of memory: the central executive, responsible for controlling attention; the visuospatial

sketchpad, responsible for storing visual and spatial information; and the phonological loop, responsible for storing sound-based information. Although Baddeley's model was designed to account for working memory in adults, Gathercole, Pickering, Ambridge, and Wearing (2004) took measures of assessment designed to correspond separately to each of the three components in Baddeley's model to examine the structure of children's working memory. Importantly, they found evidence to suggest that from the age of 6 years old, children's working memory operated in terms of the same structure advocated by Baddeley, although children between the ages of 4 and 15 varied in the functional capacity of each component in the working memory system, such that capacity developed with age. There will now be a brief description of how children might mentally represent spatial and verbal information.

In a copying task, children may encode the graphical forms of the letters and the spatial layout of the word, as suggested by Graboswki et al. (2010). In other recall tasks that require children to remember a graphical presentation of spatial layout, Hale, Bronik, and Fry, (1997) have shown that children rely on visuospatial working memory to maintain a mental representation of spatial layout. They reached this conclusion by observing how 10 year old children's performance suffered from a secondary task that interfered with spatial working memory, but not from a secondary task that interfered with verbal working memory. In the primary task, children were asked to store the spatial location of a single filled square in a grid, over multiple presentations of this grid. In the spatial interference secondary task, when each filled square was presented, children were also asked to look at an arrangement of coloured circles, and point to the circle with a particular colour name. This concurrent processing of a second spatial layout prevented children from maintaining their stored representation of the locations of the sequence of filled squares in the grid, so at the end of the trial, children struggled to recall the sequence of locations of the filled square. In the verbal interference task, children were only asked to verbally say the name of a colour, which did not require concurrent spatial processing. Throughout the trial, children could rehearse their stored spatial representations, so were more accurate at recalling the sequence of locations of the filled square. These findings suggested that children relied on visuospatial working memory to store and concurrently process visually presented information about spatial layout. In a word copying task, if children did mentally represent spatial information relating to the spatial layout of the reference model and the graphical forms of the letters, they may rely on visual working memory to store and concurrently process relevant spatial information.

Alternatively, after children visually analyse letter forms during encoding, another way that letter forms might be stored might be through verbal working memory, and Baddeley (2003) suggested that information related to language is primarily mentally represented in terms of the phonological loop. Because the orthographic letter forms can be related to the corresponding spoken forms, printed text can be related to speech-based information and represented in verbal working memory. In Baddeley's model of the phonological loop, the visually-presented information might be transferred from an orthographic to a phonetic code by way of phonological recoding, registered within the phonological output buffer that enables temporary storage, and maintained using rehearsal. If this were the case, then in tasks that involve maintenance of a phonological representation by using the phonological loop, one of the indications of phonological rehearsal would be a phonological similarity effect, whereby children were more accurate at recalling phonetically dissimilar than similar items. Support for this was found by Siegel and Linder (1984), showing that typically developing children from the age of 7 engaged in phonological recoding of printed text, as evidenced by decreased performance when recalling phonologically similar than dissimilar items. Furthermore, in tasks that involved recalling nameable shapes that could be stored in terms of their spatial or verbal information, Swanson (1978) demonstrated that 9 year old children preferred to store perform the task by using a verbal rather than spatial mental representation. In a word copying task, if children did mentally represent verbal information relating to phonetic letter forms of the reference model, they may rely on verbal working memory to store and concurrently process relevant verbal information.

These mechanisms of the way in which children might encode and maintain a mental representation of spatial information by using spatial working memory, and of verbal information by using verbal working memory are not theorised to vary between children in the current study. However, it might be that some children's working memory operates more efficiently compared to other children in that they might be able to store more spatial or verbal information. This can be explained through a description of how working memory develops. In terms of the Time-Based Resource-Sharing model (Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009; Case, Kurland, & Goldberg, 1982), working memory capacity is suggested to develop through processing becoming more resource efficient. Available cognitive resources are divided between tasks of concurrent processing and storage, from a limited amount of resources. As processing becomes more resource efficient, there are more available resources for

storage, the storage components can use a greater amount of resources, and so can store more information, resulting in an increase in working memory storage capacity.

Drawing together this research about how children's working memory is structured and developed, it might be that individual differences in children reflect how much spatial and verbal information can be stored in relation to their storage capacities, and how efficiently information is concurrently processed in relation to their concurrent processing capacities. So far, research in the copying literature has not examined the extent to which children's working memory capacities impact on their encoding behaviour. However, Alamargot, Caporossi, Chesnet, and Ros (2011) did show a difference in the way in which adults with high and low working memory capacities encoded information. They asked adults to use information in a reference text in order to compose their own text about assembling a turbine. While not a direct copying task, when adults looked at the reference text, they were presumed to be encoding information in order to plan and programme writing events. Alamargot et al. divided their participants based on their performance on tests of both spatial and verbal working memory capacity. They found that adults with high working memory capacities made more fixations on the reference model than adults with low working memory capacities. If the number of fixations is proportional to the amount of information encoded, these findings might mean that copiers with higher working memory capacities can encode a greater amount of information in readiness for written production than copiers with lower working memory capacities. Nonetheless, from this research, it is difficult to distinguish the functionality of spatial working memory from verbal working memory, so the nature of the mental representation formed after encoding is still not clearly understood.

In relation to written production, working memory capacity might constrain the amount of information that can be stored during encoding. This might be expected to impact on the time-course of encoding.

5.3.5 Working memory capacity in relation to written production.

After encoding and mentally representing information, specifically in the context of a copying task, adults are thought to rely on working memory throughout written production. Different models of writing are constructed on the basis that particular components of working memory are needed for specific processes in written production. While some processes in written production are more relevant to a task in which text is composed rather than copied, (such as planning and translating), in a

copying task, (Hayes & Chenoweth, 2006) identify two key processes in written production in a word copying task: programming and executing. In the relatively more conservative model put forward by Kellogg (1999), neither spatial or verbal working memory have a role in programming or executing written production. In contrast, in the model put forward by Hayes (1996), working memory is described as a resource that is available to be used by all sub-processes involved in text production, which include programming and executing written production.

So far, research using a copying paradigm falls more in line with the ideas outlined by Hayes. For instance, Alamargot, Caporossi, Chesnet, and Ros, (2011) demonstrated links between individual differences in memory capacity and written production behaviour. As described above, adults with either high or low working memory capacities (in relation to both spatial and verbal memory) used a source text for the basis of their written production. Adults with high compared to low working memory capacities needed longer and less frequent pauses between writing events, perhaps indicating that these adults were able to programme and execute larger writing events. Alamargot et al. argued that working memory was important for written production because it determined the frequency of task switching between storage and processing.

Drawing concepts from Just and Carpenter's (1992) capacity theory, Alamargot et al. suggested that storage and processing of spatial and verbal information during written production drew on a limited pool of attentional resources. In individuals with large working memory capacities, resources may be divided efficiently between storage of letters not yet written and concurrent processing of planning and executing writing events. Individuals with smaller working memory capacities may be forced to process and store smaller amounts of information, so need to engage in task-switching between storage and processing more often, slowing down written production. However, Alamargot et al. did not specify individual roles for spatial and verbal memory capacity.

So far in children's written production performance, there has only been tentative support for a role of spatial, but not verbal working memory capacity. Grabowski et al. (2010) asked 8 and 10 year old German children to copy as much information from a paragraph as possible within 1.5 minutes. The paragraph was either composed of meaningful text, consonant strings, numbers, or letter-like symbols. Surprisingly, verbal working memory span was not related to the number of characters children could copy per minute, from any of the paragraphs. It seems that children's verbal memory capacities were not constraining the speed of written production, and

one potential explanation might be that children were programming and executing writing events based on a spatial mental representation of the graphical letter forms. Yet, this was not the case for all children, as 8 year old children copied a similar number of characters irrespective of their spatial memory capacities. Then, for the 10 year olds, compared to children with lower spatial memory capacities, children with greater spatial memory capacities copied more characters per minute only in the number and consonant conditions, not the meaningful text. Their findings provided mixed support in identifying the extent to which children's mental representations reflect the spatial and verbal characteristics of the text. Most importantly, there was no support for the idea that the extent to which children can store a verbal representation of printed text impacts on their written production efficiency. In contrary to Hayes' (1996) model of writing, it may be that in copying, children did not consistently rely on verbal working memory throughout production.

The extent to which copiers rely on verbal working memory has also been investigated in copytyping tasks with adults. Instead of looking at individual differences, researchers used an articulatory suppression paradigm to control the extent to which copiers could rely on verbal working memory. The idea of articulatory suppression (Murray, 1968) is to occupy the phonological rehearsal process with a secondary task, such as repeating a particular sound aloud. When carrying out the primary task, any part of that task that typically makes use of phonological rehearsal will be prevented from doing so. Consequently, in comparison to typical task performance, there should be a decrease in performance. Using articulatory suppression has since become a well-established approach, also shown to be effective in evaluating participants' reliance on verbal working memory in tasks that involve encoding and mental representation of printed text, such as reading for meaning (Coltheart, Avons, & Trollope, 1990). In relation to a copying paradigm, if written production relied on representations of verbal information mentally represented in verbal working memory, articulatory suppression should interfere with efficient production behaviour.

Indeed, this is what was found by Hayes and Chenoweth (2006), when they asked adults to copytype paragraphs. Participants who copied text while repeatedly saying the word "*tap*" aloud produced fewer words per minute than the two other participant groups. One group of participants copied while carrying out a secondary task of foot tapping that did not engage phonological rehearsal, and the other group of control participants copied with no secondary task. Hayes and Chenoweth interpreted these findings as evidence that written production processes did rely on verbal working

memory when they programmed and executing writing events, in line with the model of written production by Hayes. However, while control participants copied about 46 words per minute, articulatory suppression only reduced this rate by about 6 words. While the phonological loop may be used to facilitate efficient written production, successful copying was not wholly dependent on intact functions of verbal working memory.

It might be that the extent to which written production relies on verbal working memory is determined by the characteristics of the words. Service and Turpeinen (2001) showed that the length of Finnish words determined whether or not articulatory suppression impacted on the time-course of written production. In a backwards copytyping task, participants were presented with the word, repeated it aloud, and then typed a written copy. The written production behaviour of participants who copied without the use of phonological rehearsal by repeating the pseudoword “*palah*” aloud did not consistently differ to participants who copied with no secondary task. When copying short 5-6 letter words, both groups of participants showed no difference in latency to first keystroke (which may have reflected the initial spelling programming associated with the first writing event), pause time between letters (which may have reflected additional programming of writing events) or typing time per letter (which may have reflected execution of writing events). Service and Turpeinen suggested that instead of storing letter representations in verbal memory necessitating maintenance with phonological rehearsal, participants may have stored letter representations in terms of graphemes in readiness for written production. Yet, in 7-8 letter word copying, articulatory suppression increased the latency to first keystroke, pause time between letters and typing time per letter, indicating a disruption in planning and execution written production. Service and Turpeinen suggested that although letters may be stored in graphemes, for words that are programmed in more than two writing events, verbal memory may be needed to monitor ongoing progress of written production.

In relation to written production, working memory capacity might constrain the amount of information that can be stored and the efficiency with which information can be concurrently processed. This might be expected to impact on the time-course of written production.

5.3 The Current Study

To recall, Experiment 1 looked at group differences between adults and children, examining how the characteristics of word units modulated sub-processes of encoding,

mental representation and written production during an isolated word copying task. As outlined in the introduction of this Chapter, findings in Experiment 1 raised questions concerning the extent to which encoding involved word reading, and the nature of the mental representation that children formed after encoding. The current study adopted an individual differences approach to test the idea that sub-processes during copying were functionally constrained by individual differences in reading ability and working memory capacity, which in turn may indicate the extent to which children did draw on their abilities to read, store and concurrently process spatial and/or verbal information.

To investigate, the current study examined the extent to which children's reading ability, spatial working memory capacity and verbal working memory capacity predicted their copying performance. Measures of individual differences in children's reading abilities and working memory capacities were collected for the same children as in Experiment 1. These individual differences were used to predict systematic patterns in children's encoding and production behaviour in relation to the eye tracking data already collected and reported in Experiment 1.

Few studies have directly looked at individual differences in relation to separate sub-processes in a word copying task. Yet, these studies introduced above, along with concepts drawn from other research in relation to reading and memory, guided several predictions. In relation to reading ability, if reading ability constrains the efficiency of word reading in relation to the weight of orthographic-semantic connections (as drawn from Plaut et al, 1996) and this constraint impacts on the efficiency of encoding during copying, higher word reading ages will predict shorter encoding times. Similarly, if pseudoword decoding ability constrains the efficiency of subword decoding in relation to the weight of orthographic-phonetic connections (as drawn from Plaut et al, 1996), and this constraint impacts on the efficiency of encoding during copying, higher pseudoword decoding ages will predict shorter encoding times. In turn, it could be expected that reading ability constrains the efficiency of rehearsing a mental representation (as drawn from Kail, 1997), and this constraint impacts the amount of information that can successfully be maintained throughout written production (as seen in Rieben and Saada-Robert, 1997), children with higher word reading ages might forget less information. Word reading age will predict number of gaze lifts, such that higher reading ages predict fewer gaze lifts. Then, if reading ability constrains the specificity of spelling representations (as drawn from Perfetti and Hart, 2002), and this then impacts on the efficiency of spelling processing as seen in gaze time associated with written productions (similar to the effects seen in words written per minute in

Sumner et al., 2014), higher reading ages will be predictive of shorter gaze times associated with written production.

In relation to working memory, if spatial storage capacity constrains the amount of information stored about the spatial layout of the reference model (as drawn from Baddeley, 2003), and this impacts on the place-finding efficiency of targeting return visits after beginning written production (as suggested in Grabowski et al., 2010), greater spatial storage capacities will predict shorter secondary encoding times. If verbal storage capacity constrains the amount of letter information successfully stored throughout written production (as drawn from Baddeley, 2003), this impacts on the extent of secondary encoding necessary, and children only re-encode letters not yet written, greater verbal storage capacities will predict shorter secondary encoding times. During encoding, if spatial and verbal processing capacities constrict the resource efficiency with which mental representations of spatial and verbal information are constructed (as drawn from Barrouillet et al., 2009), and this constraint impacts on the time efficiency of encoding during copying, greater spatial and verbal processing capacities will predict shorter encoding times.

During production, if spatial storage capacity determines the way in which resources are divided between storage and concurrent processing, which constrains the extent to which storage and programming of spatial aspects of written production can occur online, and this constraint impacts on the extent to which copiers pause for task switching between storage and programming of written production during copying (as seen in Alamargot et al., 2011), greater spatial storage capacities will predict less gaze time associated with written production. If verbal storage capacity similarly constrains the extent to which storage and programming of verbal information occurs online, and this constraint impacts the frequency of pausing due to task switching (as seen in Alamargot et al., 2011), and the online monitoring of programming and execution (as seen in Hayes & Chenoweth, 2006 and Service & Turpeinen, 2001) greater verbal storage capacities will predict less gaze time associated with written production.

5.4 Methods

5.4.1 Participants.

Developmental participants were the same children as described in Experiment 1, already reported in Chapter 3. To recall, there were 15 children in total aged between 7-10 (8 male), with a mean age of 9 years, 1 month. Of these 15 children, 13 children

completed all tests of reading ability and working memory capacity, so 2 children were excluded in the current study.

5.4.2 Materials and Procedure.

Recall that children had already copied 32 words orthogonally manipulated for word length and frequency (see Appendix O). Either in the same or separate testing sessions, children completed tests of individual differences: 2 tests in relation to reading ability; 2 tests in relation to working memory capacity. In the case of multiple testing sessions with an individual child to collect the eye movement data reported in Chapter 3, and the data on individual differences in relation to the current Chapter 5, testing sessions occurred within a maximum of 2 weeks apart.

Reading ability. The Word reading and Pseudoword decoding tests, as described in Experiment 2, were used from the reading subsection of the Wechsler Individual Achievement Test (Wechsler, 2005). To recall, the word reading test required children to read aloud from a progressively challenging word list using retrieved word knowledge, resulting in a measure of reading age. The pseudoword decoding test required children to read aloud a list of orthographically legal, pronounceable nonwords using phonetic decoding skills, resulting in a measure of pseudoword decoding age.

Working memory capacity. Two of the tests in the short form assessment of the Automated Working Memory Assessment (Alloway, 2007) were chosen, as these tests generated measures of children's spatial working storage capacity, spatial concurrent processing capacity, verbal working storage capacity and verbal concurrent processing capacity. Each test took about 15 minutes including practice and assessment trials. One test related to spatial memory, involving mental representation of visual images and location information. One test related to verbal memory, involving mental representation of verbal material expressed in spoken language.

Spatial working memory: the test of spatial recall. In this test, children saw a series of shape pairs; the shape on the right with a red dot on it, was either the same shape or a reflected mirror image, illustrated in Figure 8. Also, the shape could be rotated 120 degrees clockwise or anticlockwise so that the red dot position was at the top, the lower left or the lower right of the image. For each shape pair, children judged whether, apart from the rotation, the shape with the dot was the same or an opposite shape (requiring concurrent spatial processing). At the end of the sequence of shape pairs, children were shown the triangle of possible dot positions, and recalled the position of each dot, in the correct order (requiring simultaneous spatial storage).

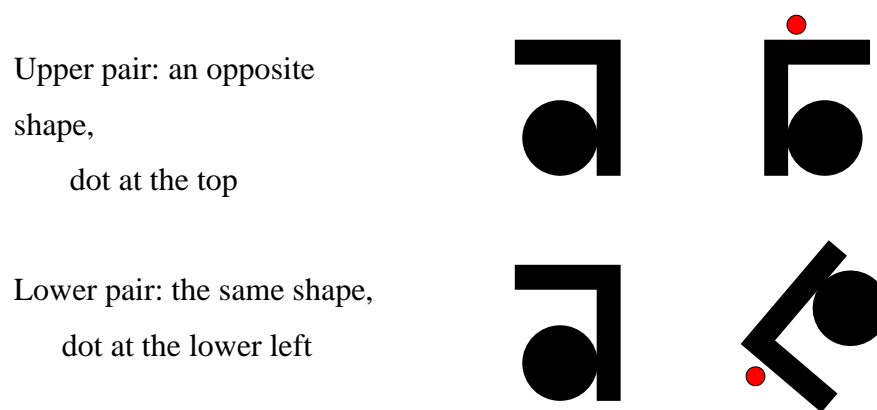


Figure 8. Demonstration of shapes in the spatial recall

In each successive block of 6 trials, the number of shape pairs in the sequence increased by 1 until a block was not completed successfully with 4 out of 6 correct answers, at which point the test ended. Higher spatial recall scores indicated a greater storage capacity of spatial information at the same time as processing additional spatial information. Higher spatial recall processing scores indicated a greater processing capacity of current spatial information at the same time as storing previously presented spatial information.

Verbal working memory: the test of listening recall. In this test, children heard a series of individual sentences, “*apples ride bicycles*”, and immediately judged whether each sentence was true or false, “*false*”, (requiring concurrent verbal processing). At the end of each series, children recalled the last word of each sentence, in the correct order, “*bicycles*” (requiring simultaneous verbal storage). In each successive block of 6 trials, the number of sentences in the sequence increased by 1 until a block was not completed successfully with 4 out of 6 correct answers, at which point the test ended. Higher listening recall scores indicated a greater storage capacity of verbal information at the same time as processing additional verbal information. Higher listening recall processing scores indicated a greater processing capacity of current verbal information at the same time as storing previously presented verbal information.

These working memory tests provided age-normed standardised measures of verbal and spatial working memory. For spatial memory, the spatial recall test provided a measure of working spatial storage capacity and a measure of working spatial processing ability under concurrent task demands. For verbal memory, the listening recall test provided a measure of working verbal storage capacity and a measure of working verbal processing ability under concurrent task demands.

5.5 Results

Linear mixed models were run using the lme4 package (Bates, Maechler, Bolker, & Walker, 2014) in R, version 3.2.3 for each dependent variable. Each model specified fixed factors of word length, word frequency, word reading ability, pseudoword decoding ability, spatial storage capacity, spatial processing capacity, verbal storage capacity and verbal processing capacity. Sum contrasts were used to compare the two levels of words length, and the two levels of word frequency. Although the effects of word length and frequency have already been reported in detail in Experiment 1, these word characteristics were included again in the current study to account for sources of variance in the data.

Each measure of reading ability and working memory capacity was centred (each score minus the mean) so that a score of 0 corresponded to a meaningful value, the mean of each predictor. For these continuous variables, centring scores helps to reduce multicollinearity.

For each dependent measure, the model began with the maximal random effects structure as suggested by Barr, Levy, Scheepers, and Tily (2013). If the model with the maximal random effects structure failed to converge, or there were too many parameters to fit the data, as indicated by correlations of 1 or -1 in the random structure, random slopes and correlations between random slopes were removed from the model. Model specifications for the final models resulting from this process can be found in Appendix R.

5.5.1 Encoding measures.

The summary of the linear mixed models predicting children's encoding behaviour in relation to characteristics of the word and measures of individual differences is shown in Table 12. To recall, total encoding time, the sum of all gaze durations on the board during the entire trial, was broken into initial encoding time, and secondary encoding time. Initial encoding time only included the encoding time on the first encoding episode. Secondary encoding time summed the encoding time across all return encoding episodes that occurred by way of a gaze lift between the written copy and the board. Each measure will now be discussed in turn.

Table 12. Summary of LMMs for encoding times and number of gaze lifts on words manipulated for length and frequency in Experiment 1 in relation to children’s reading abilities and working memory capacities.

	Word characteristics			Reading abilities		Working memory capacities			
	Word length	Word frequency	Length x frequency	Reading age	Pseudoword decoding age	Spatial storage capacity	Spatial processing capacity	Verbal storage capacity	Verbal processing capacity
Total encoding time									
<i>b</i>	1034.92	-27.16	-98.04	-397.86	144.86	-64.86	88.95	-195.83	181.12
SE	112.96	112.75	112.91	223.01	197.64	72.89	79.51	127.04	112.31
<i>t</i>	9.16	-0.24	-0.87	-1.78	0.73	-0.89	1.12	-1.54	1.61
Initial encoding time									
<i>b</i>	188.66	-7.69	-64.53	1.81	9.45	0.74	0.20	-17.40	17.20
SE	58.46	32.85	32.88	43.39	38.11	14.21	15.62	24.60	21.88
<i>t</i>	3.23	-0.23	-1.96	0.04	0.25	0.05	0.01	-0.71	0.79
Secondary encoding time									
<i>b</i>	1420.01	82.55	-177.59	-489.19	107.40	-61.55	117.44	-217.91	196.08
SE	178.67	165.57	166.56	188.55	164.38	61.15	64.78	105.54	93.88
<i>t</i>	7.95	0.50	-1.07	-2.59	0.65	-1.01	1.81	-2.06	2.09
Number of gaze lifts									
<i>b</i>	1.27	0.10	-0.18	-0.42	0.09	-0.05	0.09	-0.23	0.18
SE	0.14	0.13	0.13	0.24	0.22	0.08	0.09	0.14	0.12
<i>t</i>	9.21	0.74	-1.35	-1.70	0.43	-0.62	1.00	-1.63	1.49

Total encoding time. First looking at encoding time over the whole trial, results in Experiment 1 were replicated in that word length, but not frequency reliably predicted encoding behaviour such that children spent more time on long than short words.

In relation to individual differences, although reading ability, pseudoword decoding ability and working memory processing capacity were predicted to modulate encoding times, there were no reliable effects.

Initial encoding time. In the analysis of time taken during only the first encoding episode, results in Experiment 1 were replicated in that word length and frequency jointly modulated children's encoding behaviour. Children spent more time on low frequency than high frequency short words, but a similar amount of time on all long words irrespective of word frequency.

As in total encoding time, in initial encoding time and against predictions there were no reliable predictors of encoding time from any measure of individual differences in relation to reading ability, pseudoword decoding ability, or working memory processing capacity.

Secondary encoding time. After beginning to write, on occasions where children made a gaze lift back to the board for secondary encoding, they behaved in a different way to their initial encoding episode. As reported in Experiment 1, the only word characteristic that impacted encoding time was word length, such that more time was needed for long words compared to short words.

Importantly, there were reliable predictors of secondary encoding time in relation to both reading ability and working memory capacity. Recall that word reading age was predicted to moderate secondary encoding time. Indeed, this was what was found, as word reading age predicted encoding time such that compared to children with lower word reading ages, children with higher word reading ages spent less secondary encoding time. Pseudoword decoding age was not a reliable predictor, despite expectations that children with higher pseudoword decoding ages should need less secondary encoding time than children with lower pseudoword decoding ages.

In relation to working memory, there was no evidence to support the predictions that either spatial storage or spatial processing capacity modulated secondary encoding times.

Both verbal storage capacity and verbal processing capacity were reliable predictors of secondary encoding time. The effect of verbal storage capacity was in the direction predicted, such that children with greater verbal storage capacities needed less

secondary encoding time. In contrast, the effect of verbal processing capacity was the opposite direction to that predicted. Children with greater verbal processing capacities took more secondary encoding time.

Number of gaze lifts. As in Experiment 1, reliable effects of word length suggested that children made more gaze lifts between their written copy and the board on long words compared to short words.

In relation to individual differences, recall that reading ability was suggested to moderate the number of gaze lifts. The observed results suggested that although there were trends in the anticipated direction, these effects were not reliable. Neither spatial nor verbal working memory capacities predicted children's gaze lift behaviour.

5.5.2 Written production measures.

Table 13 contains the summary of the linear mixed models that used word characteristics and measures of individual differences as predictors of children's written production behaviour. To recall, gaze time associated with written production was calculated as all gaze time on the paper throughout the trial. This is suggested to represent the planning and execution of spelling processes associated with written production. Written production duration is a measure of the time between starting and completing written production. This might only reflect processing associated with executing writing events.

Table 13. Summary of LMMs for children’s written production behaviour on words manipulated for length and frequency in Experiment 1 in relation to children’s reading abilities and working memory capacities.

	Word characteristics			Reading abilities		Working memory capacities			
	Word length	Word frequency	Length x frequency	Reading age	Pseudoword decoding age	Spatial storage capacity	Spatial processing capacity	Verbal storage capacity	Verbal processing capacity
Gaze time associated with written production									
<i>b</i>	1456.92	-42.24	169.19	-753.34	521.03	-200.68	208.68	-267.32	273.85
SE	196.36	172.28	164.97	297.38	280.13	98.77	108.43	172.48	152.81
<i>t</i>	7.42	-0.25	1.03	-2.53	1.86	-2.03	1.92	-1.55	1.79
Written production duration									
<i>b</i>	2700.01	-52.71	-61.22	-1064.92	578.04	-149.61	145.19	-324.98	410.20
SE	127.53	126.94	128.29	484.42	434.01	160.03	174.66	279.08	246.36
<i>t</i>	21.17	-0.42	-0.48	-2.20	1.33	-0.93	0.83	-1.16	1.67

Gaze time associated with written production. In relation to predictors of word characteristics, only word length was a reliable predictor. As in Experiment 1, children needed more gaze time associated with written production for long words than short words.

With regard to individual differences, reading age was a reliable predictor. As predicted, children with higher reading ages spent less time looking at the written copy during the trial than children with lower reading ages. However, children spent the same amount of time looking at the copy irrespective of their pseudoword decoding ability.

In relation to working memory capacity, only spatial storage capacity reliably predicted gaze time associated with written production. Children with greater spatial storage capacities took less time than children with smaller storage capacities, and this finding was in the direction expected. In contrast to the other predictions about the influence of spatial processing, verbal storage and verbal processing, there were no reliable effects on gaze time associated with written production.

Written production duration. In this final measure of copying behaviour, word length reliably predicted written production durations in the same way as found in Experiment 1. Children showed longer written production durations for long words compared to short words.

The only other reliable predictor of written production was reading ability. Children with higher reading ages needed less time to produce words compared to children with lower reading ages.

5.6 Discussion

In the current study, the aim was to investigate the extent to which individual differences in children's reading abilities and working memory capacities predicted their copying behaviour in relation to encoding, mental representation and written production. The pattern of results did not provide evidence to support the idea that reading abilities and working memory capacities modulated total and initial encoding times. After the initial encoding episode, when children returned gaze to the board for additional encoding episodes, there was a different pattern of results in relation to the amount of secondary encoding time taken. Children's secondary encoding times depended on both reading ability and verbal storage capacity, but not spatial storage capacity. During written production, reading ability modulated the duration of gaze time associated with written production and written production duration. In addition, spatial but not verbal storage capacity modulated children's gaze times associated with written

production. These results in relation to encoding and written production will now be discussed in turn. Because a different pattern of effects was found for secondary encoding compared to initial encoding, encoding times will be separated this way rather than considered in terms of total encoding times.

5.6.1 Encoding.

Initial encoding. During the initial encoding sub-process of copying, children were expected to encode letter identities and letter positions, and cognitively activate word or subword units. It was predicted that reading ability would modulate initial encoding times by constraining the efficiency with which word units and subword units were activated. In relation to Plaut et al.'s (1996) connectionist model of word recognition, children with higher reading ages should have been able to rely on relatively better established orthographic-semantic connections when encoding word units. When activating word units, children with relatively better established connections between orthographic and semantic information should have activated word units faster, and so needed less initial encoding time. However, this was not the case, as children initially encoded information in the same amount of time irrespective of whether or not their word reading age indicated that they had relatively established orthographic-semantic connections that would have facilitated fast word activation. This suggested that children did not consistently access semantic information during initial encoding. Recall from Experiment 1 that children did not consistently activate word units for all words, as evidenced by word frequency effects only appearing in words with 4 letters, but not words with 8 letters. This indicated that children did not consistently activate whole word units for long words. Hence, children did not consistently carry out cognitive processing operations to the extent of accessing the word units, which is a prerequisite for activating the associated semantic information. In this case in the current study, there may not have been opportunity for reading ability to determine the efficiency of connecting orthographic and semantic information for all words, and in turn modulate encoding time consistently. With a larger dataset, it would be possible to test the idea that word reading ability selectively predicted only the initial encoding episodes in which word units were activated. However, the current findings in relation to reading ability are in line with the conclusions drawn in Experiment 1, that children did not automatically engage in linguistic processing based on whole word units for all words.

Instead of activating whole word units during initial encoding, another way in which children could cognitively process the encoded letter forms is in relation to their phonology. Rather than relying on connections between orthography and semantics, children could use connections between orthography and phonology. If they did, it was anticipated that children with relatively better established orthographic-phonetic connections would be more efficient at mapping sounds to letters. According to the model described in Plaut et al., children's processing of subword units should become faster as children establish weightier connections between orthography and phonology. If children engaged in letter-sound mapping, children with relatively better established orthographic-phonetic connections, as reflected by their pseudoword decoding ability, should activate subword units faster, and so need less initial encoding time. Surprisingly, pseudoword decoding did not predict any measure of encoding behaviour, indicating no benefit for proficient letter-sound mapping. These results of reading and pseudoword decoding ability in relation to initial encoding times did not provide evidence to support the idea that children carried out any further cognitive processing after visually encoding individual letter forms. It was particularly surprising that children's ability to decode letter-sound relationships did not influence encoding, because during initial encoding, it was predicted that children would activate letter sound information, even if they did not activate whole word units. This sound information would be needed in order to maintain a verbal mental representation in terms of the letter sounds associated with the printed text rather than a visual mental representation in terms of the letter forms.

Another way of testing whether children did consistently maintain a verbal mental representation was to look at their use of the phonological loop, the component of working memory specialised for storing speech-based information (Baddeley & Hitch, 1974; Baddeley, 2003). To make use of the phonological loop, children would need to recode each encoded orthographic letter form into the corresponding phonetic form. Recall that evidence supporting the idea that 7-10 year old children mentally represent written text in this way has been previously presented from studies showing a phonological similarity effect in the recall of visually presented material (Siegel & Linder, 1984).

However, children with greater verbal concurrent processing capacities did not initially encode information in less time than children with smaller verbal concurrent processing capacities. Recall that concurrent processing capacity was predicted to be related to the resource efficiency with which mental representations of verbal

information were constructed (as drawn from Barrouillet et al., 2009), when children concurrently processed and then stored each letter sound. The children who could concurrently process information in a more resource efficient manner were suggested to perform concurrent processing operations more quickly than children whose processing employed more resources. These null effects of concurrent processing capacity on initial encoding time still did not provide support for the idea that children constructed a verbal mental representation of individual letter sounds. However, it could have been that rather than decoding and constructing a mental representation of letters one-by-one, children instead activated sound-based characteristics of subword units that were in between the size of a single letter and a word. One sound-based subword unit found to be important in organising children's written production is that of a syllable unit (Kandel & Valdois, 2006a), but research so far has not looked at whether children also activate syllable units during encoding. If it was the case that children concurrently processed multi-letter linguistic units of syllables, because each word in the current study had 2 syllable units, children might have consistently processed 2 phonetic units, rather than 4 or 8 individual letter-sound units. In this case, differences due to speed of concurrently processing only 2 linguistic units may have been too subtle to detect, but children would still have engaged phonological memory mechanisms to maintain the constructed verbal representation.

Gaze lifts. In order to maintain information in this phonological loop, children would use mechanisms of rehearsal to continually refresh the stored representation. Kail (1997) suggested that reading ability constrained the speed at which information could be rehearsed by determining sub-vocal articulation rates. Children with higher word reading abilities were expected to rehearse information at a faster rate than children with lower reading abilities, resulting in less forgetting between encoding and production. In relation to word copying, because children with higher reading abilities were expected to forget less information than children with lower reading abilities, they were expected to need fewer gaze lifts for secondary encoding episodes in which they would re-encode forgotten information. However, this was not the case, as children with relatively slower rates of rehearsal, indicated by lower reading ability compared to higher reading ability, did not consistently need more gaze lifts as a consequence of forgetting. This suggested that children did not consistently rely on the phonological loop to maintain a mental representation throughout written production. So far, the results in relation to initial encoding time and number of gaze lifts raised the question of whether children

consistently activated phonetic information and maintained a verbal mental representation of the text.

Secondary encoding. Yet unlike initial encoding, both word reading ability and verbal working memory capacity predicted secondary encoding times. This effect of reading ability was surprising, because findings in Experiment 1 did not show evidence of an effect of word frequency during secondary encoding, leading to the conclusion that children did not activate word units, let alone semantic information during secondary encoding. Drawn from Plaut et al.'s (1996) model of word recognition, effects of word reading ability were suggested to reflect the efficiency with which children connected orthographic and semantic information. In contrast to the ideas outlined in the Introduction about how reading ability should constrain whole word processing operations during encoding, these findings indicated that reading ability constrained cognitive processing of linguistic units smaller than a word. Also recall that in Experiment 1, the number of gaze lifts and the durations of secondary encoding times were proportional to the length of the word. These findings indicated that children's secondary encoding processes operated at the level of letter units. Could it be that reading ability constrained the efficiency with which cognitive processes operated with respect to encoding letter units during secondary encoding?

In order to encode printed text, children need to visually extract identity and position information in relation to each letter unit. As discussed in relation to transposed letter priming in the literature review, children aged between 8 and 10 are still developing the specificity with which they code letter position information (Castles et al., 2007; Lete & Fayol, 2013). This specificity is suggested to develop alongside print experience in order to cope with a growing lexicon. As children learn more words, a more detailed representation of letter position is needed to distinguish between similar, but not identical, words (Castles et al., 1999). The important point is that although reading ability may have reflected the extent to which children had established connections between orthographic and semantic units (as drawn from Plaut et al., 1996), in the course of developing this greater level of reading ability, children also developed relatively more precise letter coding mechanisms. Even when encoding strings made up of letter-like symbols for which no lexical knowledge can be used, and semantic information cannot be accessed, reading ability is still highly correlated with accurate position coding. Pammer, Lavis, Hansen, and Cornelissen (2004) showed children a target string of 5 letter-like symbols for 100ms, followed by a mask. Children were then given two alternative options, one correct and one with the correct symbols in the

incorrect order, and asked to choose which string matched the target string. Even at age 10, at which age children are still developing specific letter position encoding (Castles et al., 2007) and children can visually extract letter information needed to identify words in under 100ms (Blythe et al., 2009) Pammer showed that children with higher reading ability had more specified mechanisms for coding information in relation to the position of symbols within a string.

In relation to secondary encoding sub-processes in a copying task, children needed to re-encode the letters that had not yet been written. In order to do this, they might need to integrate their representation of the written copy with the reference model, calculating their progress over each successive cycle of encoding and production. This would require precise letter position coding in order to pick up re-encoding at the exact position within a word at which written production had paused. If children with higher reading ability were also relatively more efficient at encoding specified letter positions than children with lower reading ability, this would have impacted on secondary encoding times. Less time would be needed as reading age increased as the mechanism by which specified letter positions were coded became more efficient. This account might also contribute towards explaining the findings by McBride-Chang et al. (2011), who showed a relationship between 8-10 year old Chinese children's reading ability and the number of characters copied from unfamiliar scripts of Korean, Vietnamese and Hebrew. Written copies were scored in terms of the letter shapes and correct letter positions; children with higher reading abilities copied a greater number of words accurately. McBride-Chang considered explanations of efficient letter encoding and attention to detail, but they did not report the number of correctly copied letters in incorrect letter positions. It could have been that high reading ability related to the number of correct copies because these children encoded letter position more accurately.

So far, findings in relation to initial encoding behaviour suggested that children encoded letter forms, but there was no evidence to support the idea that children went beyond these letter forms and cognitively activated phonetic information. However, findings in relation to working memory and secondary encoding behaviour suggested that over repeated cycles of encoding and production, after encoding letter forms, children maintained a mental representation of corresponding sound-based information in verbal working memory.

Perhaps the most important finding in the study was that of verbal storage capacity in relation to secondary encoding. Children with greater verbal storage

capacities needed less secondary encoding time, and this is the key finding that provided evidence for the idea that children mentally represented printed text in terms of a verbal, not visual representation. As discussed in the introduction, within the context of Baddeley's model of working memory, (Baddeley & Hitch, 1974; Baddeley, 2003), children could potentially rely on either visuospatial or verbal working memory to store a representation of printed text, either by mentally representing letter forms or letter sounds.

Only verbal, not spatial storage capacity predicted secondary encoding time, and this indicated that copying performance over repeated cycles of encoding and production was determined by limits on how much information about letter sounds, not letter forms, could be mentally represented. If, as suggested in Experiment 1, children selectively re-encoded only the letters to be written in secondary encoding, children's secondary encoding time was expected to be proportional to the amount of information they needed to re-encode. The finding that, compared to children with greater verbal storage capacities, children with smaller verbal storage capacities needed more secondary encoding time indicated that these children were re-encoding a larger amount of information. This suggests that children with smaller verbal storage capacities were forced to cognitively operate over smaller units of information between encoding and production.

Within the framework of the Time-based Resource-sharing model (Barrouillet et al., 2009), children are said to maintain stored representations by frequently switching between tasks of concurrent processing and refreshing the stored representation. As soon as cognitive resources are switched from refreshing the stored representation to concurrent processing, the stored representation begins to decay. The longer the time between task switching, the more stored representations decay and the more information is forgotten. Between encoding episodes, children would need to maintain the stored representation of the encoded information while concurrently programming writing events. Because children with larger storage capacities developed these capacities through resource efficient processing, it might have been that the concurrent processing operations in these children were quicker than children with smaller storage capacities and so information had less time to decay between task switching. In this case, children with greater verbal storage capacities would forget less information over repeated cycles of encoding and production, so need to re-encode less information, taking shorter amount secondary encoding times. This would mean that between encoding and written production, children maintained a verbal representation of the printed text.

Yet, verbal working processing capacity modulated secondary encoding times in the opposite direction to that expected. It was anticipated that, in a similar manner as children with greater storage capacities, children with greater processing capacities would process information in a more resource efficient, so time efficient manner. In contrast, children with larger verbal processing capacities needed more secondary encoding time than children with smaller processing capacities. Instead of concurrently processing verbal information more time-efficiently in secondary encoding, it could have been that children used their processing capacities to encode and mentally represent as much information about the stimulus as possible. In this case, secondary encoding time would be proportional to the amount of information concurrently processed. In the view of Unsworth and Engle (2007) attentional mechanisms in working memory are needed in order to discriminate task relevance of incoming information. If there is more incoming information, this discrimination operation of sorting task irrelevant and relevant information might take longer, and so impact on encoding times such that children who are concurrently processing more information need more time. The important point is that both verbal storage and verbal processing capacities predicted children's secondary encoding time, indicating that children engaged in construction and maintenance of a mental representation in relation to sound-based information. This means that children did not simply encode visual letter forms with no further cognitive processing in readiness for written production.

In contrast to the evidence for a role of verbal memory in secondary encoding, children's spatial storage capacity did not predict secondary encoding times. This went against the idea of Grabowski et al. (2010), who suggested that information about the spatial layout of the reference model might be used for efficient place-finding behaviour on return encoding visits. If children could store more spatial information using a larger capacity, their decisions about where return fixations should be targeted could be based on more information, so children should find their place more efficiently. There are at least three possible explanations for this lack of difference.

One explanation might be that the characteristics of the spatial layout might not be used in targeting return visits. It might be that children did construct and maintain a mental representation of spatial information in visuospatial working memory in a similar manner to tasks with oral recall of spatial information (as described in Hale et al., 1997), but this spatial representation was not necessary for efficient place-finding.

Alternatively, it could have been that there was only a relatively small time benefit for accurate place-finding in relation to a single word. Grabowski et al. (2010)

discussed the importance of mentally representing a spatial layout within the context of a paragraph copying task. In the current study in which children copied isolated words with between 1-4 encoding episodes in each trial, there may not have been enough repetitive cycles of encoding and production in order to accumulate a time benefit due to efficient place-finding.

The third explanation is that the younger children relied on mental representations of spatial information for place-finding to a lesser extent than the older children, creating noise in the results. In their study, Grabowski et al. (2010) only found correlations between spatial memory capacity and copying performance in 10 year olds, not 8 year olds. In the future, this possibility could be tested with a dataset large enough to break down the developmental population of 7-10 year old children in to multiple age groups. However, Grabowski et al. only found that spatial memory capacity facilitated copying of consonant strings and number strings, not meaningful text composed of words. When copying words, children might rely on verbal information to a greater extent than spatial information, as was found in the current study.

These findings of reading ability and verbal working memory in relation to encoding times suggested that children encoded information about letter forms, and over repeated cycles of encoding and production, mentally represented the encoded letter forms by storing phonetic information in verbal working memory.

5.6.2 Written production.

After encoding and mentally representing the text, children programmed writing events to produce each letter. Reading ability and spatial working memory capacity modulated written production behaviour, but the differences due to spatial storage capacity were only seen in the measure of gaze time associated with written production that included spelling processes in readiness for programming writing events.

Findings in relation to reading ability were in line with the idea that there is a link between reading fluency and spelling processing (Sumner et al., 2014), due to the reliance of both reading and spelling processes on letter-sound mappings (Edwards-Santoro, Coyne, & Simmons, 2006) . In the current study, children with higher reading abilities were expected to have a greater number of highly specified spelling representations, in the context of Perfetti and Hart's (2002) lexical quality hypothesis. In relation to a copying task, the idea was that a greater amount of highly specified spelling representations enabled less effortful, so more fluent programming of writing events, and this would impact on the length of gaze time associated with written

production. Similar patterns were found in Sumner et al., who showed a relationship between reading ability and the speed of children's written production, and this was explained in terms of the time efficiency of spelling programming. In the current study, reading age predicted gaze time associated with written production such that higher reading ages predicted shorter gaze times. This suggests that children with higher reading ages carried out programming of writing events in less time, based on specified representations of spelling. In terms of models of writing such as that of Van Galen (1991), the specificity of spelling representations could affect the speed with which allographs are selected when programming the writing events for each constituent letter in a word. The same letter sound may be represented by a different allograph depending on the letter place in the word, and the surrounding letters. For instance, the phoneme represented by *a* in *bake* could plausibly be represented by a range of different letters; *ay* as in *bay*, or *ai* as in *bait*, and even graphemes that do not contain the letter *a* at all, such as *igh* as in *weigh*. In selecting which allograph is correct, it is likely that specification of spelling representations, as indexed by reading ability, would contribute towards the time efficiency of the selection when programming writing events.

Yet, the findings in relation to working memory suggested that spelling processes involved storage of orthographic, not phonetic characteristics of information. The speed of programming and executing written production was dependent on the amount of spatial, but not verbal information that children could store in working memory. These findings are not wholly in line with either model of writing considered in the Introduction that specified roles for components of working memory in relation to written production. While predictions drawn from Kellogg's (1999) model would be that neither spatial nor verbal working memory should impact on programming or executing written production; predictions drawn from Hayes' (1996) model would be that both spatial and verbal working memory could impact on written production.

Children relying on greater spatial storage capacities during written production needed less gaze time associated with written production than children with smaller spatial storage capacities. As suggested by Alamargot et al., (2011), these findings supported the idea that spatial storage capacity determined the way in which resources were divided between storage and concurrent processing (as drawn from the capacity theory, Just & Carpenter, 1992). In turn, this constrained the extent to which storage and programming of spatial aspects of written production can occur online. If children programmed written production on the basis of spatial characteristics, then children with greater spatial storage capacities would have been able to carry out more of this

programming online with execution, needing to pause for task switching between storage and processing less often (as seen in Alamargot et al., 2011). This would suggest that during written production, information was mentally represented in terms of visual letter forms.

Unlike the findings of copytyping behaviour in adults that relied on phonological rehearsal during written production, children's written production was not facilitated by larger verbal working memory capacities. However, recall that the speed of adults' written production was only affected by prevention of phonological recoding when copytyping short, but not long words (Service & Turpeinen, 2001). In the current study, children copied both short and long words. If processes of phonological recoding were involved only when copying long words, it may have been that noise in the data from short words reduced the consistency with which children relied on verbal working memory during written production. On the other hand, recall from Experiment 1 that children often copied long words by building up a written copy of partial word representations over multiple cycles of encoding and production, whereas adults engaged in a single episode of written production without pausing for gaze lifts. A more likely explanation is that there were differences between adults and children in the size of the linguistic unit over which production operated. Adults processed longer letter strings in written production than children. If adults consequently engaged in more place-keeping behaviour than children, they would have relied to a greater extent on verbal working memory.

Together, these findings in relation to how reading ability and spatial working storage capacity predicted gaze time associated with written production suggested that during written production, children's verbal mental representation from the encoding sub-process was co-ordinated with a visual representation of letter forms during the written production sub-process. As such, there was a difference in the extent to which encoding and production rely on phonetic and orthographic information, with phonetic information being functional during encoding, and orthographic information being functional during production.

In addition, findings that reading ability predicted written production duration can be accounted for by the idea that children under the age of 10 years are still developing automaticity in executing physical motor movements for producing letters (Graham et al., 2001). The idea is that because spelling ability and reading ability follow a similar time-course of acquisition (Ehri, 2000), children with relatively more developed spelling abilities had also developed relatively greater levels of automaticity.

This automaticity then constrained the speed of executing motor movements in written production. What is more interesting is that spatial memory only predicted gaze time associated with written production, not written production duration. The key difference is that gaze time associated with written production also included time in which spelling programming occurs in readiness for writing events, not just time in which motor actions are carried out. This means that children only retained a mental representation of the stored orthographic letter forms as far as programming, not executing written production. In turn, the point at which children co-ordinated the verbal representation maintained from secondary encoding with the spatial representation used in written production occurred before physically carrying out pen movements. This might indicate that children co-ordinated representations used over encoding and written production during spelling programming in readiness for written production.

5.7 Overview

Overall, children's reading ability predicted both their encoding and written production behaviour, but children relied on different components of working memory in different sub-processes during copying.

Findings in relation to reading ability suggested that children operated at least at the level of individual letter forms over visual encoding and written production. However, reading ability was only a reliable predictor in secondary encoding and written production measures, in which children's cognitive processes were consistently operating on subword linguistic units. It may have been that during initial encoding, effects were not reliable because there was greater variance in the nature of linguistic units over which encoding operated, depending on word length.

Over repeated cycles of copying, children cognitively went beyond visually encoded letter forms and activated corresponding phonetic information when mentally representing the information in readiness for written production. Yet, written production processes operated using a spatial mental representation of orthographic letter forms. This led to the conclusion that children co-ordinated phonetic and orthographic information between visual encoding and execution of motor movements for written production.

The next chapter will report a third experiment that aimed to assess the extent to which both adults and children activated phonetic characteristics of linguistic units during encoding and production, and whether children consistently activated the same

linguistic units over successive secondary encoding episodes during repeated cycles of encoding and production.

CHAPTER 6

TO WHAT EXTENT ARE SYLLABLE UNITS FUNCTIONAL IN ENCODING AND PRODUCTION DURING A COPYING TASK?

6.1 Introduction

As shown in Experiment 2, children can cognitively process both long and short whole word units, but as seen in Experiment 1, during a word copying task, the length of the letter string determines the extent to which children's encoding operated on word or subword units. Children's copying primarily relied on subword units for long words, and also perhaps for short words as well, after the initial encoding episode. If partial word, not whole word representations underlie children's copying performance, then one way in which children might encode and produce information might be by engaging in cognitive processes operating on letter-sound correspondences.

Surprisingly, this did not seem to always be the case when considering the data presented in Chapter 5 from which the contribution of individual differences in relation to children's copying in Experiment 1 were assessed. Pseudoword decoding ability did not predict any measure of children's copying performance, and verbal working memory only predicted children's secondary encoding times, not written production behaviour. It was expected that children cognitively processed letter-sound information during encoding, and formed a mental representation of this phonetic information, maintained by verbal working memory, while writing events were being programmed and executed. If this was the case, then individual differences in the ability to decode letter-sound relationships and differences in the capacity to store verbal units of information should have facilitated both encoding and production. This raised the question of whether children activated phonetic information to a different extent in encoding and production.

The Experiment reported in Chapter 6 addressed the following questions: 1) the extent to which phonetic characteristics of linguistic units are functional during copying; 2) whether children and adults activate the same phonetic subword units during copying; and 3) whether the same phonetic subword units are functional over both encoding and production during copying. To do this, the focus of Experiment 3 was the extent to which characteristics in relation to syllable units influenced encoding and production behaviour of adults and children.

The following section will outline why syllable units were chosen as the characteristics of the stimuli to be manipulated. Next, the Introduction will review

findings and conclusions drawn from existing research that assessed the extent to which adults or children activated syllable units in isolated sub-processes during copying task. Then, there will be a consideration of how gaze lift analysis could be informative about the nature of the subword units that copiers can encode, mentally represent and produce in a single copying cycle. The methods of gaze lift analysis used in previous research will be described, and then the rationale for the analysis of gaze lift data in Experiment 3 will be presented.

6.1.1 Syllables as functional units during visual encoding

In word recognition tasks in which participants encode and mentally represent printed text, one unit that has been shown to be functional for both adults and children is that of syllables. Findings in relation to adults and children will now be outlined in turn.

Even in adult readers who no longer need to decode corresponding phonology from visually presented orthographic letter forms in order to identify words, syllable units are still cognitively processed during visual word recognition. As reviewed in Carreiras, Alvarez and de Vega (1993), this cognitive processing has been suggested to occur on a perceptual level of processing operating on orthographic letter forms, and a higher level of processing operating on subword units during lexical identification. To demonstrate perceptual processing of syllable units, Prinzmetal, Treiman and Rho (1986) asked participants to detect the colour of a target letter in a briefly presented letter string, in which letters were presented in two different colours. Importantly, participants reported that the colour of the target letter was the same as the other letters in the same syllable, even if the target letter was not the same colour (e.g., report the target *Y* in *MAYBE* to be the same colour as *M* or *A* more often than *B* or *E*). Prinzmetal et al. argued that readers imposed structural organisation on perceptual units, and that these findings indicated that adults perceived a syllable as a visually perceptual unit. In addition, syllables have been described by Taft (1979) as *lexical access units*. He suggested that word entries were represented in the lexicon in relation to the orthographic characteristics of the first syllable unit, and that the whole word representation is accessed through activating the orthographic code of the first syllable (eg. *spider* accessed through activating *spi*). Adults were quicker to identify word items when a mid-word space was located at the syllable boundary rather than located within a syllable (*SPI DER* vs. *SPID ER*). He suggested these findings reflected the ease of retrieving word items, and that retrieval was disrupted to a greater extent by the mid-syllable space. This input resulted in lexical retrieval operations on a unit of information

that did not match the way in which the orthographic representations were stored, in terms of its first syllable units. In a similar manner, Alvarez, Garcia-Saavedra, Luque and Taft (2016) asked 7 year old Spanish children to identify word items embedded at the beginning of pseudowords. Children were quicker when the syllable boundary (denoted here by the full stop) matched the morpheme boundary (*FIN* in *FIN.LO*) compared to when the initial syllable boundary was before the morpheme boundary (*FIN* in *FL.NUS*). These studies suggested that both adults and children visually encode and cognitively process syllable units of printed text.

In relation to child readers, as discussed at the beginning of the literature review in Chapter 1, approximately at 7 years old, children can efficiently use multiple phonetic units to decode visually presented text, including individual phonemes (Colé et al., 1994), as well as 2 and 3 letter rimes (Colé et al., 1994; Savage et al., 2011) and, importantly, 2-3 letter syllable units (Maïonchi-Pino et al., 2010). Out of all the units that children could use, why might the syllable unit be functional?

One reason for why syllable units might facilitate efficient decoding of printed text is that, compared to cognitively processing each constituent phoneme individually, it may be cognitively less demanding to process a single, larger linguistic unit (Maïonchi-Pino et al., 2010). Maïonchi-Pino et al. framed this idea in terms of children's reading acquisition, in that one way in which children have been suggested to develop visual word recognition is to begin by decoding small letter-sound units, then progressively rely on comparatively larger linguistic units (Seymour & Duncan, 1997). Maïonchi-Pino et al. suggested that the available cognitive resources of the child, as determined by task difficulty, determined the extent to which children could engage in cognitive processing of a syllable unit in comparison to smaller units of constituent phonemes. They found that when 6-8 year old Spanish children were asked to identify whether a target syllable was present at the beginning of a letter string (eg. *pa* in *parade*), children processed high frequency syllables as syllable units and low frequency syllables as phoneme units. This was evidenced by the way in which children took a similar amount of time to identify high frequency syllables irrespective whether they were made up of 2 or 3 letters, suggesting the syllable was accessed as a single unit. In contrast, children were quicker at identifying low frequency syllables made up of fewer letters. This effect of length suggested the use of phonological recoding in the low frequency (but not high frequency) syllable units that took more time as the number of letters to decode increased.

In relation to a word copying task, it might be that although children may not consistently engage in whole word identification, during visual encoding, they may have enough cognitive resources to engage in processing of syllable units, rather than encoding individual letters. If this is the case and copiers engage in cognitive processing of subword units in a similar manner to that observed in visual recognition, it might be that the syllable is a functional unit of encoding during copying.

6.1.2 Do copiers activate syllable units during encoding?

So far, copying research has not directly addressed the extent to which both adults and children activate syllable units during visual encoding. Yet as described in the literature review, there are four studies of adults' copying behaviour that report writing latency as an indication of visual encoding and preparatory spelling processes before starting to execute the first writing event.

Afonso and Álvarez (2011) manipulated the frequency of the second syllable unit, the idea being that if syllable units were activated, lower unit frequency might determine ease of access, and so low frequency syllables would take more time to access than high frequency syllables, resulting in longer writing latencies. They found no reliable effects on adults' writing latency times, and concluded that accessibility of the syllable unit did not modulate cognitive processing during copying before beginning written production.

Kandel, Alvarez and Vallée (2006) manipulated the complexity of the consonant vowel structure of the initial syllable, the idea being that more complex CCVC syllables (*trac.tus*) may be more difficult to process than CCV syllables (*tra.ceur*) during visual encoding and preparatory writing processing. However, the writing latencies were not affected by complexity of syllable structure, leading Kandel and Valdois to question whether writing latency was too noisy to capture the effects.

Lambert et al. (2008) took a different approach, manipulating words and pseudowords in terms of number of syllables, rather than number of consonants within a syllable. In addition, they dissociated visual encoding from preparatory writing processes by having participants place their pen at a starting point, after finishing encoding and before planning any writing movements associated with letters. If the number of syllables modulated processing before writing onset, then writing onset should increase in a linear fashion with an increase in the number of syllable units that were being activated. They found that as the number of syllables in items doubled,

adults took more time to start writing, but only for nonwords (*coutrait* vs. *covinima*), not words (*fonction* vs. *activité*).

Finally, Lambert, Sausset and Rigalleau (2015) tried comparing orthographic and phonetic syllables within words, and found trends in the expected direction that did not reach significance. Words with 2 syllables (*citron*) took about 35ms less time to encode than words with 3 syllables (*lavabo*). There are two competing explanations for these findings. It might be that the task demands of word copying influenced the extent to which syllable units were activated during visual encoding, such that syllable units were not functional linguistic units in a word copying task. Alternatively, it might have been that the act of programming a motor movement to put the pen in a specific location on the page produced noise in small effects that arose from the encoding period. In this case, an isolated measure of just encoding time as obtained by eye movements on the reference model would overcome sources of potential noise from hand movements in readiness for written production.

6.1.3 Syllables as functional units during written production.

Within models of written production, a different amount of importance is given to linguistic units in between words and individual letters. In Van Galen's (1991) model, there is a hierarchy of modules responsible for processing aspects of written production in a sequentially more detailed manner. For instance, higher processing levels involve the conceptualisation of intentions, and high-level information about the text to be produced in terms of semantic and syntactic characteristics. After these multi-word representations, the spelling module concerns how allographs are selected for each word (for instance, selecting *F*, *f*, or *ph*). In the spelling module, processing operations transition from operating on word units to operating on grapheme units. However, other researchers have suggested that spelling processes associated with written production might also operate on units of letter clusters between the size of words and letters.

Houghton and Zorzi (2003) put forward a connectionist dual route architecture of spelling, proposing that when processing spelling, individuals activated two routes in parallel. In one route, whole word representations are mapped onto letter representations; in the other route, sound representations are mapped directly to letter representations. The important point for the current study is that the way in which sound and letter representations were said to be syllabically structured, irrespective of the route. Each constituent phonetic input and graphemic output representation was said to be chunked in terms of a whole syllable unit. Houghton and Zorzi outline the concept of

a “graphosyllable”, with syllable sized chunks of both phonetic and graphemic input carrying information about constituent components of the syllable unit, such as the onset, rime and coda components. So far, a large amount of the existing copying research has focused on identifying functional word and subword units, such as syllables, in processing associated with spelling.

6.1.4 Do copiers activate syllable units during written production?

A range of subword units may be used to organise written production (Kandel et al., 2011), but the syllable unit could be considered as one of the most powerful subword units. This is because syllable boundaries have been shown to be a strong cue for segmenting separate writing events, across different languages, with both child and adult copiers. Kandel and Valdois (2006b) showed that written production was consistently programmed on a syllable-by-syllable basis for all children aged 6-11, through all school grades. Using a digitiser to access the time-course of writing each letter in a word, the idea outlined in the studies by Kandel and colleagues is that spelling programming takes time. Programming events can occur in a pause between writing one letter and starting the next letter, and programming events can also continue online while writing a letter. The pause time between two letters, and the writing duration of a single letter could then provide an indication of the extent to which programming events occurred at that time-point. Compared to time-points at which programming events are not occurring, if programming events occur between two letters, there should be a longer pause than typical; if programming events occur while writing a letter, there should be a longer letter writing duration than typical.

Investigating the time-course of children’s written production of 2 syllable words, they observed that that the first syllable was programmed before starting any writing movements, then the second syllable was programmed online while writing its first letter. The following studies showed similar support for the idea that syllabic structure determined the time-course of children’s written production, in French: Kandel et al., 2009; Kandel, Soler, et al., 2006; Kandel & Soler, 2010); and Catalan: Kandel & Soler, 2010; Soler & Kandel, 2009; but not Spanish: Kandel & Valdois, 2006a. Likewise, sensitivity is also evident in adults, so even skilled writers organise production in terms of subword units. Those units have been based on syllabic structure, in French, (Kandel, Alvarez, et al., 2006; Sausset et al., 2012) and Spanish (Afonso & Álvarez, 2011). Overall, there is a strong case to consider syllables as a modulating factor of written production during copying, and this can be explained by models of

spelling such as Houghton and Zorzi (2003) that suggest that during the course of processing a word's spelling in readiness for written production, the phonetic and orthographic representations are structured and chunked in terms of syllable units.

6.1.5 Syllables as functional units over repeated cycles of encoding and production.

It could also be argued that individuals should mentally represent information in syllable units between encoding and production. Syllable units might be activated during encoding, and the encoded information forms the basis for the input of written production, which is organised in terms of syllable units at the level of spelling modules. Mentally representing information in terms of a common unit that is functional over both encoding and written production would not necessitate re-processing encoded information, which might take time and cognitive effort. Up until now, the copying research presented in this Thesis has predominantly focused on time-based measures of visual encoding (in Experiments 1 and 2) and written production (in Experiment 1). However, in a copying paradigm in which children might need several cycles of encoding and production to build up a written copy, there is (at least) one other non-time-based measure that could be informative about the nature of the linguistic unit that was cognitively maintained during each cycle. So far, gaze lift behaviour, instances in which children have paused written production to return their gaze to the board for an additional encoding episode, has not been examined in detail. As will be discussed next, looking at where, within written production of a word, children pause for gaze lifts has been suggested to indicate the nature of subword units that can be maintained during piecemeal written production (Kandel & Valdois, 2006a, 2006b; Transler et al., 1999)

In a copying task, copiers might make a gaze lift during written production because at that time-point, the mental representation held by the copier does not contain all the information needed to programme all the writing events in order to complete the written copy. This could be because only a partial representation of the information was initially encoded, and/or because copiers had forgotten part of the encoded information. Because research so far has not related gaze lift locations to the units of information that were encoded, these two potential causes have not been investigated separately. However, investigations into children's gaze lift behaviour have been informative about the amount of information that could successfully be maintained throughout written production during one cycle of encoding, mental representation and written production.

6.1.5 Does children's piecemeal written production accumulate in syllable-by-syllable units?

By looking at how many letters children have written before making each gaze lift, and the linguistic units to which those letters correspond, researchers can infer how much information has been successfully maintained from encoding through to written production. If gaze lifts consistently occurred after a particular linguistic unit in a systematic fashion, this would indicate that the linguistic unit might be a functional unit in which information could be encoded, mentally represented and produced during a copying task. For French words at least, as will be made clear, young children are more likely to make a gaze lift back to the model during production after writing the last letter of a syllable, compared to after other letters within the word. This gaze lift behaviour indicated that children could remember syllable-sized units during production, even if more information was originally encoded. As of yet, existing research has highlighted two factors that determine the extent to which children base gaze lifts around syllable units.

One factor is the age of the child. Rieben, Meyer and Perregaux (1989, cited in Kandel & Valdois, 2006b) showed that 5 year old children could not remember any more than 1 or 2 letters at a time, but 6 year old children could, and these older children started to systematically make gaze lifts at syllable boundaries. Humblot, Fayol and Longchamp (1994, cited in Transler, Leybaert, & Gombert, 1999) found that 7 year old children copied in syllable sized units much more than 6 year old children, who could only use the large syllable units for producing familiar, but not unfamiliar or irregular words. By the age of 7, children's written production accumulated in syllable units even for long words with more than 2 syllables (Kandel & Valdois, 2006a, 2006b), and by the age of 8, children still relied on syllable sized production units for long words (Transler et al., 1999). To summarise these studies using gaze lifts to look at piecemeal written production, children seem systematically build up written production of whole words in syllable-by-syllable units from the age of 7 years old.

In addition to the age of the child, the language in which the information is copied also contributes towards whether syllable units systematically determine gaze lift locations. Unlike French children, Spanish children who were copying in a relatively less opaque language did not systematically make gaze lifts at syllable boundaries (Kandel & Valdois, 2006a). Compared to French children of the same age, Spanish children made gaze lifts later in the word, suggesting that they could maintain a larger

linguistic unit over a single copying cycle. To explain these differences, it might be that written production according to smaller syllable-by-syllable units, instead of larger word units, is a behaviour arising from inconsistent letter-sound relationships of an orthographically opaque language. The idea is that spelling operations are based on retrieved representations of word and subword units. As children learning Spanish progress in spelling ability more quickly than reading ability (Borzone de Manrique & Signorini, 1994), Kandel and Valdois argued that in the framework of Perfetti and Hart's (2001) lexical quality hypothesis, the Spanish children would hold representations of large linguistic units that are highly specified in terms of spelling. In contrast, children learning a language with relatively more inconsistent letter-sound relationships such as French need to rely on a larger range of subword units to decode words in reading. In this case, the spelling representations of large linguistic units such as words would not be as highly specified as the representations of the subword units on which children depend to a greater extent. In line with this argument, Kandel and Valdois (2006a) found that the units in which children organised writing events over repeated copying cycles were smaller in French than in Spanish. In a language with opaque sound-letter relationships, such as French, gaze lift locations showed that children often built up a copy of a word by producing partial word representations, and those representations were organised in terms of syllable units. In English, a language known for inconsistency in its sound-letter relationships (Seymour, Aro, & Erskine, 2003), children also organise piecemeal written production in terms of subword units, as shown in Experiment 1. It might be that, as in the French language, the syllable is a functional unit of written production for children operating in the language of English during a word copying task.

To reiterate the key points outlined in the introduction above, syllable units were chosen as the topic of investigation in the current chapter because the syllable is a linguistic unit, often between the size of an individual letter and a whole word, that both adults and children have been shown to activate during tasks involving printed text processing that required visual encoding and mental representation. In relation to a copying task, there has been very tentative evidence to suggest that adults might also activate syllable units during visual encoding. A wider array of evidence supported the idea that both adults and children organise writing events in syllable units, irrespective of whether written production is accumulated over several cycles of encoding and production. However, what is not clear is whether adults activate syllable units during visual encoding (without incorporating processing time associated with spelling

programming), and the extent to which children activate syllable units over both encoding and production. Furthermore, there might be limitations of conclusions drawn from gaze lift behaviour because of how researchers analysed their measure of the likelihood of gaze lifts on syllable boundaries. Methods for analysing gaze lift behaviour will be outlined, before a description of the current study.

6.2 Previous Approaches to Gaze Lift Analysis.

In the papers reporting gaze lift analysis by Transler et al. (1999) and Kandel and Valdois (2006a, 2006b), the authors took a measure of where within the production of a word children made a gaze lift back to the model for additional encoding. The common aim was to assess the extent to which letter strings were produced systematically in syllable units over repeated copying cycles. The studies of Transler et al., and Kandel and Valdois will be described in turn.

6.2.1. The approach used by Transler, Leybaert, and Gombert (1999).

In the approach in Transler et al., the critical question researchers asked could be phrased as “When children make a gaze lift, do gaze lifts occur after syllable boundaries more often than could be expected by chance?” They calculated a single chance threshold based on the number of gaze lift locations at a syllable boundary in relation to the number of total possible gaze lift locations in the 20 items (40 out of 146). Using this ratio, they expected a gaze lift to occur by chance at a syllable boundary in 5 out of 20 items. If children made a gaze lift at a syllable boundary on more than 5 of the 20 words, it was said that gaze lifts occurred at syllable boundaries systematically more often than expected by chance.

This analysis was based on a winner-takes all approach, prioritising gaze lifts that occurred after a syllable boundary over all other gaze lifts within that trial. If one gaze lift in a trial occurred at a syllable boundary, the entire word was said to have been copied syllable-by-syllable, even though there may have been additional gaze lifts on that word that occurred within syllable units. This analysis did not reflect a representative account of all gaze lift behaviour.

In addition, Transler et al. considered both words and nonwords in the same analysis. This is another problem, because Lambert, Kandel, Fayol and Espéret (2008) found that the number of syllables modulated adults’ writing latencies for pseudowords not words. Lambert et al. suggested that the functionality of a syllable unit depends on lexical status. If this is the case, then in Transler et al.’s study, it may have been that

pseudowords were driving an apparent systematic pattern of gaze lifts that was not the same for words.

6.2.2 The approach used by Kandel and Valdois (2006b).

In the study by Kandel and Valdois, the critical question researchers asked could be phrased as “When children make a gaze lift, do they make more gaze lifts after the last letter of a syllable compared to after the adjacent letters?” In each word, the syllable boundary was described as after letter n , and letter n is flanked either side with $n-1$ to the left and $n+1$ to the right. In their example (the syllable boundary denoted here by the full stop) “*pou.let*”, the critical region is “*ou.l*”.

In their analysis, Kandel and Valdois compared whether there were more gaze lifts after letter n compared to $n-1$ or $n+1$. This did allow Kandel to show very neatly that when the syllable boundary moved from the third letter to the fourth letter of words up to 7 letters long, gaze lifts moved with the syllable boundary. But, this method might have downplayed gaze lifts after letters outside the critical region. In a 7 letter word, children could look up after a letter at 7 different locations; Kandel and Valdois only compared 2 out of the 5 non-syllabic locations to 1 mid-word syllabic location. This may have increased the likelihood of gaze lifts systematically occurring at syllable boundaries.

6.2.3 Proposal of a potentially more representative approach.

An alternative approach could be used that takes into account each gaze lift at each syllable boundary in relation to every other gaze lift in that trial at any other letter within the word, out of all the letters within the word. This could be done by simulating the location of all the gaze lifts that occurred in the observed data, based on the statistical assumption that gaze lifts were equally likely to occur after any letter, irrespective of syllable boundaries. This would enable calculation of a region of chance for comparison with the observed data for measuring the proportion of gaze lifts occurring after a syllable boundary out of all gaze lifts within a trial. Critically, these measures will be based on all gaze lifts that occurred on every letter, rather than using a single chance threshold or comparing gaze lifts within a critical window smaller than the word.

6.3 The Current Study

The current study aimed to assess the extent to which copiers activated syllable units during encoding and production sub-processes of copying. Specifically, whether adults and children activate syllable structure in a similar way during encoding, and whether children produce words syllable-by-syllable in a single word copying task.

Studies into the role of syllable sized units have so far considered either children (Kandel & Valdois, 2006a, 2006b; Kandel, Soler, et al., 2006; Soler & Kandel, 2009; Kandel et al., 2009; Kandel & Soler, 2010) or adults (Kandel, Alvarez, et al., 2006; Lambert, Kandel et al., 2008; Afonso & Álvarez, 2011; Sausset et al., 2012; Lambert, Sausset et al., 2015), not comparing the performance of both groups directly. If, as seen in Experiment 1, children are more reliant on partial word representations in copying than adults, syllables may modulate copying behaviour in children and adults to a different extent, being more functional for children than adults. In addition, studies investigating functional units in children's piecemeal copying have looked at gaze lifts in relation to written production alone. Using an eye movement paradigm, the location of gaze lifts can be related to the duration of individual secondary encoding episodes as well as the letters that have been produced before each gaze lift. In Experiment 1, measures of total secondary encoding time were used to assess whether word units were consistently being encoded throughout the copying process, finding no support for the activation of word units in secondary encoding. Now, in Experiment 3, measures in the current study will break down this secondary encoding process in more detail, looking at whether subword units of syllables are encoded throughout the copying process. Then if they are, whether this is consistent across individual secondary encoding episodes, or whether children also rely on other subword units.

To address these issues, eye movements of adults and children were recorded as they copied single words from a wall-mounted whiteboard onto a paper notebook. Critically, the number of syllables varied between items (either 1, 2 or 3 syllables). Because Experiment 1 showed that the length of the word unit affected encoding time such that adults and children took more time for longer words, the number of letters in the word was controlled in the current study. Consequently, as words contained more syllable units, each syllable unit consisted of fewer letters. There were 3 potential outcomes of this manipulation with respect to the way in which the syllable manipulation could be seen to modulate encoding time. The number of syllable units could be expected to modulate encoding behaviour in a similar way as the number of syllable units modulated written production behaviour of children (Kandel et al., 2009)

and adults (Sausset et al., 2012). If this was the case, extra time should be required to encode each syllable unit, so a linear *increase* in encoding time with number of syllables might result. As well as the number of syllable units, the size of syllable units could be expected to modulate encoding behaviour in a similar way as the size of word units modulated encoding behaviour of children and adults in Experiment 1. In this case, extra time should be required to encode larger units, so a linear *decrease* in encoding time with number of syllables might result. If both the number of syllable units and the length of those syllable units jointly modulate encoding behaviour, there may not be a linear pattern. Instead, there may be a quadratic curve, such that 3 syllable words with the most units to activate, and 1 syllable words with the largest unit to activate take more time than 2 syllable words, with relatively few, small units to activate.

If participants engage in cognitive processing of syllable units during encoding in a similar manner as in visual word recognition, syllable units will be activated in initial encoding for adults (as in Taft, 1979), and children (as in Alvarez, Garcia-Saavedra, Luque, & Taft, 2016). These patterns of the effect of syllable characteristics described above should be evident for both age groups. Still before beginning written production, effects of the syllable manipulation could be expected to modulate initial encoding times to a greater extent than writing onset times. As has suggested to be a potential explanation for the findings in Lambert et al., (2015), the cognitive processes involved in initial encoding might be more reliant on syllable units than spelling processes associated with programming the initial writing event. After the initial encoding episode, as in Experiment 1, piecemeal copying of subword units should underlie the copying behaviour of children, but not adults. If this is the case, age group should determine the probability of making a gaze lift such that children have a higher probability than adults. If children systematically copy words in syllable-by-syllable units (as in Transler et al., 1999; Kandel and Valdois, 2006a, 2006b), there would be several following predictions in relation to their secondary encoding and gaze lift behaviour in this piecemeal copying. If children activate syllable units in a consistent manner over each encoding episode, the syllable manipulation will modulate each secondary encoding episode. It may then follow that gaze lift should be sensitive to the number of syllable units and location of syllable boundaries.

The number of gaze lifts should be proportional to the number of syllable boundaries, such that as the number of syllable units in a word increases, a greater number of gaze lifts should be needed. Children should also show a higher probability

of making a gaze lift on a syllable boundary should be higher than expected by chance, and the proportion of gaze lifts on a syllable boundary out of all the gaze lifts in a single trial should be higher than expected by chance.

Finally, irrespective of whether or not gaze lifts are required, if children (Kandel et al., 2009) and adults (Sausset et al., 2012) programme writing events in single syllable units, extra programming time would be needed for each additional unit. For all copiers, there should be a linear increase in gaze time associated with written production and written production duration as the number of syllables in a word increases.

6.4 Methods

6.4.1 Participants.

The skilled reader group consisted of 24 undergraduate adults (4 male, 20 female). Beginning readers were 25 children (12 male, 13 female), either 7 or 8 years of age, (M age = 8 years, 0 months). Using the Word Reading section of the Wechsler Individual Achievement Test (Wechsler, 2005) to measure reading ability, all children scored a typical, or above typical reading age ($M = 8$ years, 7 months, $SD = 2$ years, 6 months). Children also showed typical scores of IQ ($M = 105$, $SD = 10$), using the Wechsler Abbreviated Scale of Intelligence (Wechsler, 2011). All participants spoke English as a first language, had normal or corrected-to-normal vision and no known reading difficulties.

6.4.2 Materials and design.

The experiment was a mixed design, comparing between 2 groups (adults vs. children), within factors of number of syllables (1, 2 or 3). Two sets of stimuli were developed, one appropriate for the reading experience of adults, the other appropriate for the reading experience of children. In keeping with the first copying experiment, adult and child stimuli were respectively sourced from Thorndike-Lorge norms (Thorndike & Lorge, 1944) and the Children's Printed Word Database (Masterson et al., 2010). All words were content words, selected for their single morpheme structure.

Each set of adult and child stimuli contained 32 words, with 12 words in each condition made up of either 1, 2 or 3 syllables, see Appendix S. Characteristics of word frequency and bigram frequency were controlled, and the frequency counts per million are shown in Table 14. Note that the word length was controlled at 6-7 letters. In each condition, there were an equal number of 6 and 7 letter words.

Table 14. Characteristics of the 6-7 letter words presented to adults and children in Experiment 3, manipulated for the number of syllables.

		1 Syllable words		2 Syllable words		3 Syllable words	
		Adults	Children	Adults	Children	Adults	Children
Word frequency	<i>M</i>	18	18	15	15	16	17
	<i>SD</i>	(9)	(15)	(6)	(10)	(8)	(15)
Bigram frequency	<i>M</i>	468	466	431	433	445	426
	<i>SD</i>	(101)	(176)	(58)	(93)	(94)	(133)
Age of acquisition	<i>M</i>	10	6	9	6	10	7
	<i>SD</i>	(3)	(2)	(2)	(1)	(2)	(2)

Two-way between subjects ANOVAs with stimuli set and number of syllables as fixed factors showed no differences in word or bigram frequency between adult and children stimuli sets, or between 1,2, and 3 syllable words. However, there were differences in age of acquisition ratings for the words between the adult and child stimuli sets. These results are shown in Table 15.

Table 15. Summary of statistical differences between the stimuli presented to adults and children in Experiment 3, in relation to word frequency, bigram frequency and age of acquisition.

	Stimuli set (adults vs. children)	Number of syllables (1, 2, or 3)	Group by Syllables interaction
Word frequency	$F(1,66) = .01, p = .99$	$F(2,66) = .33, p = .71$	$F(2,66) = .01, p = .99$
Bigram frequency	$F(1,66) = .06, p = .81$	$F(2,66) = .69, p = .51$	$F(2, 66) = .06, p = .94$
Age of acquisition	$F(1,64) = 37.44,$ $p < .0001$	$F(2, 64) = .79, p = .46$	$F(2, 64) = .51, p = .60$

According to the Kuperman, Stadthagen-Gonzalez, and Brysbaert (2012) norms, the words in the adult stimuli set were typically acquired 3-4 years later in print experience than the words in the child stimuli set. Recall that according to the Children's Printed Word Database, all words in the children's stimuli set appeared in age-graded reading books intended for children of 7 years old.

The location of syllable boundaries was provided for the children's stimuli by the CPWD database. Objective locations of syllable boundaries for the adult stimuli were sourced from the Wuggy Database (Keuleers & Brysbaert, 2010), which syllabifies letter strings in accordance with orthographic rules of the language.

6.4.3 Apparatus.

Viewing was binocular, but left eye movements were tracked, recording gaze location every 40ms using the Ergoneers Dikablis cable eye-tracking system, D Lab version 2.5. The headmounted field camera recorded visual environment to allow coding of when written production started and ended. A video projector was used to present individual words in a random order on a wall-mounted board. The font was monospaced 24-pt Courier New, with each letter horizontally extending and 1.25° of visual angle, at a distance of 135cm. Participants used a pen and a separate sheet of paper to copy each target word.

6.4.4 Procedure.

Participants were familiarised with the eye tracker and the task before the eyetracker was fitted and calibrated. During calibration, participants sequentially fixated four points in a square on the board. Calibration was validated, with tracked location aligned to within 1.48 degrees accuracy, so that at the start of the trial, the gaze location cross at least partially overlapped the central fixation cross. Re-calibration occurred between trials as necessary.

During each trial, a central fixation cross was presented on the board; when gaze was on the cross, the word was presented and remained on screen for the remainder of the trial. Participants were instructed to look at each word then copy it to the paper as quickly and as accurately as possible. To indicate copying was complete, participants checked a box on the paper, ending the trial. Before the experimental trials, 3 practice items were copied to assimilate participants. Children copied their own set of 32 words; adults copied both their set of 32 words and the children's set of 32 words, in a counterbalanced order.

6.5 Results

Linear mixed models were run using the lme4 package (Bates et al., 2014) in R, version 3.2.3 (RCoreTeam, 2015) for each dependent variable, with the number of syllables as a fixed factor. Each model tested for an effect of group – whether there was

a difference between the behaviour of children, compared to adults copying children's stimuli, and also compared to adults copying adults' stimuli. Each model also tested for an effect of condition – whether there was a difference between 1, 2 and 3 syllable words. Polynomial contrasts were used to assess whether there were linear and/or quadratic relationships between conditions. The linear comparison tested whether the difference resembled a successive increase or decrease between the 3 conditions. The quadratic comparison tested whether the difference resembled a nonlinear pattern between the conditions, such that the dependent measure in 1 condition was significantly higher or lower than the other 2 conditions.

For data about gaze lift probability that originated from a binomial distribution of either 0 or 1, a generalised linear mixed model was run with a logistic link function. For time-based measures of encoding and written production, the skewed raw data were log transformed so as to reduce deviation from a normal distribution.

For each dependent measure, the model began with the maximal random effects structure as suggested by Barr, Levy, Scheepers, and Tily (2013). If the model with the maximal random effects structure failed to converge, or there were too many parameters to fit the data, as indicated by correlations of 1 or -1 in the random structure, random slopes and correlations between random slopes were removed from the model. Model specifications for the final models resulting from this process can be found in Appendix T.

Although participants were offered breaks throughout to encourage focused attention, 2% of all trials contained an error or disruption or were incomplete and were excluded from analysis. To ensure writing duration time remained accurate, pen data were excluded when pen tip location was not within visual camera range when participants started or ended written production, so 1% of pen data was excluded.

Next, data concerning errors in written production will be reported. Then, the following sections of the results section will systematically outline results in relation to time-based measures of encoding, and then written production, for both adults and children together. The final section will then focus on the number and within-word locations of children's gaze lifts in order to assess the systematicity of syllable boundaries acting as cues for gaze lifts during written production.

6.5.1 Errors.

As in Chapter 3, results were separated into accurate trials, and trials that contained errors. Similar to the Experiment 1, children made more errors than adults.

Trials containing an error made up 10% of children's data, 2% of adults' data for the adult words, and 1% of adults' data for the children's words; altogether, 4% of the total dataset was excluded. The following results concern the error free data.

6.5.2 Time-based measures of encoding.

As in the first study, several eye movement measures were calculated to measure encoding over different temporal periods during copying: *total encoding time*, the sum of all gaze time on the board; *initial encoding time*, the sum of all gaze time on the board before gaze left the board for the first time; *writing onset*, the trial time between stimuli presentation onset and writing onset, was calculated as an extended measure of initial encoding, which included preparatory writing processing; and *total secondary encoding time* the sum of all gaze time on the board during return visits.

Total secondary encoding time was further split into individual episodes of secondary encoding, giving *first return encoding time*, the sum of all gaze time on the board on the first return visit; *second return encoding time*, the sum of all gaze time on the board on the second return visit; and *third return encoding time*, the sum of all gaze time on the board on the third return visit).

Table 16 shows mean encoding times for both adults and children, with the reliable predictors displayed in Table 17.

Table 16. Gaze times during encoding (ms) in relation to total encoding, initial encoding and writing onset on words manipulated for number of syllables in Experiment 3.

		1 syllable	2 syllables	3 syllables
Total encoding				
Adults:	<i>M</i>	1165	1008	1095
adults' words	<i>SD</i>	(399)	(305)	(352)
Adults:	<i>M</i>	980	856	977
children's words	<i>SD</i>	(311)	(240)	(304)
Children	<i>M</i>	2490	2264	2918
	<i>SD</i>	(1122)	(1148)	(1213)
Initial encoding				
Adults:	<i>M</i>	1070	977	1045
adults' words	<i>SD</i>	(362)	(284)	(320)
Adults:	<i>M</i>	939	822	938
children's words	<i>SD</i>	(276)	(210)	(267)
Children	<i>M</i>	1149	1112	1293
	<i>SD</i>	(547)	(434)	(574)
Writing onset				
Adults:	<i>M</i>	2041	1944	2010
adults' words	<i>SD</i>	(525)	(454)	(489)
Adults:	<i>M</i>	1968	1861	1943
children's words	<i>SD</i>	(430)	(354)	(395)
Children	<i>M</i>	2292	2257	2454
	<i>SD</i>	(758)	(739)	(868)

When very first presented with the word, both adults and children spent a similar amount of time encoding, although recall that children very often returned for at least one additional encoding episode for each word.

Table 17. Summary of LMMs for total encoding, initial encoding and writing onset times on words manipulated for number of syllables in Experiment 3, for both adults and children.

	Total encoding			Initial encoding			Writing onset		
	<i>b</i>	SE	<i>t</i>	<i>b</i>	SE	<i>t</i>	<i>b</i>	SE	<i>t</i>
<i>Age group comparison</i>									
Children vs. Adults: adult words	0.76	0.12	6.27	0.09	0.10	0.92	0.12	0.07	1.60
Children vs. Adults: child words	0.89	0.12	7.69	0.21	0.09	2.28	0.15	0.07	2.01
<i>Syllables comparison</i>									
Linear relationship	0.04	0.03	1.36	0.03	0.02	1.18	0.01	0.01	0.56
Quadratic relationship	0.11	0.03	3.28	0.07	0.02	2.75	0.03	0.01	2.96
<i>Interactions</i>									
Children vs. Adults: adult words x Linear relationship	0.17	0.06	2.70	0.08	0.05	1.69	0.05	0.02	1.88
Children vs. Adults: adult words x Quadratic relationship	0.08	0.06	1.25	0.00	0.05	0.09	0.01	0.02	0.34
Children vs. Adults: child words x Linear relationship	0.14	0.03	4.93	0.07	0.03	2.76	0.04	0.02	2.31
Children vs. Adults: child words x Quadratic relationship	0.05	0.03	1.71	-0.05	0.03	-1.99	0.00	0.02	-0.17

Total encoding time. As gaze time on the board was indicative of the time course of cognitive processing, total encoding time, which includes both initial and secondary encoding episodes, may only show reliable effects if syllable units were activated during all encoding episodes. In total encoding time, there was a reliable effect of group, whereby children needed more encoding time than adults, irrespective of whether adults were copying the children's or the adults' stimuli.

Importantly, the number of syllables in the word also influenced behaviour, such that copiers spent less time looking at 2 syllable words compared to both 1 and 3 syllable words over the whole trial. The relationship between syllable conditions was also qualified by linear interactions with age group.

Irrespective of whether adults and children were encoding exactly the same words or words with age-appropriate frequencies, children showed a stronger linear relationship between syllables than adults. The difference between the time needed for 2 and 3 syllable words was greater for children than adults. It might have been that children found activating multiple syllable units more difficult than adults.

Initial encoding time. Next, total encoding time was broken down into individual encoding episodes, which will be considered in turn. When copiers first encoded the word, there was a reliable difference between adults and children only when copying exactly the same words. When adults copied words with age-appropriate frequency counts, adults and children took a similar amount of initial encoding time.

Similar to total encoding time, both adults and children took the most time looking at 1 and 3 syllable words compared to 2 syllable words, suggesting that the length and number of syllable units influenced encoding behaviour from the outset of the copying task. Copiers took more time on 1 than 2 syllable words, when activating a single syllable unit meant that they were required to process a perceptually larger unit. This suggests that the size of the syllable unit influences the time efficiency with which information is encoded, and this impact acts on visual, perceptual processing operations. All copiers also took more time on 3 than 2 syllable words, which is the key finding that provides evidence to support the idea that individual syllable units are activated during cognitive processing of the visually encoded information. Again, children were affected by increasing syllable numbers to a greater extent than adults, finding it more difficult to activate more syllable units. It may be that there were differences in the way in which adults and children activated syllable units, for instance through operations of assembly or retrieval.

Only on the children's items were the syllable and age group effects qualified by interactions. For adults, 2 syllable words took the least amount of time, and the difference between 1-2 and 2-3 syllable words was similar. For children, there was a stronger linear pattern, such that although 2 syllable words took the least amount of time, the difference between 1-2 syllable words was smaller than the difference between 2-3 syllable words.

Writing onset. Writing onset reflected initial encoding time as well as time associated with planning of production. Writing onset findings were almost identical to initial encoding, despite the predicted interference from preparatory writing processes. Adults only showed shorter writing onsets than children when adults were copying children's words. The number of syllables predicted writing onset such that both children and adults took more time to start writing 1 and 3 syllable words compared to 2 syllable words. When adults and children copied exactly the same words, the difference between 2 and 3 syllable words was greater for the children than for the adults.

After the first encoding episode, copiers planned and executed writing events. During written production, copiers could make as many gaze lifts for secondary encoding episodes as needed. Secondary encoding data are only reported for children, who made gaze lifts on 73% of their trials. As predicted, adults rarely made gaze lifts, on 8% of adults' words and 5% of children's words, preventing meaningful analysis. Secondary encoding times for the children are shown in Table 18.

Table 18. Children’s secondary encoding times (ms) on cumulative and individual secondary encoding episodes on words manipulated for number of syllables in Experiment 3.

		1 syllable	2 syllables	3 syllables
Total secondary encoding				
Children	<i>M</i>	1703	1521	1923
	<i>SD</i>	(814)	(787)	(920)
First return encoding				
Children	<i>M</i>	999	965	1062
	<i>SD</i>	(517)	(565)	(503)
Second return encoding				
Children	<i>M</i>	497	364	637
	<i>SD</i>	(392)	(344)	(557)
Third return encoding				
Children	<i>M</i>	152	102	161
	<i>SD</i>	(260)	(195)	(210)

Secondary encoding time. The secondary encoding times were calculated for trials that contained a gaze lift (about three quarters of children’s data). As in Experiment 1, the eye tracking records allowed a measure of total secondary encoding time, the cumulative amount of time children spent on all return visits. In Experiment 3, as children often made 1-3 gaze lifts, secondary encoding time was further split into individual episodes for each return visit.

Children did not always need more than one encoding episode. When they did, secondary encoding episodes were typically shorter than the initial encoding period, and encoding time tended to decrease on each successive return visit. The LMM model summaries for secondary encoding times are shown in Table 19.

Table 19. Summary of LMMs for children’s secondary encoding times on cumulative and individual secondary encoding episodes on words manipulated for number of syllables in Experiment 3.

	<i>b</i>	SE	<i>t</i>
Total secondary encoding			
Linear relationship	0.15	0.07	2.13
Quadratic relationship	0.16	0.07	2.45
First return encoding			
Linear relationship	0.07	0.04	1.70
Quadratic relationship	0.03	0.05	0.63
Second return encoding			
Linear relationship	0.10	0.05	2.12
Quadratic relationship	0.16	0.06	2.56
Third return encoding			
Linear relationship	-0.12	0.07	-1.81
Quadratic relationship	0.06	0.10	0.56

The number of syllables seemed to determine encoding behaviour in the overall measure of total secondary encoding in a similar way as in initial encoding.

In that least time was spent encoding 2 syllable words than 1 or 3 syllable words. The difference between 2 and 3 syllable words was greater than between 1 and 2 syllable words, suggesting that children needed to re-encode the greatest amount of information on words containing the most syllable units. . This would suggest that children activated syllable units on return visits. However, when total secondary encoding time was broken down into each individual encoding episode, this effect was only reliable on the second, not the first or third return visit. Children spent almost twice the amount of time encoding 3 syllable words compared to 2 syllable words, and these results suggest that children regularly activated syllable units on this second return encoding visit, at least for multisyllable words. It was the second return visit drove the robust relationship in total encoding. Although children may activate syllabic structure on return visits, this did not happen on every return visit. On the first and third return visits, children’s encoding was based on subword units, but these units were not influenced by number of syllables in the word. Syllables were not consistently

functional linguistic units throughout every encoding episode. On the first and third return encoding visits, it appears that children's encoding operated over either individual letter units, or multiletter subword units other than syllable units. Note that syllable units were activated in multisyllable words during alternate encoding episodes. To reiterate, syllable units were activated on the initial encoding episode, not on the first return visit, activated on the second return visit, and then not on the third return visit. If gaze lifts did arise due to forgetting, it may have been that children were attempting to operate over syllable units, but needed to re-encode partial syllable units after forgetting during written production.

6.5.3 Time-based measures of written production.

Eye movement data also enabled calculations of *gaze time associated with written production*, the sum of all gaze time in the paper area; then, *written production duration*, the time between writing onset and writing completion, was coded from pen tip location. Mean gaze times associated with written production and written production duration are displayed in Table 20 for both adults and children, with reliable predictors summarised in Table 21.

Table 20. Written production behaviour in relation to gaze times and written production duration (ms) for adults and children on words manipulated for number of syllables in Experiment 3.

		1 syllable	2 syllables	3 syllables
Gaze time associated with written production				
Adults:	<i>M</i>	3518	3629	3613
adults' words	<i>SD</i>	(580)	(530)	(567)
Adults:	<i>M</i>	3599	3632	3555
children's words	<i>SD</i>	(511)	(552)	(510)
Children	<i>M</i>	7208	7289	7311
	<i>SD</i>	(2933)	(2735)	(2839)
Writing duration				
Adults:	<i>M</i>	2666	2778	2789
adults' words	<i>SD</i>	(381)	(338)	(375)
Adults:	<i>M</i>	2680	2750	2703
children's words	<i>SD</i>	(364)	(345)	(340)
Children	<i>M</i>	7912	7685	8228
	<i>SD</i>	(3224)	(2735)	(3328)

Table 21. Summary of LMMs for written production behaviour in relation to gaze times and written production duration for adults and children on words manipulated for number of syllables in Experiment 3.

	Gaze time associated with written production			Writing duration		
	<i>b</i>	SE	<i>t</i>	<i>b</i>	SE	<i>t</i>
<i>Age group comparison</i>						
Children vs. Adults: adult words	0.62	0.09	7.23	0.99	0.08	12.31
Children vs. Adults: child words	0.62	0.08	7.41	1.00	0.07	13.39
<i>Syllables comparison</i>						
Linear relationship	0.01	0.03	0.34	0.03	0.03	0.95
Quadratic relationship	-0.03	0.02	-1.17	0.00	0.03	-0.18
<i>Interactions</i>						
Children vs. Adults: adult words x Linear relationship	0.02	0.06	0.36	0.00	0.05	-0.03
Children vs. Adults: adult words x Quadratic relationship	-0.03	0.05	-0.55	0.04	0.05	0.71
Children vs. Adults: child words x Linear relationship	0.04	0.05	0.97	0.03	0.02	1.74
Children vs. Adults: child words x Quadratic relationship	-0.04	0.03	-1.13	0.04	0.01	2.41

Gaze time associated with written production. There were strong main effects of group alone. Children spent much more time looking at the page compared to adults, irrespective of whether adults were copying children's or adults' words. This suggested that adults needed less time planning, executing, and then verifying their written production compared to children. Also recall that adults did not need regular gaze lifts, unlike children. It may have been that children needed more gaze time looking at their written copy due to a greater amount of place-finding when transferring gaze between the board and the paper. Although the number of syllables was predicted to impact the length of gaze time associated with written production, there were no reliable effects of the phonetic characteristics of the stimuli.

Written production duration. Similarly, there were large effects of group for the measure of written production duration. Children needed more written production time compared to adults. There was also an interaction qualifying the influence of syllables when adults and children were copying exactly the same words. For children, the 2 syllable words took the least time to write, and a greater amount of time was needed for the 1 and 3 syllable words. Adults now showed the opposite pattern, with 2 syllable words taking the longest time to write, then 1 and 3 syllable words taking less time. This is likely to be because adults and children were programming a different number of writing events, based on different linguistic units. However, this possibility cannot be further investigated for both adults and children without more detailed measures of the time-course of written production in isolation from measures of gaze lifts. Still, gaze lift behaviour can be informative about functional units of written production in children's piecemeal copying.

6.5.4 Measures of gaze lift behaviour.

As well as the time-course of secondary encoding, eye tracking also enabled identification of gaze lifts between the written copy and the reference model. This then allowed calculation of *gaze lift probability* (likelihood that gaze returned at least once to the board) and *number of gaze lifts* (the amount of times gaze transferred from the copy to the model throughout the trial). Gaze lifts were further related to written production, as the field camera enabled calculation of the number and identity of letters that were written before each gaze lift. This led to some important new measures in Experiment 3.

First, how many letters had been produced by the first, second and third gaze lifts. Second, whether or not gaze lifts were located directly after writing a letter that

marked the end of a syllable boundary. The observed data of the number and probability of gaze lifts also provided a baseline of gaze lift behaviour for use in analysing the systematicity of gaze lift locations with regard to syllable boundaries. The observed data were used to estimate the variability characteristics of a distribution in which the same number of gaze lifts were made, and the location of every gaze lift was just as likely to happen after any letter by chance. Ten thousand experiments were simulated, each with the same number of children as in the observed data, with the same likelihood and number of gaze lifts the observed children made, for 1, 2 and 3 syllable words. This enabled calculation of a region of chance containing 95% of the simulated data, for the probability of making gaze lifts after a syllable boundary, and the proportion of gaze lifts made after a syllable boundary, out of all the gaze lifts made in that trial. Comparing the characteristics of the simulated and observed data, if the observed value falls within the region of chance, the observed value can be said to have occurred by chance. Critically, if the observed mean falls above the upper tail of the distribution of simulated means, the observed measure can be said to have occurred more often than could be expected by chance.

This gaze lift behaviour is summarised in Table 22, as well as the number of letters written before each gaze lift.

Table 22. Measures of children's gaze lift behaviour in relation to the likelihood, number and location of gaze lifts, for words manipulated for the number of syllables in Experiment 3.

	1 syllable	2 syllables	3 syllables
Probability of gaze lifts			
<i>M</i>	0.73	0.68	0.80
<i>SD</i>	(0.27)	(0.32)	(0.28)
Number of gaze lifts			
<i>M</i>	1.75	1.69	1.89
<i>SD</i>	(0.82)	(0.67)	(0.72)
Letters written before 1 st gaze lift			
<i>M</i>	2.89	3.11	2.62
<i>SD</i>	(1.54)	(1.59)	(1.43)
Letters written before 2 nd gaze lift			
<i>M</i>	4.15	3.92	3.90
<i>SD</i>	(1.05)	(1.06)	(1.27)
Letters written before 3 rd gaze lift			
<i>M</i>	5.06	4.72	4.82
<i>SD</i>	(1.07)	(1.49)	(0.69)
Probability of at least one gaze lift on a syllable boundary			
Simulated region of chance	0.17 – 0.26	0.26 – 0.42	0.31 – 0.54
Observed data	<i>M</i> 0.26	0.58	0.63
	<i>SD</i> (0.05)	(0.05)	(0.05)
Proportion of all gaze lifts within a trial occurring on a syllable boundary			
Simulated region of chance	0.12 – 0.20	0.26 – 0.36	0.41 – 0.52
Observed data	<i>M</i> 0.22	0.47	0.49
	<i>SD</i> (0.06)	(0.05)	(0.05)

Most of the time, children needed between 1 and 3 gaze lifts, and sometimes more, though it was rare for children to make 5-6 gaze lifts, copying letter-by-letter. This suggested that encoding and mentally representing 6-7 letters throughout written production was often beyond the children's capabilities, but children could copy in units

of more than 1 letter. It also might be that more than one factor determined where within-the-word gaze lifts occurred. Looking at the probability of making at least one gaze lift after a syllable boundary, tentatively for single syllable words, and robustly for multi-syllable words, children made at least one gaze lift in a word after a syllable boundary more often than could be expected by chance. The story is more complex when looking at syllabic gaze lifts within the context of all the other gaze lifts that occurred while copying that word. For the 3 syllable words that often had a syllable boundary after every other letter, children did not appear to make every gaze lift systematically after a syllable boundary. About half of all gaze lifts within a trial happened after a syllable boundary and this was no more than could be expected by chance. Critically, when taking into account all gaze lifts in the trial, the proportion of gaze lifts located at syllable boundaries was only greater than could be expected by chance for 1 and 2, but not 3 syllable words. The linear mixed model results of reliable predictors are shown in Table 23.

Table 23. Summary of LMMs for children’s gaze lift behaviour in relation to the likelihood, number and location of gaze lifts, for words manipulated for the number of syllables in Experiment 3.

	<i>b</i>	SE	<i>t</i> or <i>z</i>
Number of gaze lifts			
Linear relationship	0.08	0.05	1.58
Quadratic relationship	0.09	0.04	1.94
Probability of gaze lifts			
Linear relationship	0.39	0.25	1.58
Quadratic relationship	0.60	0.24	2.55
Probability of syllabic gaze lifts			
Linear relationship	1.21	0.16	7.54
Quadratic relationship	-0.37	0.14	-2.62
Proportion of syllabic gaze lifts			
Linear relationship	0.21	0.03	7.27
Quadratic relationship	-0.12	0.04	-3.24
Letters written before 1 st gaze lift			
Linear relationship	-0.28	0.19	-1.50
Quadratic relationship	-0.41	0.15	-2.69
Letters written before 2 nd gaze lift			
Linear relationship	-0.13	0.13	-0.99
Quadratic relationship	-0.16	0.14	-1.15
Letters written before 3 rd gaze lift			
Linear relationship	-0.28	0.20	-1.40
Quadratic relationship	0.16	0.22	0.73

Looking at the probability of gaze lifts, 2 syllable words were marginally less likely to require more than one encoding episode than 1 and 3 syllable words. Then, when gaze lifts were necessary, fewer gaze lifts were needed on 2 compared to 1 and 3 syllable words. Before making the first gaze lift, children also wrote more letters of a 2 syllable word than 1 or 3 syllable words. This might suggest that children mentally represented the most information from 2 syllable words throughout written production.

Findings provided mixed results on measures of whether children systematically made gaze lifts after a syllable boundary. As numerically expected, the likelihood of making gaze lifts at a syllable boundary increased as the words contained more syllable boundaries. However, this increase in probability was likely to have been due to chance, rather than children systematically making gaze lifts on each syllable boundary within a word. Although the proportion of all gaze lifts on a syllable boundary within a trial increased as the words contained more syllable boundaries, recall that comparisons between the observed and simulated data indicated that children only systematically made gaze lifts at syllable boundaries on 2 syllable words. Taken together, children's gaze lift behaviour suggested that children did not consistently mentally represent and programme writing events for syllable units all the time, for all words.

6.6 Discussion

The current study set out to investigate the extent to which adults and children activated syllable units throughout a copying task. Results in Experiment 3 suggested that the number of syllable units and the length of those syllable units jointly modulated encoding behaviour, and these effects were evident for both adults and children in measures of isolated initial encoding time and writing onset. Children, but not adults, regularly copied in a piecemeal fashion, producing partial word representations and requiring gaze lifts from their written copy for additional encoding episodes three quarters of the time. However, the syllable manipulation did not consistently affect each secondary encoding episode, suggesting that children did not always activate syllable units during encoding.

Even if syllables were activated during encoding, there was not necessarily a 1:1 correspondence between the nature of the units used in visual encoding and piecemeal written production. The size of the partial word representations in written production did not always correspond to the syllable boundaries in the word. Children were most likely to copy 2 syllable words in a syllable-by-syllable manner, but even though children made a higher proportion of gaze lifts on the syllable boundary than expected by chance, these gaze lifts only accounted for half of all gaze lifts within a trial. While syllable boundaries may be a cue for gaze lifts, even if the syllable unit was functional during part of written production, written production may not be organised in terms of syllable units alone. Findings will now be discussed in relation to encoding and production in turn.

6.6.1 Encoding.

Similar to visual processing during word identification tasks for both adults (Taft, 1979) and children (Alvarez et al., 2016), during the initial encoding sub-process of a copying task, copiers engaged in cognitive processes that activated syllable units irrespective of age group. For both adults and children, initial encoding time reliably predicted by the syllable manipulation. This means that activation of subword structure was not restricted to instances of the piecemeal encoding that underpins children's behaviour, but also took place when adults encoded the whole word unit. For multi-syllable words, more encoding time was needed for words with more syllables, suggesting that as has been found in written production measures (Kandel et al., 2009; Sausset et al., 2012), extra processing time was required for each syllable unit activated. These findings are in contrast with those of previous copying studies with adult participants, which found that the ease of accessing the syllable unit as determined by second syllable frequency (Afonso & Álvarez, 2011), the complexity of the consonant-vowel structure (Kandel, Alvarez, & Vallée, 2006), and the number of syllable units (Lambert et al., 2008; Lambert et al., 2015) did not modulate the duration of writing latency, including the initial encoding period, before starting written production.

The number of syllable units was not the only characteristic of the stimuli to modulate encoding time, as there was also evidence to suggest that the size of the syllable units influenced behaviour. Copiers took more initial encoding time on 1 syllable compared to 2 syllable words. This suggested that, as in Experiment 1, extra time was required to encode larger units of information.

Although the syllable manipulation influenced the initial encoding behaviour of adults and children in a similar fashion, there were also differences in encoding time determined by age group. When first presented with words matched for ease of accessibility as determined by age-appropriate word frequency counts, adults and children tended to take a similar amount of encoding time. This indicated that all copiers initially encoded a similar amount of information, all 6-7 letters. If this was the case, then during the trials in which children needed more than one encoding episode, these return visits would be due to forgetting, rather than incomplete encoding. These findings contributed towards refining an estimation of limitations in the amount of information that children can consistently encode, mentally represent and produce during a word copying task. Recall from Experiment 1 that on the majority of trials, children needed one encoding episode to copy a 4 letter word, and more than one encoding episode to copy an 8 letter word. From this, it was concluded that the limit for

the amount of information that children could encode mentally represent and consistently produce was approximately between 4 and 8 letters. The current findings in Experiment 3 narrowed that initial estimation to between 4 and 6 letters, as children still needed more than one encoding episode on the majority of trials in Experiment 3, which contained 6-7 letter words. This means that linguistic units that are functional for 7-8 year old children throughout a word copying task must be smaller than 6 letters.

When adults and children initially encoded exactly the same orthographic input, there was an interaction such that the difference between 2 and 3 syllable words was greater for children than for adults. Compared to the stimuli set designed for adults, the stimuli set designed for children contained early acquired words, and it was on these early acquired words that the number of syllables manipulation affected children to a greater extent than adults. The age at which words are acquired has been shown to influence ease of lexical processing in isolated word recognition tasks, such that early acquired words are identified more quickly than late acquired words (Butler & Hains, 1979; Morrison & Ellis, 1995). As outlined in the phonological completeness hypothesis (Brown & Watson, 1987) the phonological forms of words that are early acquired are stored in a complete form, whereas the phonological forms of late acquired words are stored in a more fragmented form, and require assembly during retrieval. Recall from Experiment 1 that when encoding long words, only adults, but not children engaged in lexical retrieval of whole word units, whereas children encoded partial word representations. If adults engaged in lexical processing, phonetic information about these early acquired words should be retrieved in its complete form. If children engaged in cognitive processing of subword units, they would have phonologically assembled each subword unit in a more time-consuming manner than retrieval of a single linguistic unit. This phonological assembly process would then result in activation of individual syllable units, taking more time for children than adults. Although both adults and children activated syllable units, the syllable manipulation may have been impacting different cognitive processes between adults and children due to the extent to which children relied on piecemeal copying.

After initial encoding, surprising results in relation to writing onset times showed that syllable units modulated writing onsets in a similar manner as initial encoding. Against predictions drawn from the literature on adults' copying (Lambert et al., 2008, 2015), effects of the syllable manipulation were consistent for both measures of initial encoding and writing latency in all copiers. This suggested that syllable units were activated during initial encoding and during initial spelling processes associated

with written production. This falsified the idea that Lambert et al. did not find an impact of the number of syllables on adults' writing latencies because noise in spelling processes associated with written production obscured effects that arose from cognitive operations in the initial encoding sub-process. The current study demonstrated that the measure of writing onset times was sensitive to differences in the copying behaviour of both adults and children as a result of a manipulation of the number of syllables in a word. This would suggest that syllable units were consistently functional not only during cognitive operations of retrieving syllable units (for adults) and assembling syllable units (for children), but also in the processing associated with written production during the programming of the initial writing event.

Why, then, were effects of the number of syllable units consistently observed for adult participants in the current study, but not in the French copying studies (Lambert et al., 2008; Lambert et al., 2015)? The orthographic grain size (Ziegler & Goswami, 2005) of the language determined the difficulty of activating syllable units. While French has reliable letter to sound conversions, the inconsistent sound to letter conversions are about 70% less predictable, according to Grabowski et al. (2010). This means that syllable units might be easier to activate when converting letters to sounds during encoding than when converting sounds to letters during writing. It might be that if French adults were easily activating syllable units during encoding, the difference between the time needed for 2 and 3 syllable words was too small to detect. In written production, if activating syllable units was relatively more difficult, the time needed to process each additional syllable unit might be greater in written production than in encoding, resulting in noticeable differences between the time taken to produce 2 and 3 syllable words (as shown in Lambert et al. 2008; Lambert et al., 2015). Because there are inconsistent relationships between letters and sound during encoding of English words (Seymour et al., 2003), it may have taken longer to activate each syllable unit in English than in French. In this case, the difference between 2 and 3 syllable words would be greater in English than in French. Comparing Lambert et al. (2015) to the current study, English adults took about 250ms more time to start writing than French adults; then, the difference between writing onset times for 2 and 3 syllable words in English was twice the amount as the trends in French. This comparison lends support to the idea that, although Lambert and colleagues may have been using a potentially sensitive measure of writing latency, there may be cross-linguistic differences in the extent to which syllable units modulate encoding behaviour. However, until cross-

linguistic research experimentally comparing French and English copying is carried out, this explanation cannot be directly confirmed.

After encoding, as in Experiment 1, piecemeal copying of subword units was underlying the copying behaviour of children, but not adults. This is in line with the findings of Kandel and Valdois (2006b), who showed that children needed regular gaze lifts within the first few years of primary school, but the likelihood of gaze lifts decreased as children aged from 6-11 years. Similarly to the current study and Experiment 1, the adults in Kandel and Perret (2015) made so few gaze lifts as to prevent meaningful analysis. Yet in contrast to the 6-7 year old children in Kandel and Valdois (2006b), in the current study, 7-8 year old children's piecemeal copying was not consistently on the basis of syllable units, as indicated by their secondary encoding and gaze lift behaviour. Secondary encoding times and gaze lift locations will now be discussed.

Across total secondary encoding time, similarly to initial encoding, children needed the least time for 2 syllable words. However, when looking at each individual secondary encoding episode, these patterns were only consistent enough to be reliable on the second return visit. If syllables were not consistently activated on all encoding episodes, it might be that children were using a range of subword units including, but not limited to, syllables. It might be that, as in the low frequency words in the study by Maïonchi-Pino et al. (2010), children encoded partial word representations in terms of letter units rather than syllable units. At present, it is unclear whether these return encoding episodes were systematically based on a range of subword units, or whether children encoded partial syllable units due to forgetting. Interestingly, children's encoding times indicated that syllable units were being activated on every other visit to the board. The number of syllable units modulated children's encoding times on the initial encoding episode and second return visit, but not the first or third return visits. If gaze lifts were indeed due to forgetting, this pattern appears to indicate that children encoding in terms of syllable units, but could not retain complete units throughout written production. In this case, on the first and third return visits, it is likely that children were re-encoding information from partial syllable units that had been forgotten from the previous encoding episode.

In relation to children's piecemeal copying, gaze lift behaviour was considered to see whether children consistently made gaze lifts for additional encoding after writing each syllable unit. Findings from Experiment 1 were replicated, that children needed at least one gaze lift on a long word about three quarters of the time. Comparing overall

gaze lift probability to the French and Spanish 7-8 year olds in Kandel and Valdois (2006a), the English children in the current study had higher gaze lift probabilities. Whereas the English children needed to look up about 70% of the time when copying 6-7 letter, 1-3 syllable words, when copying 4-10 letter, 2-4 syllable words, French children needed gaze lifts 60% of the time, and Spanish children needed gaze lifts about 40% of the time. This supports the idea outlined in Chapter 5, that word copying may be harder, and so more reliant on partial word representations, in languages that are relatively more difficult to verbally represent, due to the reliance on verbal memory in order to maintain a mental representation of the printed text throughout written production.

Children also copied 2 and 3 syllable words in a different manner, and this will now be discussed in turn. In relation to the 2 syllable words, there were similarities in the locations at which English and French children made their gaze lifts. The current study showed a higher proportion of syllabic gaze lifts than could be expected by chance on 2 syllable words, and this is in line with the findings of Kandel and Valdois (2006b), who observed 6-8 year old French children making the most gaze lifts after writing the last letter of a syllable, compared to the letters either side. While this seems to suggest that syllable structure can be a driving force for gaze lifts, it might not be the only cue. For the 2 syllable words in the current study, gaze lifts after a syllable boundary accounted for about half of all the gaze lifts in the trial. Recall that the proportion of gaze lifts on syllable boundaries within a trial was approximately 0.5, and children most typically made 2 gaze lifts per trial. Although children were systematically looking up at syllable boundaries, they often needed another non-syllabic mid-word gaze lift. Again, this is similar to another study by Kandel and Valdois (2006a), who show that as well as making gaze lifts after syllable boundaries, 6-8 year olds may use a range of subword units for 2 syllable words, including individual letters and graphemes. Although the syllable was a functional unit during piecemeal copying, it was not the only functional subword unit.

Regarding 3 syllable words, the current findings contrast with the existing copying research that was conducted in the French language. Although children in Experiment 3 were more likely to make a gaze lift after a syllable boundary as the number of syllable boundaries in the word increased, when these gaze lifts were analysed in the context of all other gaze lifts in the trial, children did not systematically make a higher proportion of gaze lifts after a syllable boundary than could be expected by chance. These findings contradict those of Transler et al. (1999), who reported that

7-8 year old French children were more likely than chance to make at least one syllabic gaze lift on a 3 syllable word. Instead, for the children in the current study, syllable boundaries were not the predominant driving force behind gaze lifts for all words.

These findings were surprising, because children activated syllable units during initial encoding, and sometimes during secondary encoding. Why were syllable units being produced over repeated copying cycles for 2, but not 3 syllable words? As seen in encoding times, the number of letters in a syllable unit might determine its functionality during written production. Kandel and Valdois (2006b) showed that as the location of the syllable boundary shifted from the 3rd to the 4th letter of a 7 letter word, the locations of children's gaze lifts reflected this shift. So far in the copying literature, there is only evidence to support the functionality of syllable units when they are a critical size of 3 or 4 letters. Similarly to Kandel and Valdois, our 2 syllable words were made up of units with 3-4 letters, and the current study replicated the finding that gaze lifts occurred systematically after syllable boundaries. In contrast to Transler et al., who used 7-10 letter words in which at least one syllable segment (denoted here by the full stop) was about 4 letters (*cham.pi.gnon*), our 3 syllable, 6-7 letter words (*ci.ne.ma; vol.ca.no*) had between 1-3 letters per unit, typically only 2 letters. This indicated that children did not consistently rely on relatively smaller syllable units of approximately 2 letters to a similarly consistent extent as they relied on larger syllable units of 3-4 letters during written production.

In that case, what was happening on the times that each syllable unit did not match the critical letter length? One possibility is that syllable units of 1-2 or 6-7 letters were respectively either too small or too large to be functional during production, so the children relied on alternative subword units. When copying in the language of French, children have been shown to organise written production in subword units of individual graphemes (Kandel, Soler, et al., 2006) and bigrams (Kandel et al., 2011). It may be that the children copying in English also relied on these subword units. Still, this explanation is not in line with the secondary encoding times that suggested syllable units were activated on the second return encoding visits. Another possibility is that children may have attempted to remember multiple syllable units, but needed a gaze lift before the end of a syllable due to forgetting, as raised earlier in the discussion. In this case, the reliance on alternative subword units might have arisen as a compensatory consequence of forgetting, rather than a preferential reliance on a functional subword unit.

Cowan (2010) argued that individuals temporarily store mentally represented information in terms of about 3-5 meaningful units, with 7-8 year old children tending

to work with a smaller capacity than adults, about 1.5 units (Cowan, Morey, Aubuchon, Zwillig, & Gilchrist, 2010). If the information is mentally represented in terms of syllable units, children might attempt to store multiple syllable units, but concurrent processing in programming and executing written production might not happen fast enough for children to mentally retain a stored representation of both complete units. Applying the concepts of time based resource-sharing in memory (Hitch, Towse, & Hutton, 2001; Towse & Hitch, 1995), during copying, children need to balance two tasks of storing the encoded information at the same time as processing additional task demands, in this case preparatory writing events and refreshing the representations online at the same time as carrying out writing events. When storing more than one unit, there may be an extra task of storing the second unit while processing production of the first unit. Then, the delay between initial storage and recall of the second unit might allow opportunities for time-based forgetting of at least some of the second unit. In this case, forgetting parts of a syllable unit resulted in children's gaze lifts falling out of sync with syllable boundaries on multi-syllable words as written production progressed. If forgetting did result in piecemeal written production operating on subword units irrespective of syllable boundaries, it could be expected that individual differences in verbal storage capacity should predict the proportion of gaze lifts that occurred on syllable boundaries. This will be returned to in the next chapter.

6.6.2 Written production.

Finally, findings in relation to written production times will be discussed. As predicted, children needed more time to programme and execute writing than adults, and this was in line with the idea outlined in Chapter 5, that children may be programming writing events from relatively less specified spelling representations (Perfetti & Hart, 2002), and that children are still developing fluent writing execution (Graham et al., 2001). In terms of Van Galen's model of writing (1991), these effects could be explained in that the specificity of spelling representations should constrain the time-efficiency with which allographs are selected in the spelling model. After programming spelling, the fluency of writing execution should constrain the time-efficiency with which operations of muscular adjustment and real-time movement are carried out in the motor modules.

Moving on from group differences, more surprising results were found in relation to the syllable manipulation. Previous copying studies showed how the programming of writing events is structured in terms of syllable units for both children

(Kandel & Valdois, 2006b; Kandel et al., 2009; Kandel, Soler, et al., 2006; Soler & Kandel, 2009; Kandel & Soler, 2010) and adults (Kandel, Alvarez, et al., 2006; Afonso & Álvarez, 2011; Sausset et al., 2012). In view of that, copiers in the current study were predicted to need more gaze time associated with written production and longer writing durations on words with more syllables. According to Houghton and Zorzi's (2003) model of spelling, during the course of processing a word's spelling, the phonetic and orthographic representations are structured and chunked in terms of syllable units. In this case, separate writing events might be needed for words with more syllables, taking more time.

Surprisingly, in the current study, written production behaviour was not consistently modulated by the number of syllable units, either for children or for adults. For the children, who did not always encode in terms of syllable units, it might have been that alternative subword units were used to organise written production. For the adults, the more likely explanation is that the differences in programming time associated with written production were too subtle to detect. In the study by Sausset et al. (2012), they reported that the pause time associated with programming a syllable unit in lowercase letters was 37ms. Although the recording rate of the Dikablis of 1 frame every 40ms was sufficiently detailed to capture effects in encoding time, and has provided valuable data in relation to the impact of both word characteristics, subword characteristics and individual differences throughout this Thesis, there may not be enough temporal detail to investigate relatively subtle influences on written production behaviour.

In the future, with the updated recording rate of the newest version of the Dikablis eye tracker at 20ms per frame, it may be that eye tracking during written production can provide valuable data to investigate increasingly subtle effects. In addition, co-registration between recorded eye movements and digitised writing behaviour would provide an even more robust array of measurements in a copying paradigm. So far, Alamargot, Chesnet, Dansac and Ros (2006) have developed co-registration techniques with the Eye and Pen software, synchronising handwriting and eye movement recordings to provide detailed recordings of how eye movements and pen movements relate to each other. In Alamargot, Caporossi, Chesnet, and Ros (2011), an investigation into adults' copying behaviour was achieved by way of a helmet and bite bar to minimize head movements for accurate eye tracking, and customised frame holding the digitised writing tablet at an angle (not reported, but advised to be 30-50 degrees in Alamargot et al., 2006). Their experimental setup allowed an exceptionally

high degree of control. This approach did allow detailed investigation on a fixation-by-fixation basis, and writing behaviour with much more temporal and spatial detail than the current study. However, in relation to the current research topic examining children's copying behaviour in a naturalistic classroom copying task, in designing mobile research methods, it is important to balance the temporal and spatial detail of the measures with the practical concerns of carrying out the experiment. The area of word copying research is still fairly new in comparison to more well-understood topics of word reading. Until there is a fuller knowledge of the basic phenomena and a solid theoretical framework in relation to a word copying task, it might be that techniques requiring such spatial and temporal detail are not yet necessary to provide valuable data that can be used to develop and clarify the initial platform of understanding in relation to the cognitive processes in a copying task.

6.7. Overview

To summarise, this study investigated eye movement behaviour during copying of single words with a varied number of syllables, in English children and adults. There was evidence to suggest that syllable units were activated during both encoding and written production processes, but the number of syllables may not consistently be the predominant factor that determined encoding difficulty, with the size of the syllable unit also predicting encoding times. For children, there was not necessarily a 1:1 correspondence between the granularity of the units used in encoding and written production. Forgetting and differences between languages were suggested to result in a range of subword units being functional over successive copying cycles of encoding and production. For English children at least, after the initial encoding period, sound-based characteristics of syllables alone did not seem to be the primary determinant of subword encoding and production for children during a copying task.

This calls into question the extent to which children consistently rely on a word's phonetic information over both sub-processes of encoding and production during a copying task. The next and final experimental chapter will reconsider children's encoding and production behaviour in relation to individual differences in their ability to read and verbally represent information in short term and working memory.

CHAPTER 7

CHILDREN'S COPYING BEHAVIOUR IN RELATION TO READING ABILITY, VERBAL SHORT TERM MEMORY AND VERBAL WORKING MEMORY CAPACITY

7.1 Introduction

Throughout this Thesis, one reoccurring topic has been questioning the extent to which children rely on different characteristics of printed text during a copying task. As a reflection of speech, printed text carries additional information that those letter forms represent, such as word units that can be further related to semantic meaning, and sound-based patterns of syllable units that can be further related to the way in which letter sounds associated with those letter forms are grouped together when spoken. As presented in Chapter 3, Experiment 1 was designed to examine the extent which children activated word units. Children encoded the letter forms, as evidenced by their making a correct written production of the same letter forms in the same order. However, their encoding times did not indicate that children cognitively went beyond the literal representation of individual letter forms in order to consistently activate word units represented by multiple letter forms. This raised the issue of whether children were just encoding letter forms alone, and if this was the case, whether they mentally represented this information in terms of its visual characteristics of letter forms, not verbal characteristics of sound-based linguistic units.

To address this, the data presented in Chapter 5 was used to investigate whether individual differences in children's verbal memory capacity modulated copying behaviour. Children's secondary encoding times were predicted by their storage capacities in relation to verbal working memory, but not spatial working memory. This suggested that children maintained a mental representation of text in terms of its verbal, not visual form.

Next, as presented in Chapter 6, the aim of Experiment 3 was to further examine the linguistic nature of the information that children encode and mentally represent in relation to subword units. If children encode letter forms and go beyond these letter forms in terms of some verbal characteristics, but not to the extent of a whole word, syllable units might be functional partial word representations. In initial encoding, findings indicated that children did activate syllable units. In contrast, syllable units were not always activated during secondary encoding, and gaze lift locations suggested that children's piecemeal production did not always build up in

syllable-by-syllable units. Instead of mentally representing the encoded information in terms of syllable units, children could have stored a representation of letters either as single letter sounds, or other subword units.

Presented in this last experimental chapter, the final study aimed to investigate whether children's mental representation and production was based on single letter and multi-letter subword units, and assess whether there were differences between children in the extent to which a syllable was a functional unit in piecemeal written production. To address these points, an individual differences perspective was applied in the research presented in Chapter 7, with two key questions:

1) Did children mentally represent text over repeated cycles of encoding by using verbal short term or verbal working memory? As will be outlined below, this could inform the extent to which children relied on mental representations of single letter or multi-letter units.

2) Did children's reading abilities and verbal working memory capacities modulate the extent to which text was consistently produced in syllable-by-syllable units? As will be outlined below, this could inform the extent to which syllable units are functional partial word representations.

The next sections in the introduction will address these two questions in turn. First, there will be a description of verbal short term and verbal working memory, and how children might rely on each mechanism to maintain mental representations of text. Second, there will be a discussion of ideas about how individual differences in relation to the copier might modulate the functionality of syllable units during word copying.

7.1.1 Short term and working verbal memory as mechanisms for maintaining a mental representation of text.

From the findings of the contribution of individual differences in verbal working memory capacity to children's secondary encoding times reported in Chapter 5, there is evidence to reason that children mentally maintain a verbal representation of printed text during copying of isolated words. There are two cognitive mechanisms by which verbal mental representations can be temporarily held in a mentally accessible state (Baddeley, 2000): short term memory and working memory.

Conceptualising short term and working verbal memory. When discussing the differences between short term and working memory, Cowan (2008) ultimately concluded that there was no definite answer, as researchers used the term working memory to refer to similar, but not identical, cognitive operations. However, looking at

the ways in which researchers have conceptualised short term and working memory, Cowan identified the focusing of attentional mechanisms as a key point that differentiated the two.

Short term memory could be described in relation to the ideas of Atkinson and Shiffrin (1968), in that short term memory enables a limited amount of information to be temporarily held in an accessible state. Working memory could be said to relate to the planning and carrying out of behaviour, described by Miller, Galanter, and Pribram (1960). Miller et al. suggested that working memory might include temporary storage, but also engage other processing mechanisms to help make use of short term memory. One of these mechanisms is attentional control in relation to managing maintenance and retrieval of information (Unsworth & Engle, 2007). In particular, Unsworth and Engle argued that to overcome automatic tendencies in behaviour, individuals engaged mechanisms of attentional control in working memory. In addition, these mechanisms enabled individuals to maintain an accessible representation of new information, discriminate task relevant and irrelevant information, and retrieve a representation of task relevant information.

Cowan (2008) further suggested that working memory might involve consciously holding a subset of information from short term storage in a focus of attention. Then, individuals could impose structure on the subset of items held in focus from short term memory. Cowan refers to this in relation to Miller's concept of *chunking*, grouping together smaller units of information into an organised representation of a multi-item larger unit (Miller, 1956). For instance, grouping representations of individual letter sounds into a structured linguistic unit, such as a syllable.

7.1.2 Mentally representing printed text in verbal memory.

In relation to maintaining a mental representation of printed text, both short term memory and working memory have been suggested to be involved (Swanson & Berninger, 1996). Critically, short term and verbal working memory are said to contribute independently to different processes involved in cognitively processing printed text, within the context of a reading task. Swanson and Berninger argued that low-order surface aspects involved in reading (such as identifying letters) were related to accessing a phonological code from short term memory. High-order complex aspects involved in reading (such as integrating information and comprehension) required executive functioning from working memory.

The key study they used to support their ideas about low-order aspects in relation to short term memory is that of Salamé and Baddeley (1982). Salamé and Baddeley demonstrated that recall of visually presented information stored in short term memory reflected the use of a phonological code. When compared to typical performance on recall of a sequence of visually presented digits, participants made more errors when auditory noise was presented at the same time as the visual digits. Importantly, participants made more errors when recalling a 9-digit sequence presented with phonologically similar non-digit words made up of the same phonemes as the digits (eg. the spoken words “*fix*”, “*heaven*”, “*fate*” presented alongside visual digits of 6, 7, 8) compared to conditions with non-phonologically similar words (“*tennis*”, “*jelly*”, “*tipple*”) and conditions with other digits (eg. “*one*”, “*two*”, “*three*”, presented alongside visual digits of 6, 7, 8). The central finding was that recall was sensitive to interference from individual phonemes, not phoneme sequences. Salamé and Baddeley concluded that phonological information was stored at the level of individual phonemes in short term memory.

To support the idea that high-order aspects of reading relied on working memory, Swanson and Berninger highlighted the work of Cantor, Engle, and Hamilton (1991), who showed how verbal working memory capacity correlated with performance on measures of complex reading comprehension. In addition, Daneman and Carpenter (1980) showed that working memory capacity correlated with accuracy of identifying syntactically ambiguous information, such as the referent of pronoun in a passage. Even though children’s sentence comprehension may not always be as accurate as that of adults’ (Paterson, Liversedge, Rowland, & Filik, 2003), between children, working memory capacity has still been shown to facilitate accurate reading comprehension. For instance, 7-8 year old children who have higher verbal working memory capacities also perform better in tasks that involve comprehending and integrating information, such as identifying conflicting and anomalous information within a short story (Cain, Oakhill, & Bryant, 2004).

7.1.3 How might children rely on verbal short term memory during word copying?

In relation to a word copying task, one way in which children could mentally represent text in verbal memory is in terms of individual letter sounds. To do this, children would visually encode letter forms, and then temporarily activate a

representation of corresponding letter sounds associated with the recognised letter forms in short term memory storage.

In this case, it would be expected that children who could mentally represent more letter sounds in short term memory would encode and mentally represent a greater amount of letter sounds on each encoding episode, and so copy at a faster rate. Indeed, this is what Swanson and Berninger (1996) found when they asked 10-12 year old children to copy as much of a short story as possible in 90 seconds. The number of words the children accurately copied correlated with their verbal short term memory, but not verbal working memory. With this finding, Swanson and Berninger then concluded that copying, which did not involve higher order generation of ideas and gist, relied to a greater extent on short term, not working memory.

In turn, if copiers maintained a mental representation of the text in short term memory (as shown by Swanson & Berninger), and items in short term memory are stored in terms of individual phonemes (as in Salamé & Baddeley), then it should follow that copiers mentally represented printed text in individual phonemes during a word copying task. In a large scale study that aimed to provide norms for verbal short term storage capacity of 1112 children aged 4-10 years old, Orsini et al. (1987) reported that 8 year old children could hold 5 single digits in their verbal short term memory. Accordingly, when Bosse, Kandel, Prado, and Valdois (2014) asked 8 year old children to make a written copy of a visually presented short story, they found that children tended to write 4-5 letters between each gaze lift in repeated cycles of encoding and production. As the number of letters maintained throughout written production matches up with the norms of short term storage capacity, it might have been that the children in Bosse et al. stored information in terms of single letters.

In contrast, when Grabowski, Weinzierl, and Schmitt (2010) asked 8 and 10 year old children to copy as much of a paragraph as possible in 120 or 90 seconds (younger children were allowed more time), they found that neither verbal short term nor verbal working memory directly correlated with the number of characters children copied. This lack of a reliable correlation was found irrespective of whether children copied meaningful text (*Thomas spielt auf dem Gehweg*) or consonant strings (*tjxggl pgkkfkq dtd rtt mpwdfv*) that were expected to be mentally represented in terms of individual phonemes in short term memory. So far, it is not clear how consistently children mentally represent text in terms of individual letter sounds in a copying task, and whether they rely on short term memory for this mental representation.

7.1.4 How might children rely on verbal working memory during word copying?

Instead of using short term memory, another way in which children could maintain a mental representation of text during copying is by using working memory. In relation to a word copying task, it might be that children visually encode letter forms, and then temporarily activate a representation of corresponding letter sounds associated with the recognised letter forms in short term memory. Then, copiers might cognitively process this information beyond stored letter sounds, focusing on a subsection of this temporarily activated representation in the way described by Cowan (2008). If copiers impose organisation on the focused subset of information, such as structuring the individual letter sounds in terms of a syllable unit, or another linguistic unit, this would involve working memory storage.

This is how text was expected to be mentally represented from the outset of the Thesis, and 2 key results from Experiment 1 are in line with the idea that secondary encoding processes might rely on mechanisms of attentional control and concurrent processing that are conceptualised to be part of working memory, not short term memory.

1) In Experiment 1, the hallmark effect of word frequency as an indicator of whole word processing was not present in secondary encoding times. This suggested that children were not engaging in lexical processing, an operation which is said to be automatic (Stanovich, 2000), but can be suppressed due to task demands (Bub et al., 2006). In relation to Unsworth and Engle's (2007) ideas about mental representation outlined above, working memory is engaged when individuals override automatic response tendencies. If children override processing of word units in order to encode and mentally represent partial word units, they should rely to a greater extent on working memory than short term memory.

2) Patterns of data in Experiment 1 indicated that children needed gaze lifts about half of the time during copying. After making a gaze lift, children produced only letters that had not been written before the gaze lift; they did not re-write an entire copy of the word. In order to do this, it is likely that during secondary encoding episodes, children integrated the representation of their written copy with the reference model, deciding which letters needed to be encoded in readiness for written production. This is not the high-order semantic integration that Swanson and Berninger (1996) suggested to be involved in reading. However, the decision of re-encoding particular letters would involve integrating two conflicting representations of text (the written copy and the

reference model), and as seen in Cain et al. (2004), integrating text relies on working memory. This is also in line with Unsworth and Engle's (2007) ideas that working memory is used to discriminate task irrelevant information (such as the letters already written) and retrieve task relevant information (such as the letters yet to write). Together with Cowan's (2008) ideas that working memory is involved in mentally updating task progress, these concepts create a platform for suggesting that children's secondary encoding processes would involve working memory.

So far, the copying literature looking at the relationship between verbal working memory and copying performance has only looked at the measure of the number of characters (Grabowski et al., 2010) or words (Swanson & Berninger, 1996) written in a time-limited paragraph copying task. Both of these studies did not find a reliable relationship between verbal working memory and copying performance. In agreement, the individual differences data in Experiment 1, reported in Chapter 5, showed that neither verbal storage capacity nor verbal concurrent processing capacity predicted written production duration. Children with better verbal memory did not write words faster than children with poorer verbal memory. In contrast, both verbal working storage and verbal working processing capacities predicted secondary encoding times. Children engaged in processes of organising the encoded representation in terms of linguistic units using working storage, and mentally updated task progress by integrating information using working processing. These effects were observed during measures reflecting the encoding, not written production, sub-processes of a copying task. It might have been that measures used by Grabowski, and Swanson and Berninger were not sensitive to individual differences in copying performance as a result of differences in encoding behaviour.

Thinking about the research presented above about the contribution of short term and working memory to children's copying performance, there is not a consistent picture of children preferentially relying on short term or working memory. Rather than only relying on short term or working memory, it might be that children use a flexible range of linguistic units in their mental representations at different time-points during a word copying task. If this is the case, then children might rely on both short term and working verbal storage.

7.1.5 Individual differences in the efficiency with which children cognitively process information during a copying task.

In Chapter 5, the research looked at how individual differences in reading ability, spatial working memory and verbal working memory capacity predicted copying behaviour. Results in relation to reading ability suggested that cognitive operations in encoding and production were more efficient in children with higher word reading ages than children with lower word reading ages. Children with higher reading ages needed less secondary encoding time, and less gaze time associated with written production. Recall that children with higher reading ages were suggested to have more specified letter position coding mechanisms (as drawn from the lexical tuning hypothesis in Castles et al., 1997). It was suggested that extracting precise letter position information in relation to the point within the reference model at which children needed to start re-encoding letters. Children with higher reading abilities engaged in more time efficient position coding, and so needed less secondary encoding time. Also recall that children with higher reading ages were suggested to have more specified spelling representations (as drawn from the lexical quality hypothesis in Perfetti & Hart, 2002). It was suggested that specified spelling representations contributed towards more time-efficient programming of writing events by specifying the correct selection of allographs (in the context of Van Galen's 1991 model of writing), in order to programme writing events for each letter form.

Yet, results surprisingly did not provide support for the idea that children with higher reading ages could mentally maintain a larger amount of information between encoding and production. Recall that it was suggested that reading ability constrained articulation rates, which were suggested to determine the speed at which information could be rehearsed in order to prevent forgetting (Kail, 1997). However, children with higher reading ages did not need a greater number of gaze lifts, suggesting that they forgot just as much information as children with lower reading ages. The current study presents opportunity for these findings to be re-tested so as to thoroughly assess the contribution of individual differences to children's copying performance.

Furthermore, if children with higher reading ages have specified spelling representations of large linguistic units, as suggested in Chapter 5 in line with Perfetti and Hart's (2002) lexical quality hypothesis, individual differences might determine the extent to which syllables are functional units over piecemeal written production. The syllable is the largest sound-based unit smaller than a word, and it might be that children with lower reading ages do not yet hold specified representations of such large

units, and instead operate using smaller units of production. This is a similar argument to that outlined by Kandel and Valdois (2006a) in relation to the units of production used by Spanish and French children. They said that due to the differences in the orthographic grain size of the language, Spanish children would develop specified representations of spelling at a faster rate than French children. Consequently, Spanish children's production would be based on larger units; children would make gaze lifts less often, and produce larger linguistic units between each gaze lift. Indeed, this is what they found, as Spanish children's production was most often organised in terms of word units, then syllable, then letter units; French children's production was most often organised in terms of letter units, then syllable, then word units.

In relation to the current study, English children with higher reading ages should be more likely to organise production in terms of syllable or letter units than word units. As outlined earlier in the context of Houghton and Zorzi's (2003) model of spelling, spelling representations are structure in terms of syllable units and constituent syllable units such as the syllable onset, rime and coda. Because children with higher reading ages have a greater number of specified spelling representations of large linguistic units, they should primarily structure spelling programming events in terms of syllable units. Children with lower reading ages may not have developed specified spelling representations of as many syllable units, so they should primarily structure smaller spelling programming events in terms of constituent components of a syllable unit. In this case, reading ability should determine the extent to which syllable units are functional cues for gaze lifts over repeated production episodes.

Reading ability might not be the only characteristic of the copier to determine the extent to which children produce piecemeal copies of words syllable-by-syllable. If children mentally represent information in working memory in terms of a structured linguistic unit (as drawn from the ideas of Cowan, 2008), then this unit will form the phonetic input information for the basis of programming spelling for orthographic output (as drawn from Houghton & Zorzi's model, 2003). Verbal working memory capacity should then limit the amount of information can form the basis of the phonetic input. Compared to age-based norms, children with relatively small working memory capacities should only be able to maintain small linguistic units, whereas children with larger working memory capacities should be able to maintain larger linguistic units. It might be that only children with relatively large working memory capacities can maintain a mental representation of syllable units in readiness for and during written production, so systematically make gaze lifts at syllable boundaries to a greater extent

than children with smaller working memory capacities. The nature of the linguistic unit that children mentally represent may determine the functionality of a syllable unit during piecemeal written production.

7.1.6 The current study.

The current study tested the extent to which sub-processes during copying were functionally constrained by individual differences in reading ability and verbal memory capacity. In turn, this will inform about the extent to which children drew on their abilities to encode and store partial word representations of individual letter sounds or multi-letter sounds, in particular, letter sounds grouped in terms of syllable units.

To investigate, the current study examined the extent to which children's reading ability, verbal short term working memory capacity and verbal working memory capacity predicted their secondary encoding and piecemeal written production behaviour. Measures of individual differences in children's reading abilities and verbal memory capacities were collected for the same children as in Experiment 3. These individual differences were used to predict systematic patterns in children's secondary encoding and written production behaviour in relation to the eye tracking data already collected and reported in Experiment 3, Chapter 5. Several predictions were drawn from the conclusions in Chapter 5, and the literature described above. These predictions will be outlined in turn in relation to reading ability, short term verbal memory capacity and working verbal memory capacity, for total secondary encoding time, and then proportion of gaze lifts occurring systematically at syllable boundaries.

If reading ability determines the efficiency of specified letter coding, this will constrain the ease of place-finding during secondary encoding, so reading age should predict total secondary encoding time. As found in Chapter 5, children with higher word reading ages should take less secondary encoding time than children with lower word reading ages. If children store a mental representation of letter sounds, they should maintain this mental representation by using verbal memory. This then leads to the expectation that if letters are stored in individual letter sounds, short term storage capacity will predict secondary encoding time; if letters are stored in terms of a larger linguistic unit, working storage capacity will predict secondary encoding time. As in Chapter 5, children with larger capacities will be able to store a larger amount of information throughout production than children with smaller capacities. These children with larger capacities will therefore take less secondary encoding time, as they should need to re-encode a smaller amount of information during secondary encoding. As well

as verbal storage, working verbal processing capacity should predict secondary encoding time. During secondary encoding, children should engage attentional control (as drawn from Unsworth & Engbert, 2007) in order to mentally update and integrate progress in the written copy with the reference model on return visits to the board. As shown in Chapter 5, children with greater processing capacities should take more secondary encoding time. These children should concurrently process a greater amount of information than children with smaller concurrent processing capacities, so the processes of discrimination of task irrelevant and relevant information should take more time.

After encoding, individual differences are also expected to influence children's written production behaviour. If the results found in Chapter 5 are to be replicated, in comparison to children with lower reading abilities, children with higher reading abilities should need less gaze time associated with written production and shorter written production duration. With regard to gaze lift behaviour in relation to syllable boundaries, if reading ability determines the number of specified spelling representations of large linguistic units (as drawn from Perfetti & Hart, 2002), this will constrain the size of the units in which writing events are programmed (as drawn from Kandel and Valdois, 2006a). Reading age should predict the proportion of gaze lifts that occurred at syllable boundaries. Children with higher word reading ages will programme spelling based on larger units than children with lower word reading ages, so should make a higher proportion of gaze lifts on syllable boundaries. Finally, if working memory capacity determines how much information children can store in readiness for written production, children with larger capacities should consistently be able to store large subword units such as a syllable. Children with larger working memory capacities should be more able to consistently maintain syllable units throughout production than children with smaller working memory capacities, so make a higher proportion of gaze lifts on syllable boundaries.

7.2 Methods

7.2.1 Participants.

Child participants were the same as in Experiment 3, already reported in Chapter 6. To recall, there were 25 children in total aged between 7-8 years old, with a mean age of 8 years, 0 months. Of these 25 children, 24 children completed all tests of reading ability and working memory capacity, so 1 child was excluded in the current study.

7.2.2 Materials and Procedure.

Recall that children had already copied 36 words manipulated for number of syllables, with either 1, 2, or 3 syllable units in each. Children also completed tests of individual differences: 1 test in relation to reading ability; 2 tests in relation to verbal working memory capacity. In the case of multiple testing sessions with an individual child to collect the eye movement data reported in Chapter 6, and the data on individual differences in relation to the current Chapter 7, testing sessions occurred within a maximum of 2 weeks apart.

Reading ability. The Word reading tests, as described in Experiment 2, was used from the reading subsection of the Wechsler Individual Achievement Test (Wechsler, 2005). To recall, the word reading test required children to read aloud from a progressively challenging word list using retrieved word knowledge, resulting in a measure of standardised reading age.

Working memory capacity. Two of the tests in the short form assessment of the Automated Working Memory Assessment (Alloway, 2007) were chosen, as these tests generated measures of children's short term verbal storage capacity, working verbal storage capacity and concurrent verbal processing capacity. These tests provided age-normed standardised measures of verbal memory capacity. The digit recall test provided a measure of short term memory capacity. The listening recall test provided a measure of working verbal storage capacity and a measure of working verbal processing ability under concurrent task demands.

Verbal short term memory: the test of digit recall. In this test, children heard a fixed-number sequence of digits and recalled the numbers in the correct order. To complete a block successfully, children must correctly recall at least 4 sequences out of 6. In each successive block, the amount of numbers in the sequence increased by 1 until a block was not completed successfully, at which point the test ended. Higher digit recall scores indicated a greater storage capacity of verbal information for immediate recall.

Verbal working memory: the test of listening recall. In this test, children heard a series of individual sentences, "apples ride bicycles", and immediately judged whether each sentence was true or false, "false", (requiring concurrent verbal processing). At the end of each series, children recalled the last word of each sentence, in the correct order, "bicycles" (requiring simultaneous verbal storage). In each successive block of 6 trials, the number of sentences in the sequence increased by 1 until a block was not completed successfully with 4 out of 6 correct answers, at which point the test ended.

Higher listening recall scores indicated a greater storage capacity of verbal information at the same time as processing additional verbal information. Higher listening recall processing scores indicated a greater processing capacity of current verbal information at the same time as storing previously presented verbal information.

7.3 Results and Discussion

Linear mixed models were run using the lme4 (Bates et al., 2014) in R, version 3.2.3 for each dependent variable, with the number of syllables as a fixed factor. For each model, polynomial contrasts were used to assess whether there were linear and/or quadratic relationships between conditions. Each model also specified fixed factors of word reading ability, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity. As in Chapter 5, each measure of reading ability and working memory capacity was centred.

For each dependent measure, the model began with the maximal random effects structure as suggested by Barr, Levy, Scheepers, and Tily (2013). If the model with the maximal random effects structure failed to converge, or there were too many parameters to fit the data, as indicated by correlations of 1 or -1 in the random structure, random slopes and correlations between random slopes were removed from the model. Model specifications for the final models resulting from this process can be found in Appendix U.

Summaries of the linear mixed models will first be reported for secondary encoding time, and then for time-based measures of written production. The final section will report gaze lift behaviour during written production in relation to syllable boundaries.

7.3.1 Measures of encoding.

As shown in Table 24, the linear mixed model for children's total secondary encoding times suggested that both the characteristics of the stimuli and the characteristics of the copier predicted how long children spent overall looking at the board during secondary encoding episodes.

Table 24. Summary of LMM model for children’s total secondary encoding times in relation to reading ability and verbal memory capacity on words manipulated for number of syllables in Experiment 3.

		Total secondary encoding time		
		<i>b</i>	SE	<i>t</i>
Number of syllables	Linear relationship	0.14	0.07	1.86
	Quadratic relationship	0.16	0.06	2.51
Reading ability	Reading age	-0.23	0.04	-5.27
	Short term storage	0.01	0.01	2.38
Verbal memory capacities	Working storage	0.03	0.01	1.87
	Working Processing	-0.03	0.01	-1.97

As in Chapter 6, the number of syllables modulated children’s encoding time. In the current chapter, the results in relation to individual differences are more important, and these provided a more complex story than anticipated. In line with predictions, reading age did predict total secondary encoding time, such that children needed less secondary encoding time if they had higher compared to lower reading ages. These findings replicated those found in Chapter 5, in line with the interpretation that reading ability constrained the ease of place-finding during secondary encoding.

Surprisingly, findings in relation to verbal memory were in direct contrast to those found in Chapter 5. While verbal storage did predict secondary encoding time, the direction was opposite to that predicted, such that children with smaller verbal storage capacities needed less encoding time than children with greater verbal storage capacities. In addition, only short term storage capacity, not working storage capacity, predicted secondary encoding time. This finding alone might suggest that children primarily stored a mental representation of the text in terms of individual letters rather than a larger linguistic unit. However, working memory processing capacity significantly predicted secondary encoding time. This suggested that children were engaging in concurrent processing operations that drew on the working memory system during secondary encoding, not simply storing a short term representation of individual letters. Also, the direction of the relationship was in the opposite direction of that expected, such that children with higher working processing capacities spent less secondary encoding time than children with lower working processing capacities.

Working memory processing did not constrain secondary encoding in a similar manner during Experiment 1, reported in Chapter 5, and Experiment 3, reported in the current study.

The pattern of findings in relation to individual differences and total secondary encoding time was not directly comparable between Experiment 3 and Experiment 1. Before presenting results in relation to gaze lift behaviour, next there will be a more systematic breakdown of secondary encoding behaviour in order to characterise this surprising data. There were two clear differences between Experiments 1 and 3 that could have given rise to a differential pattern of findings: the age of the children and the length of the words that were copied. These will be outlined and examined in turn.

Children in Experiment 3 were from a narrower, younger age range than children in Experiment 1. The age of the child determines their reliance on regular gaze lifts, and children who regularly rely on gaze lifts might re-encode information in a different way compared to children who do not regularly need gaze lifts. As discussed in the Introduction in relation to existing published research, age of the child determined regularity of gaze lift behaviour, such that younger children relied on more, and more regular gaze lifts compared to older children. In Experiment 1, the 4 year variance in age range of 7-10 year olds may have resulted in older children relying on gaze lifts to a lesser extent than younger children. In Experiment 3, the 7-8 year olds could be expected to all still need regular gaze lifts. Within this group of children who regularly rely on gaze lifts during copying, there could have been a trade-off between the amount of time spent during secondary encoding and the number of gaze lifts made. When regularly copying with gaze lifts, it might be efficient to only engage in worthwhile re-encoding of the maximum amount of information that can be stored, rather than all the information not yet written. Compared to children with larger capacities, children with smaller storage capacities might be forced to operate over smaller units, encoding less information in each secondary encoding episode and so need more gaze lifts. If this is the case, the data in relation to secondary encoding times might have arisen as a consequence of children with smaller short term storage capacities operating over smaller units, needing a greater number of gaze lifts than children with larger capacities. Children with large short term storage capacities would have needed more time to construct a relatively large single representation of several letters, whereas children with smaller short terms storage capacities needed less time overall, as on each secondary encoding episode, they constructed a relatively less demanding, smaller representation.

This can be tested by assessing the contribution of individual differences in relation to the number of gaze lifts needed in order to copy each word, seen in Table 25.

Table 25. Summary of LMM model for individual differences in children in relation to the number gaze lifts for secondary encoding episodes on words manipulated for number of syllables in Experiment 3.

		Number of gaze lifts		
		<i>b</i>	SE	<i>t</i>
Number of syllables	Linear relationship	0.08	0.05	1.48
	Quadratic relationship	0.10	0.05	2.13
Reading ability	Reading age	-0.14	0.03	-4.80
	Short term storage	0.00	0.00	1.03
Verbal memory capacities	Working storage	0.01	0.01	0.76
	Working Processing	-0.01	0.01	-1.67

As reported in Chapter 6, the number of syllables modulated the number of gaze lifts required. In addition, reading age significantly predicted the number of gaze lifts, such that children with higher reading ages made fewer gaze lifts than children with lower reading ages. Most importantly, there was no evidence to support a relationship between the number of gaze lifts, and either short term or working memory storage capacity. Children who were able to store a larger amount of information made a similar number of gaze lifts as children who were only able to store a relatively smaller amount of information. This means that the findings in relation to total secondary encoding time cannot be explained by a potential trade-off between secondary encoding time and the number of gaze lifts needed.

Moving on to the second clear difference between Experiments 1 and 3, the word length varied between experiments. Words were made up of either 4 or 8 letters in Experiment 1, and 6 or 7 letters in Experiment 3. In Experiment 1, children needed gaze lifts on approximately 50% of words, and longer words contributed a greater amount of secondary encoding data than shorter words. In Experiment 3, the length of the stimuli resulted in a comparatively higher likelihood of gaze lifts on approximately 70% of words. The increased amount of data from the stimuli in Experiment 3 that were controlled for word length provided an opportunity that was not offered by the data in Experiment 1. Secondary encoding time could be split down from cumulative total

secondary encoding time into secondary encoding time on individual secondary encoding episodes for each successive return visit to the board. Also recall that there was less variation in the number of gaze lifts children needed in Experiment 3 than Experiment 1. In Experiment 1, children needed twice the number of gaze lifts on 8 letter words compared to 4 letter words, so it was not uncommon for children to require at least 4 gaze lifts, and sometimes 7 gaze lifts in a single trial. In Experiment 3, children typically made 2-3 gaze lifts, and it was rare for children to make more than 3 gaze lifts. The next results focus on whether individual differences predicted secondary encoding time on the first, then the second, then the third return visit to the board after the initial encoding episode.

It might be that children stored a different sized unit of information over successive return visits. This can be likened to the way in which children programme successive writing events. As outlined in the Introduction when discussing existing copying research, between-letter pauses in children's production of Catalan words suggested that they programmed 2 successive writing events for a single word. Importantly, there was a different amount of information between the writing events, with the first writing event programming a greater number of letters than the second. It might be the case that in the current study, over successive secondary encoding episodes, children also re-encoded a larger unit of information after the first return visit. If this occurred, the surprising findings in relation to total secondary encoding may have been driven by only one of the 3 secondary encoding episodes. In this episode, limitations in verbal memory capacity might determine the size of unit that was re-encoded. Compared to children with smaller storage capacities, children with greater storage capacities would operate over larger units, and so require more secondary encoding time on an individual secondary encoding episode. Children with larger short term memory capacities would spend more secondary encoding time than children with smaller capacities as they were encoding a greater amount of information. To test this, total secondary encoding data were systematically split into the amount of encoding time spent upon each successive gaze lifts in order to assess whether individual differences contributed differentially to successive return visits for secondary encoding. Table 26 shows the model summary in relation to the first gaze lift.

Table 26. Summary of LMM model for individual differences in children in relation to the amount of secondary encoding time spent on the first return encoding visit on words manipulated for number of syllables in Experiment 3.

		First return encoding time		
		<i>b</i>	SE	<i>t</i>
Number of syllables	Linear relationship	0.06	0.04	1.46
	Quadratic relationship	0.02	0.05	0.40
Reading ability	Reading age	-0.08	0.04	-2.06
	Short term storage	0.01	0.01	2.05
Verbal memory capacities	Working storage	0.01	0.01	0.79
	Working processing	0.00	0.01	-0.15

Irrespective of the number of syllables, children spent a similar amount of encoding time on all words on the first return visit after a gaze lift. This does not support the idea that syllable units were re-activated during this encoding visit. Reading ability was also a reliable predictor of encoding time, such that children with higher reading ages spent less encoding time than children with lower reading ages. Most importantly, short term storage, but not working memory storage predicted how long children spent encoding on the first return visit. Children with lower capacities spent more encoding time compared to children with higher capacities. This suggests that children who could store a large amount of individual letter sounds encoded more information in the first return visit than children who could not store as many individual letter sounds.

The linear mixed models for the second gaze lift are summarised in Table 27.

Table 27. Summary of LMM model for individual differences in children in relation to the amount of secondary encoding time spent on the second return encoding visit on words manipulated for number of syllables in Experiment 3.

		Second return encoding time		
		<i>b</i>	SE	<i>t</i>
Number of syllables	Linear relationship	0.12	0.05	2.33
	Quadratic relationship	0.16	0.07	2.40
Reading ability	Reading age	-0.07	0.04	-1.67
	Short term storage	0.01	0.01	1.41
Verbal memory capacities	Working storage	0.02	0.01	1.90
	Working processing	-0.02	0.01	-1.66

After the first gaze lift, children programmed at least one writing event, but often needed another gaze lift before completing written production. On this second return visit for secondary encoding, children activated syllable units, taking more time for 2 compared to 1 and 3 syllable words. Individual differences did not modulate children's secondary encoding time. Children spent a similar amount of encoding time irrespective of reading age, and both short term and working memory capacity. Note that unlike the first return visit, on the second return visit in which encoding times indicated that syllable units were activated, all children appeared to encode a similar amount of information. The linear mixed model for the third gaze lift can be seen in Table 28.

Table 28. Summary of LMM model for individual differences in children in relation to the amount of secondary encoding time spent on the third return encoding visit on words manipulated for number of syllables in Experiment 3.

		Third return encoding time		
		<i>b</i>	SE	<i>t</i>
Number of syllables	Linear relationship	-0.10	0.07	-1.53
	Quadratic relationship	0.07	0.08	0.88
Reading ability	Reading age	-0.03	0.06	-0.46
	Short term storage	0.01	0.01	1.81
Verbal memory capacities	Working storage	0.03	0.01	2.69
	Working processing	-0.03	0.01	-3.13

On this third return visit for secondary encoding, the number of syllables did not influence encoding time. However, individual differences in verbal memory did modulate how long children spent looking at the board. Unlike the pattern of individual differences for the first return encoding visit, only working memory, not short term memory predicted secondary encoding time. There were also differential effects of working storage capacity and working processing capacity. Children with greater working storage capacities took more time than children with smaller capacities. It may have been that these children with larger working storage capacities were encoding a relatively larger linguistic unit after the third gaze lift. Also, children who could concurrently process a greater amount of information needed less encoding time on the third return visit than children with smaller concurrent processing capacities, perhaps because their concurrent processing was more resource-efficient, so time-efficient.

7.3.2 Time-based measures of written production.

The following section of results reports findings in relation to time-based measures of written production. For comparison with data previously presented in the Thesis, recall that in Chapter 5, individual differences in children's reading ability, but not verbal working memory capacity, predicted performance in relation to written production. In both measures of gaze time associated with written production, and written production duration, children with higher reading abilities were expected to need less time than children with lower reading abilities. As in Chapter 5, measures of gaze time associated with written production were suggested to incorporate the planning and

execution of spelling processes associated with written production. Written production duration was suggested to reflect motor processing associated with executing writing events. The linear mixed model for children’s gaze time associated with written production is reported in Table 29, and written production duration in Table 30.

Table 29. Summary of LMM model for individual differences in children in relation to children’s gaze time associated with written production on words manipulated for number of syllables in Experiment 3.

		Gaze time associated with written production		
		<i>b</i>	SE	<i>t</i>
Number of syllables	Linear relationship	0.04	0.06	0.65
	Quadratic relationship	-0.04	0.05	-0.89
Reading ability	Reading age	0.02	0.05	0.36
Verbal memory capacities	Short term storage	0.00	0.01	-0.51
	Working storage	-0.02	0.02	-1.12
	Working processing	0.02	0.01	1.07

There were no significant predictors of how much time children spent looking at their written copy, either in relation to experimentally manipulated number of syllables, or individual differences. Irrespective of their reading age or verbal working memory capacity, children all needed a similar amount of gaze time associated with written production.

Table 30. Summary of LMM model for individual differences in children in relation to children's written production duration on words manipulated for number of syllables in Experiment 3.

		Written production duration		
		<i>b</i>	SE	<i>t</i>
Number of syllables	Linear relationship	0.03	0.04	0.82
	Quadratic relationship	0.03	0.04	0.63
Reading ability	Reading age	-0.07	0.04	-1.70
	Short term storage	0.00	0.01	0.71
Verbal memory capacities	Working storage	0.00	0.01	-0.37
	Working processing	0.00	0.01	0.29

As with gaze time associated with written production, the measure of written production duration was not sensitive to any systematic differences either in relation to characteristics of the stimuli or characteristics of the children in relation to reading ability and verbal memory capacity.

7.3.3. Measures of gaze lift behaviour.

The final section of results reports findings in relation to the location of gaze lifts with regard to syllable boundaries. Recall that these results aimed to assess whether the syllable unit was functional throughout written production to a similar extent for all children. Table 31 shows the model summary in relation to the proportion of gaze lifts that occurred at syllable boundaries, out of all the gaze lifts made on each word.

Table 31. Summary of LMM model for individual differences in children in relation to the proportion of gaze lifts that occurred at syllable boundaries on words manipulated for number of syllables in Experiment 3.

		Proportion of gaze lifts on syllable boundaries		
		<i>b</i>	SE	<i>t</i>
Number of syllables	Linear relationship	0.20	0.03	7.28
	Quadratic relationship	-0.12	0.03	-4.25
Reading ability	Reading age	0.10	0.02	5.88
	Short term storage	0.00	0.00	-2.33
Verbal memory capacities	Working storage	-0.02	0.00	-3.44
	Working processing	0.01	0.00	3.11

As reported in Chapter 6, the extent to which children produced words syllable-by-syllable depended on the characteristics of the word. Children made a higher proportion of gaze lifts on a syllable boundary as the word contained an increasing number of syllable boundaries. However, children made the highest proportion of gaze lifts systematically on a syllable boundary on 2 syllable words compared to 1 and 3 syllable words. Most importantly, both reading ability and verbal memory capacity predicted the systematicity of gaze lifts occurring on a syllable boundary for individual children. These findings clearly showed that even within a narrow age range of children, who have a similar amount of print experience, individual differences in their cognitive capacities changed the way in which children operated during piecemeal written production during a word copying task.

Children with relatively higher reading ages were predicted to make a higher proportion of gaze lifts on syllable boundaries compared to children with lower reading ages. Indeed this was what was found, and this suggests that these children with relatively higher reading ages were operating with a greater number of specified representations of subword syllable units.

Verbal memory capacities also predicted children's gaze lift behaviour, but the pattern of effects was not as expected. Recall that children maintaining a mental representation by using short term memory were expected to store individual letter units, and as such these should not have correlated with systematic syllable boundaries. Also recall that children using working memory to maintain a mental representation

were expected to store linguistic subword units larger than an individual letter. When using working memory, children with larger capacities were expected to rely on syllable units, the largest subword unit, to a greater extent than children with smaller capacities. On the contrary, both short term storage capacity and working storage capacity predicted the proportion of gaze lifts on a syllable boundary in a similar manner. Compared to children with greater storage capacities, children with smaller storage capacities made a higher proportion of gaze lifts on syllable boundaries. In addition, children who could concurrently process a greater amount of information made a higher proportion of gaze lifts on syllable boundaries than children with smaller concurrent processing capacities.

7.4 General Discussion

The current study set out to investigate the extent to which particular sub-processes could be predicted by individual differences in reading abilities and verbal memory capacities when children make a handwritten copy of a word. The first key question concerned the extent to which children mentally represented text over repeated cycles of encoding by using verbal short term or verbal working memory. If children stored representations in the form of individual letter units, it should be the case that short term storage capacity modulated encoding times. If children stored multiple letters in the form of a linguistic unit, it was expected that working memory capacity should predict encoding times. Findings in relation to encoding times suggested that both short term storage and working storage capacities predicted how long children spent during individual secondary encoding episodes. However, this was not consistent across all secondary encoding episodes. It appears that children mentally represented individual letter units during the first return visit, and stored a mental representation of a linguistic unit during the third return visit. The second key question concerned whether children's reading abilities and verbal working memory capacities modulated the extent to which text was consistently produced in syllable-by-syllable units. The results showed that syllables were functional units for some words, but some children systematically produced in terms of syllable units more consistently than other children. Children with higher reading ages had a higher proportion of gaze lifts on syllable boundaries than children with lower reading ages, and this can be interpreted in the context of the development of specified spelling representations of particular linguistic units. Verbal memory capacity was also a significant predictor, but these findings were more complex and contradicted expectations that children with greater verbal storage capacities would

produce in syllable-by-syllable units to a greater extent than children with smaller verbal storage capacities. These findings will be discussed in turn after a comparison of the current findings looking at the role of individual differences in Experiment 3, and the previously presented findings looking at the role of individual differences in Experiment 1, reported in Chapter 5.

7.4.1 Comparison of results between Experiment 3 and Experiment 1.

While there was some evidence in the current study to suggest that children engaged verbal memory to mentally represent information, perhaps the most surprising aspect of the current study was the lack of replication of findings reported in Chapter 5 on the data collected in Experiment 1. Foremost, it should be recognised that the sample sizes were unusually small for an investigation of individual differences. These small sample sizes mean that some apparently reliable effects might indeed be spurious, or that unreliable predictors may have been underpowered. The discussion will return to this point in the final overview of this Chapter. However, there were differences, in the age of the children and the characteristics of the stimuli, between the Experiments that could have contributed towards a dissimilar pattern of findings in relation to individual differences. These patterns will be described for encoding, production and gaze lift behaviour.

To recall, Experiment 1 investigated how 7-10 year old children made a handwritten copy of individually presented, 2 syllable words that were orthogonally manipulated for word length (either 4 or 8 letters) and word frequency (either high or low frequency). Individual differences of reading ability, pseudoword decoding ability, spatial working memory and verbal working memory were included. Experiment 3 investigated how 7-8 year old children copied 6-7 letter words manipulated for number of syllables (either 1, 2 or 3 syllables). Individual differences of reading ability, short term memory and verbal working memory were included.

Comparison of children's encoding behaviour. The key findings in relation to the encoding sub-process in Experiment 1 were that individual differences in reading ability and verbal working memory predicted the total amount time children spent looking at the board during secondary encoding. In Experiment 3, the negative relationship between reading ability and secondary encoding time was replicated. This provided support for the interpretation outlined in Chapter 5, that children with relatively higher reading ages had also developed more efficient letter position encoding (in the context of the lexical tuning hypothesis by Castles et al., 2007), which enabled

them to find their place within a word and encode specific letters efficiently during secondary encoding. However, findings from Experiment 1 in relation to working memory predicting total secondary encoding times were not replicated. In Experiment 1, children with greater working storage capacities needed less total secondary encoding time than children with smaller capacities; children with greater working processing capacities needed more total secondary encoding time than children with smaller capacities. There was no evidence to suggest that children relied on working memory in total secondary encoding times from Experiment 3. Yet, there was a reliable relationship between short term verbal memory (which was not examined in Experiment 1) and total secondary encoding time, which suggested that children were consistently maintaining a verbal representation of text. These differences appear to suggest that overall during secondary encoding episodes, children in Experiment 1 preferred to store information in terms of linguistic units, whereas children in Experiment 3 preferred to store information in terms of individual letters. This difference could have arisen as a consequence of variation in children's age between the Experiments. As children acquire knowledge of a larger range of linguistic units through developing print experience, they may recognise a greater number of multi-letter subword units. In turn, this might reflect developmental differences within children in the extent to which particular subword units are functional during word copying. Indeed, this would be in line with research by Kandel and Valdois (2006a) outlined in the Literature Review. Their first grade 6 and 7 year old children produced French words most often in letter-by-letter units, whereas second grade 7 and 8 year olds used larger linguistic units, being more likely to produce words syllable-by-syllable, or in terms of other (unspecified) multi-letter subword units, than letter-by-letter units. It might be that children copying in English develop a preference for storing linguistic units at a relatively later age than children copying in French, in a similar manner in which children copying in French show a preference for producing in larger linguistic units at later age than children copying in Spanish (as seen in Kandel & Valdois). This is not the only instance throughout this Thesis in which an estimation of cross-linguistic differences was identified. This clearly highlights a benefit for experimental confirmation in order to either falsify or support ideas in order to develop a universal framework of the cognitive processing underlying children's behaviour in word copying task.

Comparison of children's production behaviour. As in encoding times, there was an effect of reading ability seen in time-based measures of production in

Experiment 1. Compared to children with lower reading ages, children with higher reading ages needed less gaze time associated with written production, and shorter written production durations. This was interpreted in the context of the specificity of their spelling representations associated with reading ability (Perfetti & Hart, 2002), that may have facilitated efficient planning of spelling and execution of written production. However, there were no systematic differences in either measure of children's written production behaviour in Experiment 3 as a consequence of reading ability. Again, this could be explained in relation to the narrower age range, and is in line with previous research. In their analysis gained from digitised pen movements of how long children spent planning and executing each letter of a word, Kandel and Valdois (2006a) also found no effect of school grade, comparing 6-7 year olds and 7-8 year olds. This suggests that children are still developing efficient planning and execution during written production, with no observable time gains during written production in a copying task in a 2 year period. As such, in the current studies it is likely that there was enough variance in written production behaviour between 7-10 year old children to drive observable effects in Experiment 1, but not between children of 7-8 years old in Experiment 3.

Comparison of children's gaze lift behaviour. The analysis of gaze lift behaviour was more thorough in the data from Experiment 3 than Experiment 1, owing to the increased likelihood of gaze lifts, the word length control and the control of subword structure. Nevertheless, it was appropriate to report the number of gaze lifts for both Experiments. In Experiment 1, it was surprising that reading ability did not predict the number of gaze lifts. Differences in the occurrence of forgetting between children of different reading ability were expected based on the idea that reading ability determines the speed at which sub-vocal articulation happens during verbal rehearsal (Kail, 1997). In this way, reading ability constrains how efficiently the articulatory loop operates. In order to maintain a verbal mental representation, children engaged in a process of rehearsal needed to refresh decaying memory traces (as outlined within the context of Baddeley's model of working memory, Baddeley & Hitch, 1974; Baddeley, 2000, 2003). If children could sub vocally articulate phonetic information at a faster rate, there would be less time between rehearsals for information to decay, so a greater amount of information was maintained after encoding throughout production. Children with higher compared to lower reading abilities should have employed faster rates of verbal rehearsal when they maintained a mental representation, but there was no reliable effect. As most gaze lifts were made on the long, 8 letter words, it could have been that

maintaining all 8 letters was beyond the capabilities of the children with the fastest rehearsal rates, leading to floor effects. In that case, effects might be evident in a copying task in which children were required to rehearse a smaller amount of information. In Experiment 3, the words were 1-2 letters shorter, and in this study, children with higher reading ages did need fewer gaze lifts than children with lower reading ages. This finding indicated that children were relying on mechanisms of phonological rehearsal in order to store a representation throughout written production. However, mechanisms of rehearsal have been proposed to be involved both in short term memory storage (Atkinson & Shiffrin, 1968) and working memory storage (Baddeley & Hitch, 1974). Consequently, these findings only clarify that the mental representation children hold is of a verbal nature, rather than specify which mechanism of either short term or working memory children employ in maintenance of the representation. Next, discussion will turn to findings that addressed each of the key research questions in Experiment 3.

7.4.2 Did children mentally represent text over repeated cycles of encoding by using verbal short term or verbal working memory?

To further characterise surprising findings of Experiment 3 in more detail, total encoding time was divided into individual secondary encoding episodes in order to find out whether children consistently relied on short term verbal memory during all secondary encoding episodes. Individual episodes of secondary encoding times were predicted by both verbal short term and verbal working memory capacities, but the pattern was not consistent over successive episodes of secondary encoding. Verbal short term storage capacity predicted secondary encoding time on the first return visit, but not the second or third visits. If, as Salamé and Baddeley (1982) suggest, information is stored in short term memory in terms of individual letters, this means that children's encoding on the first return visit operated on a letter-by-letter level. This effect of short term storage capacity in the first return visit likely drove apparent significant effects in total secondary encoding, and this highlights the importance of considering individual secondary encoding episodes in further research. Yet, the direction of the relationship between short term storage and secondary encoding time was not as anticipated. In line with the argument by Swanson and Berninger (1996), children with greater short term storage capacities were expected to need less secondary encoding time because they would be more efficient at accessing the phonological code for each letter form. An alternative explanation is that children with greater storage capacities spent more time

than children with smaller storage capacities on the first return visit because they were encoding a greater amount of information.

On the second return visit there were no reliable effects in relation to individual differences. This was surprising, as the findings in relation to the number of syllables modulating encoding time suggested that children did activate syllable units. It then seems anomalous that, once activated, children did not then maintain a mental representation of the syllable unit. As outlined in the introduction, Cowan (2008) described working memory as consciously holding a subset of information from short term storage in a focus of attention. In this case, it seems likely that having activated syllable structure, children had already imposed the structure of the linguistic unit on the representation, so should be storing this representation by using working memory. Therefore, it is odd that individual differences in working memory storage or processing capacity did not predict secondary encoding time on the second return visit. That the experimental manipulation results in observable effects and the individual differences variables do not may indeed suggest that the study would benefit from more statistical power. The individual differences results are perhaps the most confusing so far, although they do provide an estimation of factors that modulate copying performance. However, further research from an experimental perspective would be a more fruitful approach to clarifying the role of working memory during a copying task.

Even so, verbal working storage capacity did predict reliable effects on the third return encoding visit. This suggested that children's encoding on the third return visit focused on a linguistic subword unit (not necessarily a syllable unit) using the working memory mechanisms as described by Cowan (2008). In turn, this means that children's secondary encoding operated on linguistic units larger than a single letter in this encoding visit. Similar to the direction of effects for short term memory storage capacity, the direction of effects for working memory storage capacity were in the opposite direction to that anticipated. Children with greater working storage capacities needed more secondary encoding time on the third return visit compared to children with smaller working storage capacities. A rational explanation for this is that children spent more time because they were encoding a larger amount of information on this visit. Yet, this is not in line with findings in relation to working memory concurrent processing capacity. It was anticipated that children who could concurrently process a greater amount of information would attend to a greater amount of information during secondary encoding, and so take more time to discriminate task relevant and irrelevant information (as drawn from Unsworth & Engbert, 2007). In contrast, children with

greater concurrent processing capacities needed less secondary encoding time than children with smaller concurrent processing capacities.

When thinking about how storage capacity in working memory is expected to develop, expectations have been discussed in this Thesis in relation to the Time-based Resource-sharing model (Barrouillet et al., 2009). This model was chosen as it incorporated a developmental learning mechanism, in which gains in storage capacity arise from gains in efficiency in the resources needed for storage. As such, storage capacity and efficient resource use could be considered as two sides of the same coin. In the current paradigm, there is room for interpretation about whether the storage capacity limitations or the efficiency of resource use is responsible for the relationship between storage capacity and secondary encoding time. It could be reasoned that as capacity increases, encoding time should increase due to children encoding a greater amount of information. Alternatively, if children encoded a similar amount of information, as capacity increases, encoding time should decrease due to children encoding in a more resource efficient, thus time efficient manner. Until the experimental design is constructed in a way that it enables a measurement of how much information was encoded in a single episode (not how much information was recalled during production following that encoding episode), it is difficult to avoid confusion in interpreting the relationship between working memory storage capacity and secondary encoding time. This prevents a compelling explanation of the processing mechanisms that account for the findings, so it is not possible to make strong claims from the current data. Rather than solidify a complete account of the cognitive operations in relation to memory that occur during copying, the questions raised in the current chapter seem to be more useful in highlighting where the dependent measures need to be more specified in future copying research. Still, measures of individual encoding time are a much more detailed dependent measure than has been reported before in research that adopted an individual differences perspective to a developmental copying paradigm (Swanson & Berninger, 1996; Grabowski et al., 2010). These findings of encoding time repeatedly suggested that the nature of children's mental representation is verbal, which had so far been doubted in the literature. Yet, the patterns needed to be interpreted in the current study present a complex account of the cognitive processing in relation to multiple mechanisms that could be responsible for storing information, and over multiple instances of storing different information within a single trial of copying an individually presented word. To start developing a theoretically driven understanding of the

processing mechanisms that operate, a much narrower experimental perspective should be adopted in the next steps of further research.

7.4.3 Did children's reading abilities and verbal working memory capacities modulate the extent to which text was consistently produced in syllable-by-syllable units?

That is not to say that all interpretations of findings required such a healthy dose of caution. Perhaps the most important findings of the study were those in relation to the proportion of gaze lifts that systematically occurred at syllable boundaries. Every measure of reading ability and working memory capacity predicted gaze lift behaviour, and out of all the evidence in relation to individual differences, this is the most convincing pattern that children cognitively process and mentally represent printed text in terms of the corresponding verbal characteristics.

On the basis of the idea that reading ability determines the number of specified spelling representations of large linguistic units (as drawn from Perfetti & Hart, 2002), children with higher reading ages were suggested to also hold a greater number of specified spelling representations of large linguistic units. This was brought up in the introduction in relation to Kandel and Valdois' (2006a) findings that Spanish children who develop specified spelling of large linguistic units programmed writing events for Spanish words primarily in word units, whereas French children who relied on specified spelling of smaller units, programmed writing events for French words primarily in syllable and letter units. The idea was that reading ability, as an index of the number of specified spelling representations of large linguistic units, would constrain the size of the units in which writing events are programmed. Children with higher word reading ages were suggested to programme spelling based on larger units than children with lower word reading ages, so should make a higher proportion of gaze lifts on syllable boundaries. Indeed, this was what was found in the current study. In the context of Houghton and Zorzi's (2003) model of spelling, reading ability seemed to determine whether spelling was programmed in syllable units, or constituent units of the syllables.

Both measures of short term storage and working storage capacities predicted children's gaze lift behaviour in relation to syllable boundaries. There was a surprising contribution of short term storage capacity, such that children with greater short term memory capacities had a lower proportion of gaze lifts on syllable boundaries than children with smaller short term storage capacities. This finding could be considered at odds with the idea described above that short term storage should be on the basis of

individually stored letters (Salamé & Baddeley, 1982), as on this basis, there is no grounds to predict a relationship between short term storage and gaze lifts in relation to a linguistic unit larger than individual letters. If it were simply the case that children with greater short term storage capacities stored and produced a greater number of letters in each encoding and production cycle compared to children with smaller capacities, it should then be expected that the children with smaller capacities would need more gaze lifts as a consequence of writing fewer letters between each gaze lift. Yet this is not the case, as short term storage capacity did not contribute towards any differences in the number of gaze lifts made, but children with smaller short term memory capacities systematically made gaze lifts on syllable boundaries to a greater extent than children with greater short term memory capacities. However, throughout this Thesis, the size of the linguistic unit has consistently emerged as a critical characteristic that has modulated children's copying behaviour. A more likely explanation is these findings were driven coincidentally by the 3 syllable words. Recall that most of these words contained a syllable boundary after every other letter. If the children with smaller short term memory capacities could only store 1 or 2 letters throughout each copying cycle, their gaze lifts would continuously occur at the syllable boundaries for words with relatively small syllable units. Consequently, the systematicity may have been driven by the size of the linguistic unit rather than the nature of the linguistic unit in relation to its syllabic characteristics.

Findings in relation to working memory storage were also in the opposite direction to that expected. On the basis of Baddeley's explanation of limited capacity in the amount of information held in working memory, it was expected that children with larger working capacities should be able to store and produce larger units of information. Apart from the word unit, in the current study, the syllable unit was the largest speech-based unit, and a subword unit that children have acquired the ability to recognise by the age of 7 (Colé et al., 1994; Wood & Farrington-Flint, 2001; Savage et al., 2011). Accordingly, children with large working memory capacities were expected to store and produce large syllable units, whereas children with smaller working memory capacities might rely on smaller linguistic units, and so make a lower proportion of gaze lifts at syllable boundaries. In contrast, children with greater working memory capacities made gaze lifts less systematically at syllable boundaries than children smaller working memory capacities. Again, it could be argued that the functionality of a syllable unit during written production might depend on its size in terms of number of letters. It might be that, especially for 3 syllable words, syllable

units of 1 or 2 letters were too small to be functional for children who could mentally represent large units of information in comparison to their peers. In this case, children may have attempted to remember multiple small syllable units, but owing to the greater time delay between recall of the second unit compared to recall of the first unit, only remembered a partial representation of the second syllable unit. As explained in the previous Chapter, this would have resulted in children's gaze lifts falling out of sync with syllable boundaries as written production progressed. This idea is supported by findings in relation to concurrent processing capacity in working memory. Children who could concurrently process a greater amount of information at the same time as storing additional information systematically made a higher proportion of gaze lifts on syllable boundaries than children with smaller concurrent processing capacities. As outlined in Alamargot et al., (2001), when programming multiple writing events, copiers must maintain a representation of the stored information at the same time as programming and executing writing events, involving concurrent processing. In the current study, children with greater concurrent processing capacities may have been more able to cope with task demands programming and executing the writing event for the first syllable unit at the same time as storing the representation of the second unit. In this case, these children were able to regularly programme writing events for a complete representation of a syllable unit, and were less likely to need a gaze lift between syllable boundaries due to forgetting, which in turn raised the proportion of all gaze lifts within a trial occurring at syllable boundaries.

7.5 Overview.

In this final experimental chapter, the research returned to using an individual differences perspective in order to looking at how children employed short term and working memory. Previously in Chapter 5, results had suggested that this approach was useful, indicating that variance in children's ability to temporarily maintain a verbal mental representation of information was a factor underlying efficient task performance. However, these ambitions were perhaps beyond the practicalities of conducting developmental research in a mobile eye tracking paradigm for now. The novel paradigm presented a new way of accessing valuable measures of children's encoding and production behaviour. As of yet, published studies looking at individual differences in children's copying had only reported the number of words or letters correctly copied from a paragraph. Eye tracking measures would allow a more detailed investigation, narrowing the location of an effect of individual differences to a single sub-process

within the copying task. However, studies into individual differences typically require a large sample size, which was impractical for the current study in which eye movement recording were collected, and hand coded on a frame-by-frame basis.

So far, with a small sample, there is evidence to suggest that children rely on verbal memory during secondary encoding, be it in terms of a short term store or a working memory store. It might be that eye tracking measures are sensitive to individual differences to a greater extent than more global measures used in existing research looking at paragraph copying task, but a direct investigation with a narrower research aim and a larger sample size would be needed to confirm the interpretations drawn in the current research. Since conducting the current study, new updates to the Dikablis software emerged that have dramatically reduced the extent of hand coding needed. This means that eye tracking could be a promising tool to continue an investigation into avenue of individual differences. Having said that, variance in individuals is not the only interesting avenue to pursue in developing an understanding of the role of working memory. So far, copying research has only looked in detail at the successful copying performance. Perhaps one of the most interesting events in children's copying performance was their regular reliance on gaze lifts. It could be argued that gaze lifts are a compensatory way of bridging successful and efficient copying, as without gaze lifts, children might not be able to succeed in making an accurate handwritten copy. These gaze lifts occurred as a consequence of forgetting, which in turn leads to the question of what causes the limited capacity of working memory. In this Thesis, forgetting has been theoretically explained in relation to time-based decay of children's representations between storage and recall, and limitations in the amount of resources needed to maintain and process a certain amount of information in working memory. While the research presented in this thesis used a naturalistic experimental analogy of classroom copying task, the paradigm could be further extended to investigate the causes of forgetting in an experimental perspective rather than individual difference perspective. For instance, it would be possible to look at the construct of time-based decay of representations by experimentally manipulating the time delay between encoding and production. In addition, availability of resources can be manipulated by including a secondary task alongside the copying task. Although there was a certain extent of confusion in the current findings, the results have formed a platform for the merit of further investigation, highlighting potential next steps for future research in terms of the research questions and extending the copying paradigm accordingly.

CHAPTER 8
A DISCUSSION OF THE RESEARCH AND IMPLICATIONS
IN THE THESIS AS A WHOLE

8.1 Context of the Research

Linguistic empiricists such as Locke (1689) and Sampson (1978) argue that humans are not born with an innate knowledge or understanding of either spoken or written language. Critically, the extent to which an individual develops such an understanding can have far reaching consequences throughout the lifespan. Typically, language development is thought of in relation to the period of time in which the greatest gains occur: childhood. In England, after learning some of the basic principles of spoken language at home, children spend at least 10 years in formal education. As stated by the Department for Education, among other responsibilities, one of the chief aims of schooling children is to develop their literacy skills. This learning of literacy skills happens primarily through classroom reading and writing activities (Education Standards Research Team, 2012).

As well as consequences for efficient socialisation, personal empowerment and mental well-being, perhaps one of the most immediate impacts of language development can be seen in education achievement. As described by Chall (1983), there is a transition in education whereby children first learn to read, and then subsequently rely on reading to learn. In turn, educational achievement has been suggested to be the cornerstone of the quality of professional development, financial security, and the ability to independently make informed decisions (Stromquist, 1995). Therefore, the understanding and use of language continues to moderate quality of life and participation in society after childhood, in adults. Understanding how individuals develop and use literacy skills is important. Theoretically, it is fascinating to work out the details of cognitive operations that cannot be directly observed. It is this examination of theoretical frameworks that has been the primary focus in this Thesis. As will be covered in the concluding remarks of this Discussion, establishing a firm basis of theoretical ground-work is the first essential step in thinking about how links between research and education can address practical applications in improving literacy development.

The cognitive science literature concerning how children learn to read (Ehri, 1991; Frith, 1985) and write (Hayes & Flower, 1980) is well documented, and eye tracking paradigms are beginning to be used to assess the basic characteristics of

children's eye movement behaviour when they read and understand printed text (as reviewed in Blythe & Joseph, 2011). These eye movement characteristics are important indicators of the time-course and nature of the cognitive operations underlying reading and understanding of printed text. However, the construct of literacy does not just involve reading, but writing as well. In classroom activities that involve both reading and writing such as a word copying task, the mental representation of the encoded information is not just the output gained from the reading sub-process, as it is in the sentence reading studies discussed by Blythe and Joseph. This output then forms the input basis for the writing sub-process. In this way, reading and writing do not always occur in isolation, as has been investigated in the majority of developmental research. This observation then raised the overarching question in this thesis of how the sub-processes of reading, mental representation and written production operate when they are co-ordinated in succession.

This is a huge question, as it incorporates three areas within the field of cognitive science which are in themselves independent seminal topics. In addition, while there is an exceptionally robust understanding developed how of adults read, mentally represent, and write information, the theoretical frameworks that explain what happens during these individual tasks are somewhat limited to adult populations. That is not to say that there were no theorised learning mechanisms. Indeed, care has been taken within this Thesis to identify the functional processing mechanisms in each sub-process of a copying task and think about the changes that occur within those processing mechanisms as children develop. Recall that this was in relation to developing reading ability (Plaut et al., 1996) memory capacity and efficient storage (Barrouillet et al., 1982; Kail & Park, 1994) and written production in relation to spelling (Perfetti & Hart, 1982). However, there was uncertainty about the pace of this development, as far less is understood about how children operate in comparison to adults.

To start with, the single word copying task used in this Thesis was originally conceptualised in terms of a sequence of these three sub-processes. When an individual makes a handwritten copy of a single word presented on a classroom board, each sub-process was thought to happen in turn. The copier must visually encode the letter information, then maintain a mental representation of the encoded information, and then programme written production events until each letter has been written and the copy is complete. This paradigm created an opportunity to begin investigating how individuals co-ordinate sub-processes of reading, mental representation and written production. Yet,

as will be made clear, this initial conceptualisation was too simplistic to describe what happened when adults and children copied words. The research in this Thesis therefore informed a theoretical framework of a single word copying task, which will be presented towards the end of this Discussion. First, the aims of the research will be outlined with respect to key research questions. Next, the discussion will draw together the important findings in how they address these questions. During the opening enquiry, there were some genuinely surprising findings, and as these come up, there will be an elaboration of how these findings guided the experimental approach chosen in the subsequent studies. Together, theoretical implications will be discussed in the context of the proposition of a new framework. Naturally, the research was not without challenges, so it is important to cover how these issues were addressed in the current research. With the knowledge gained from addressing these challenges, next steps for future research will be outlined.

8.1.1 Aims of the research

This thesis set out to examine eye movement behaviour of adults and children as they made handwritten copies of individual words, containing particular linguistic manipulations, in order to investigate cognitive processing over the course of a word copying task. The eye tracking paradigm enabled an investigation of the extent to which these characteristics of the stimuli and characteristics of the copier modulated both the visual encoding and written production sub-processes during copying. Time based measures of gaze durations on the classroom board on which the word was presented, and the paper on which the word was copied, respectively indicated time associated with visual encoding and written production. Individual differences in children's capacity to mentally represent information could be investigated in relation to both time-based measures of encoding and production.

The copying experiments aimed to address three points of uncertainty that were so far not specified in detail by existing copying research. This is because most research investigating a handwritten copying task (primarily led by Kandel and colleagues in the past 10 years) has a more detailed focus on the written production sub-process than the encoding and mental representation sub-process. The research presented in the thesis aimed to address three main questions in relation to a word copying task:

- 1) What is the nature and amount of information encoded from a single word?
- 2) What is the nature of the mental representation of printed text that individuals maintain throughout encoding and production?
- 3) To what extent is there a 1:1 correspondence between the linguistic units that are functional over encoding and production?

These were originally constructed as simplistic questions to be quickly addressed in the initial studies that would allow testing of critical assumptions in the way in which copiers were expected to operate. The first fundamental question about the nature of processing was drawn from an exceptionally robust field of reading research (as reviewed in Rayner, 1978, 1998), leading to very strong predictions about the nature of cognitive operations operating on word units. Then, following studies could continue investigations into the extent to which there were similarities in the way in which reading and copying tasks involved higher level meaning and comprehension. On the contrary, some of these critical assumptions were not supported in the opening enquiry, and these are perhaps some of the most exciting findings. These results led to a greater focus on questioning the original assumptions about the nature of cognitive operations during copying. As a consequence, the story presented in this Thesis is framed in terms of assessing the functional units during sub-processes in a copying task.

8.2 Key Research Findings

8.2.1 What is the nature and amount of information encoded from a single word?

Taken together, the data presented in Experiment 1 and Experiment 3, reported in Chapters 3 and 6 suggested that copiers visually encoded letter forms, and engaged in additional cognitive processing on these letter forms during encoding, in relation to both word units and subword units. However, the age of the copier, the length of the word, and the time-point within the copying process determined the nature and amount of information encoded from a single word.

In Experiment 1, as expected, adults consistently activated whole word units for both 4 and 8 letter words, rarely needing more than one encoding episode to copy each word. This meant that the nature of information adults encoded was at least at the lexical level, and perhaps as far as semantic information becoming available, as in

reading. Had children's data patterns been similar, the next step would indeed have pursued this question of the extent to which semantic characteristics were activated. However, children behaved differently to adults, only encoding whole words for short, not long words. The length of the word unit modulated the nature of information encoded, and the heavy cognitive load of writing at the same time as remembering meant that sometimes even if 4 letters had been encoded, they could not always be remembered. This then led to children needing regular gaze lifts between the written copy and the board. Upon returning gaze to the board for a secondary encoding episode, the amount of information encoded was then dependent on the letters that had already been produced at that time-point within the trial.

First, considering the implications of regular gaze lifts, this meant that the way in which the three sub-processes of a copying task were conceptualised as impacting serially on one another was too simplistic. To be clear, the output from encoding was expected to impact the input for production, but these findings also meant that the output from production impacted the next encoding episode. Second, considering the inconsistency in children's encoding of words units, this had potential ground-breaking implications. In existing studies using paradigms such as lexical decision that involve visual encoding of a single word, (Araújo et al., 2014; de Zeeuw et al., 2014; Luque et al., 2013), the nature of the information children encoded was similar to that in sentence reading studies. Given that children have acquired a mental lexical entry for a word, this lexical entry is activated upon visual presentation (as accounted for in the Coltheart et al. 2001 DRC model of word recognition). Although children can suppress automatic word recognition when explicitly instructed to do so (as demonstrated in the Stroop paradigm by Bub, Masson, & Lalonde, 2006), this explicit instruction was not present in the copying task. This might mean that implicitly, the specific task demands of a word copying task (in that words were encoded in readiness for written production, not for making a mental decision or for spoken production) determined the extent to which children cognitively went beyond the literal encoded information of letter forms when they mentally represented the stimulus.

This possibility was so controversial that another study was planned purely around falsifying the alternative explanation that controversial findings arose as a consequence of children not having acquired the lexical entries necessary for whole word encoding. The data in Experiment 2, presented in Chapter 4 using a lexical decision paradigm showed that the nature of the information that children encoded was at the level of whole words, irrespective of the length of the word. Looking together at

the children's data from Experiments 1 and 2, when age-matched groups of 7-10 year old children encoded exactly the same words, cognitive operations during the encoding sub-process used different linguistic units, depending on whether or not the encoding episode was followed by additional task demands of written production. This led to a controversial conclusion that the task demands determined the extent to which children automatically processed whole word units. In turn, the critical implication is that children's behaviour during visual encoding in a copying task cannot be completely interpreted within models of single word recognition drawn from reading research.

Still, that is not to say that all principles of encoding during reading were violated in a copying task. As when children activated partial word representations of syllable units when single words were presented and a decision was made about whether certain letters were present (Alvarez et al., 2016), data from Experiment 3 showed similar patterns. When individual words were encoded in readiness for written production during copying, children were sensitive to the number of syllables, suggesting that they activated partial word representations of syllable units. This enabled a clarification of the question raised in Experiment 1 about the extent to which children cognitively go beyond individual visually encoded letter forms. Although word units may not consistently be functional, children do engage in cognitive processing over units of multiple letters, rather than only encoding individual letters. Critically, adults' encoding times indicated that they also activated syllable units. This implied that the activation of partial word representations as opposed to whole word representations was not in itself only a compensatory mechanism needed to encode 6-7 letters in readiness for written production. However, as in Experiment 1, in Experiment 3, children did not consistently activate the same linguistic units over every encoding episode when more than one episode was needed to copy a single word. This meant that children relied on a flexible range of multiple functional units of encoding, perhaps as small as individual letters. Whereas the copying paradigm had so far been framed in terms of investigating how sub-processes are co-ordinated, these findings highlighted how the data could speak to issues of language development more generally. Eye movement measures in a copying task could provide opportunities to examine language processing as it develops, specifically, the units over which children's encoding operates, at different points along a progressive trajectory of reading development. Traditional stage models describing reading development like Ehri, (1991, 2005) and Frith (1985) explain how children start off relying on processing individual associations between letters and sounds in an analytic way, then develop by moving on to processing

words as whole units. But another way reading has been conceptualised to develop is by relying on a variety of processing strategies at the same time, more gradually shifting reliance from small units to larger units (Siegler, 2002). It may be that a copying task provides a more stringent test than a reading task in assessing the extent to which children consistently rely on particular linguistic units.

8.2.2 What is the nature of the mental representation of printed text that individuals maintain throughout encoding and production?

The findings discussed above casted doubt on the initial assumptions that children mentally represent printed text as a representation of spoken words. If children were not consistently activating multi-letter subword units or whole word units during encoding, to what extent did they mentally represent letter information in terms of its visual or verbal characteristics? This was investigated in Chapters 5 and 7, in which an individual differences perspective was adopted for examining the relationship between working memory, short term memory and copying performance. To recall, verbal and spatial memory showed differential relationships with encoding and production, with verbal memory predicting secondary encoding, and spatial memory predicting written production. These findings suggested that after visually encoding letter forms, children engaged mechanisms of either verbal short term memory or verbal working memory to maintain a mental representation of printed text, re-coding visual letter forms into corresponding letter sounds. These sounds were stored either as individual phonemes or higher level sound-based linguistic units, over different secondary encoding episodes. However, children co-ordinated this sound-based mental representation with a representation of visual characteristics of letter forms during written production, so the nature of the mental representation of the text is not the same across different sub-processes in the copying task. The same information was represented in terms of both its verbal characteristics and its visual characteristics, depending on the time-point within the copying task.

Again, the research drew on an exceptionally robust area of work in order to inform these interpretations, conceptualising working memory in terms of the visual and verbal components put forward in the seminal Baddeley and Hitch model (1974). However, these results were perhaps the most confusing so far, preventing strong claims about the linguistic nature of a meaningful unit (as described in relation to the work of Cowan, 2008) that is held in a temporarily accessible state. This was partially attributable to the challenge of teasing apart the amount of information stored and the

efficiency of the use of processing resources. These two factors have been suggested to jointly constrain how much information can be stored over a period of time in working memory (Barrouillet et al., 2009). Again, this challenge emerged as a consequence of the surprising findings in the opening enquiry in Experiment 1. One of the critical initial assumptions was that children would encode the whole word as a unit. Therefore, further differences in encoding time or how much information was retained throughout production could be related to time-efficiency of encoding and proficient rehearsal to avoid forgetting. However, that children encoded a variable amount of information contributed towards confusion in identifying the precise mechanisms within working memory that were resulting in the behaviour. Resolving this challenge by controlling the amount of information encoded would be necessary to confirm the estimations of cognitive processing operations drawn in Chapters 5 and 7. As stated in Chapter 7, the copying paradigm would also be suited to such an investigation from an experimental perspective to enable such control.

8.2.3 To what extent is there a 1:1 correspondence between the linguistic units that are functional over encoding and production?

The third key question related to clarifying how copiers co-ordinated encoding and production behaviour, which were suggested to operate over different linguistic units. Existing ideas about how written production operated during copying (Kandel & Valdois, 2006), examined within the context of theories of handwriting alone (Van Galen, 1991) suggest that children co-ordinate comparatively larger units of encoding with smaller units of writing. So far, researchers had not taken a direct measure of encoding time that does not include spelling programming in readiness for written production, so claims in relation to encoding time have not been directly tested. The eye tracking paradigm enabled assessment of the size of linguistic units used in both encoding and production to assess the extent to which children co-ordinated different sized units between visual encoding and written production. This was investigated in Chapters 3 and 6, in relation to both whole word units and sub-word units. Between encoding and production, there was not necessarily a 1:1 correspondence in either the size or the nature of functional units. Irrespective of age group, copiers co-ordinated larger units of encoding with smaller units of production during word copying. However, between age groups, the functional units underlying children's copying were smaller than the functional units underlying adults' copying. In the children's data reported in Chapter 6, children's encoding relied to a greater extent on sound-based

characteristics of the word such as syllables compared to children's written production behaviour. Alone, the theory of how written production is organised put forward by Van Galen cannot fully account for the way in which children organised written production over repeated cycles of copying. To recall, van Galen's model describes the units of spelling transitioning from whole word units to individual letter units, with no intermediate linguistic unit. However, again returning to the controversial point in Experiment 1 that children did not necessarily encode whole word units to form the basis for the organisation of written production, writing events may proceed differently when they follow a sub-process of visual encoding compared to when written production occurs in isolation. That is not to say the organisation is completely different when encoding and production are co-ordinated. In Experiment 3, children's production was investigated in the context of Houghton and Zorzi's (2003) model of written production, which suggested that between word units and individual letters, writing events were organised in terms of syllable units, and the constituent components of those syllable units. In the case of 2 syllable words, support for this was found, as children both encoded and produce in terms of syllable units. However, the characteristics of the stimuli may determine whether written production of the stimuli is organised in constituent components of syllable units, particularly in the 1 and 3 syllable words. As of yet, the data cannot speak to which specific constituent components of the syllable were functional, however the size and nature of these constituent components may have contributed towards modulating the extent to which there is a 1:1 correspondence in linguistic units that were functional over encoding and production.

8.2.4 Mapping the data in relation to the Simple View of Writing (Berninger & Amtmann, 2003).

Looking at the key research findings together, it may be useful to relate the current findings to the work of Berninger and colleagues, who present ideas about how children's working memory might support co-ordination between text generation and transcription during a task of text composition (for instance story writing). As the current research originated from a reading approach, and focused on concepts such as activation of subword linguistic units, the Simple View of Writing (Berninger & Amtmann, 2003) has not been the most relevant theoretical framework in which to consider the findings. In designing particular research questions, the current experiments have focused on examining what happens during specified processing

mechanisms (for instance lexical retrieval) that might occur during the cognitive operations (for instance word encoding) within a particular sub-process (for instance visual encoding) of a single word copying task. Yet thinking about the copying task more globally, Berninger and colleagues put forward several useful concepts and a framework that would guide thinking in relation to the copying paradigm.

Their concepts of “language by eye” and “language by hand” relate to the idea that reading and writing are separate abilities, but draw on shared linguistic knowledge, a range of the same processes, and also unique processes. The Simple View of Writing (2003), updated to the Not-So-Simple View of Writing (Berninger & Winn, 2006) draws together several topics that emerged as relevant during the course of the research, such as reviewing and revising, retrieving representations from long term memory as well as creating representations in short term memory, and conscious awareness of language. This framework was not originally considered, as Berninger explicitly aimed to describe text generation in relation to a writer conceptualising and producing an original piece of printed text, rather than make a handwritten copy of an existing text. Her framework aims to identify components of a functional writing system. These frameworks of Berninger and colleagues were developed in the context of identifying children who are at risk of atypical or below average writing development, in order to provide effective support, such as thinking about how computer technology could make specific components of generating written text easier for the student. For this Thesis, the difference in task goals of composing and copying would result in critical differences in the nature of cognitive operations that occurred. Nevertheless, the current findings do speak to several concepts in Berninger’s frameworks. Her frameworks will now be briefly described, before reflecting on what might remain the same and what needs to be revised in light of the new findings within a word copying paradigm.

In the Simple View of Writing, the writing process is represented by a triangle. There are two base components of transcription and executive functions. These provide a stand for working memory, in order for working memory to support the third component, text generation. These components are illustrated in Figure 9. Text generation is described as a dynamic process that involves conceptualising ideas in terms of the whole text and its smaller segments such as sentences and individual words. Through activating relevant information in long term memory, the abstract ideas are represented in terms of language. The transcription component refers to both generating spellings in terms of the precise orthographic symbols that reflect the represented linguistic information, as well as carrying out motor movements to produce

letters. Throughout the whole writing activity, executive functions are said to guide the writer’s mental state in terms of what information is currently being attended, upcoming actions, and judgements in relation to the current progress of text and the whole intended text. Short term memory is used in reviewing the written text so far in relation to the ideas that were conceptualised and ideas that are yet to be written.

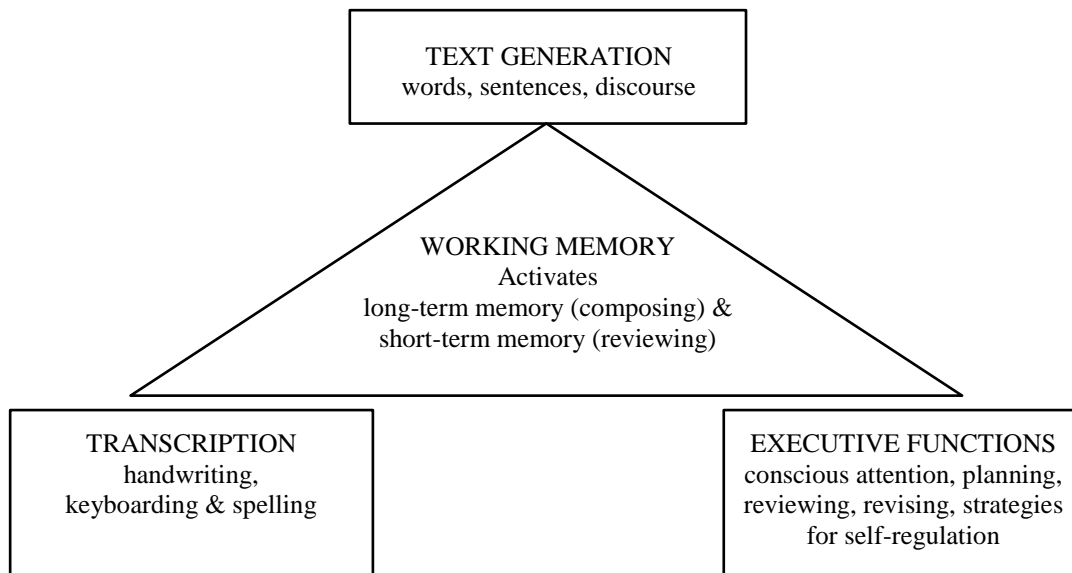


Figure 9. The Simple View of Writing, adapted from Berninger and Amtmann (2003).

In the Not-So-Simple View of Writing, the executive functions are updated. These include: supervisory attention, responsible for task management by discriminating relevant information and inhibiting irrelevant information; goal setting; planning; reviewing; revising; strategies for self-monitoring; and regulation.

How might the current research findings map onto the frameworks put forward by Berninger and colleagues? First, it is very important to note that unlike in a text composition task, in a copying paradigm, the ideas are pre-conceptualised and the spellings provided by the stimulus. Instead of operating from a starting point of abstract meaning, copiers start by encoding orthographic information, and do not necessarily go beyond the literal representation of printed letters to activate a cognitive representation to the point of semantic understanding, especially in the case of children. The text generation component handling complex abstract ideas and syntax in relation to perhaps whole paragraphs and sentences of text is not relevant to a single word copying paradigm. Second, recall that the written production sub-process within a copying task was not the primary focus of the current research, as this was the component that had

received the most attention in existing research. As such, while it was important to collect global measures of written production, and relate gaze lift behaviour to precise letter-by-letter progress of written production, the current research did not include a moment-to-moment account of pen movements. Therefore, while the aspects of handwriting fluency and spelling retrieval would have been involved in a copying task, the current research examined written production in terms of an output measure of how much information copiers could encode and maintain, rather than examine the precise operations of motor movements and execution. However, there seems to be relatively more overlap in the extent to which components of working memory and executive functions have a shared involvement in text composition and single word copying. These will be considered in turn.

During text composition, a large amount of ideas, personal experiences, linguistic knowledge in terms of word meanings and how these words relate together would be drawn from long term memory. While there is a role for long term memory during a copying task, the nature of the task does not necessitate such extensive involvement of long term memory. After visually encoding text, copiers retrieve linguistic knowledge about words, smaller linguistic units and individual letter forms. This information would be stored in long term memory and activated during operations such as lexical access, especially in the case of adults. For children, who do not consistently activate whole word units, as they constructed a mental representation of a smaller unit, it is still the case that information about letter forms and syllable units would be retrieved from long term memory, and held in a temporarily accessible state. After copiers have activated linguistic information, in order to store this information in preparation for written production, corresponding phonemes associated with retrieved letters must also be activated in order to recode information into phonological memory.

As well as retaining a mental representation of the encoded information, especially in the case of children who often needed multiple episodes of secondary encoding, copiers might also need to construct a representation of their written text in the moment. Recall that during secondary encoding, children tended to only encode the information not yet written. In order to do this, it seems likely that a representation of the written text would be compared to the reference model, reviewing which information would need to be encoded next. As in Berninger's framework, this reviewing operation would not depend on a retrieved mental representation, but a constructed representation, necessitating short term memory storage.

The current research can perhaps speak the most to Berninger's component of executive functions. As research progressed throughout the Thesis, it became apparent that children might be consciously breaking down words into specific linguistic units, and making strategic judgements about how much information to write. The eye movement measures enabled the research to directly measure what the copier was attending to. In relation to the role of *conscious attention*, both adults and children showed the same pattern of behaviour, deliberately attending a sequence of the targeted objects in environment. Information was encoded while looking at the wall mounted board, then gaze transferred to the written paper. In the case of an insufficient mental representation, both adults and children made a gaze lift, transferring gaze back to the board to begin another coping cycle. In terms of specifying what linguistic unit copiers attended, the Experiments presented in this Thesis showed evidence for copiers attending a flexible range of linguistic units, at different time points within the copying task. Typically, adults attended a large amount of information than children, though both children and adults attended similar subword structure of a single word, and written production was organised in smaller units than visual encoding. Across successive encoding episodes, children tended to attend successively smaller amounts of information. This is also relevant to the concept of *supervisory attention*, needed to discriminate relevant and irrelevant information. This concept became particularly relevant in Chapter 7, thinking about the use of working memory and short term memory, as recall that engaging in information discrimination was suggested to be a function of working memory. During children's secondary encoding episodes, recall that the pattern of activating syllable units on alternate secondary encoding episodes was related to the idea that gaze lifts had fallen out of sync with syllable boundaries, due to forgetting part of a syllable unit. It was suggested that upon return gaze to the board, children discriminated what information they needed to encode, encoding either a partial syllable unit that had been forgotten, or the next whole syllable unit yet to write, depending on what had already been written. By discriminating relevant information, children could minimise encoding time by not encoding irrelevant information in addition. Berninger's concept of *supervisory attention* encapsulates these ideas, which transfer well from the framework of writing for composition to a framework of single word copying.

The current research also speaks to the aspects of *self-regulation, strategies and planning*. In the first experiment in Chapter 3, there was a controversial idea that children activate smaller linguistic units than a whole word (in the case of long words).

There was an underlying principle that children were engaging in self-regulation, breaking down text into feasibly memorable units. When confronted with a unit beyond the size of their capacity to encode, represent and produce in a single episode, it seemed that children regulated their own behaviour in terms of their perspective of their abilities in relation to task demands, operating on smaller potentially manageable units. When children engaged in piecemeal copying over several successive encoding episodes, this strategy was suggested to compensate for high task demand. It may also have been that adults were engaging in self-regulation, though as the stimuli did not challenge adults enough for consistent secondary encoding, this cannot be confirmed. However, in a population of adult copiers who might experience difficulty performing a copying task, such as dyslexic readers, it might be that these copiers perform compensatory behaviour in a similar manner to children, making gaze lifts. If this is the case, then the copying paradigm would provide an opportunity to investigate self-regulation in adult copiers.

The final aspects of executive functions of reviewing and revising apply almost exclusively to children in the current research. Only after episodes of secondary encoding would a child need to engage in *reviewing*, comparing written copy with reference model, and *revising*, planning changes to written copy. These aspects are included just as in Berninger's framework, although the purpose of reviewing is likely to differ during copying compared to composing. Berninger considered reviewing in a global fashion, for instance reviewing the gist of what had been written in comparison to the original conceptual idea generated, and writing goals in terms of composing writing accessible for an intended audience. In a copying task, the purpose of reviewing would occur on a lower level, with specific orthographic letter forms more important than global concepts. It is worth noting that during a copying task, there may also be different types of reviewing. Recall that return encoding episodes in which a copier returned their gaze to the board were divided into secondary encoding that occurred before completion of written production, and verification encoding that occurred after the completion of written production. The nature of reviewing may depend on how much information has been written so far, determining whether the goal of reviewing is to target a specific location within a word in order to encode more information, or to check a specific location to ensure that the correct representation had been produced.

After setting out what factors should be considered in explaining word copying behaviour and how these factors are related, the existence of a specified framework provides opportunity to challenge and extend formalised ideas. Future research needs to be able to examine and clarify the relationships between the factors. For instance, the

nature of the encoded information confines the amount of information mentally represented and produced, but to what extent does working memory storage capacity restrict the information encoded? Currently, in towards building a framework, theoretical foundations have been based on a logical critique, thinking about internal consistencies within the theory. For instance, print encoding operates over levels of both word units and subword units, therefore working memory must operate not only over a conceptual level of gist (if semantic meaning is even involved at all), but be able to accommodate a flexible range of orthographic information. The Thesis has also begun to refine the theory based on critiquing new knowledge, thinking about whether the core assumptions of the theory are correct. For instance, whether the working memory slave system used to activate information is visuo-spatial or phonological in nature. Future work can then make more specified empirical investigations, testing the extent to which theoretical predictions are consistent with data. In this way, the work presented in this Thesis could serve to revitalise old discussions, for instance the work of Inhoff and colleagues in the 1980s and 1990s about the extent to which copiers activate word units and semantic meaning. The current work has advanced current discussions in the extent to which linguistic units are functional not only in written production, but over the course of a copying task, as well as highlighted differences between skilled adult and developing child populations. Finally, the methodology presented here could stimulate new discussions about the nature of cognitive operations during a word copying paradigm, in particular the extent to which operations are co-ordinated.

8.3 Proposition of the Basis for a Framework Conceptualising Cognitive Operations during a Single Word Copying Task

As has been made clear in this discussion, there was a transition throughout this Thesis in the way in which sub-processes during a copying task were conceptualised. Initially, it was thought that irrespective of age, copiers would visually encode letters and activate whole word units, mentally represent a verbal representation of this whole word unit that was already activated, and then organise written production events in the units in which the information was mentally represented. That the data went against this critical assumption of whole word encoding resulted in doubt cascading into the conceptualisation of mental representation and written production. The current section will describe the final conceptualisation of a copying task at the end of the thesis. This was driven by theory wherever possible, when it was rational to apply the established theoretical concepts discussed above that were supported by the patterns of data. When

the patterns of data suggested that the cognitive processing operations during encoding, mental representation and production occurred differently when co-ordinated as when carried out in isolation, the data informed potential adjustments to a theoretical framework.

So what happens when people copy words? The copier needs to carry out at least 3 interactive sub-processes, making up the core behavioural requirements in a copying task. In Figure 10, an illustration is presented describing some of the cognitive operations that occur during these sub-processes. Note that this illustration is not offered as a complete account of the cognitive operations during copying, but concerns the operations that have links to the topics investigated in this Thesis. This framework forms a platform for conceptualising how and where, within the copying task, additional cognitive processing operations occur under the umbrella sub-processes of visual encoding, mental representation and written production.

Copiers need to visually encode the printed text, create and store a mental representation of that text, then on the basis of the stored representation, programme writing events to produce the same letters in the same order. Depending on how much of the text was successfully encoded and remembered throughout written production, this cycle of encoding, mental representation and production may need to be repeated one or more times until all the text has been copied. In this case, the copier would need to make a gaze lift after a cycle after executing a written production event production. The copier's gaze would return their gaze to the reference text for additional encoding, and the copying cycle would begin again, starting with visual encoding. These staple sub-processes (denoted by solid box outlines) must occur, but the nature of the cognitive operations within each sub-process (denoted by dashed box outlines) may vary.

The downwards facing arrows indicate the broad chronological starting point of each sub-process for clarity. It is important to note that although that these sub-processes are now *not* suggested to occur in such an isolated, separate sequence. For instance, while eye gaze is on the stimulus presented on the board, it is likely that mental representation and visual encoding sub-processes are ongoing at the same time. This enables copiers to mentally represent one linguistic unit at the same time as encoding and activating additional units. This also enables copiers to forget information throughout a single episode of written production that includes more than one writing event. The curved lines are a reminder that information is suggested to feed backwards as well as forward: between encoding and mental representation; then between mental

representation and written production. Below the Figure, there will be a summary of the factors that have been suggested to influence the cognitive operations during a copying task. Next, there will be a more specific description of what happens during these cognitive processing operations.

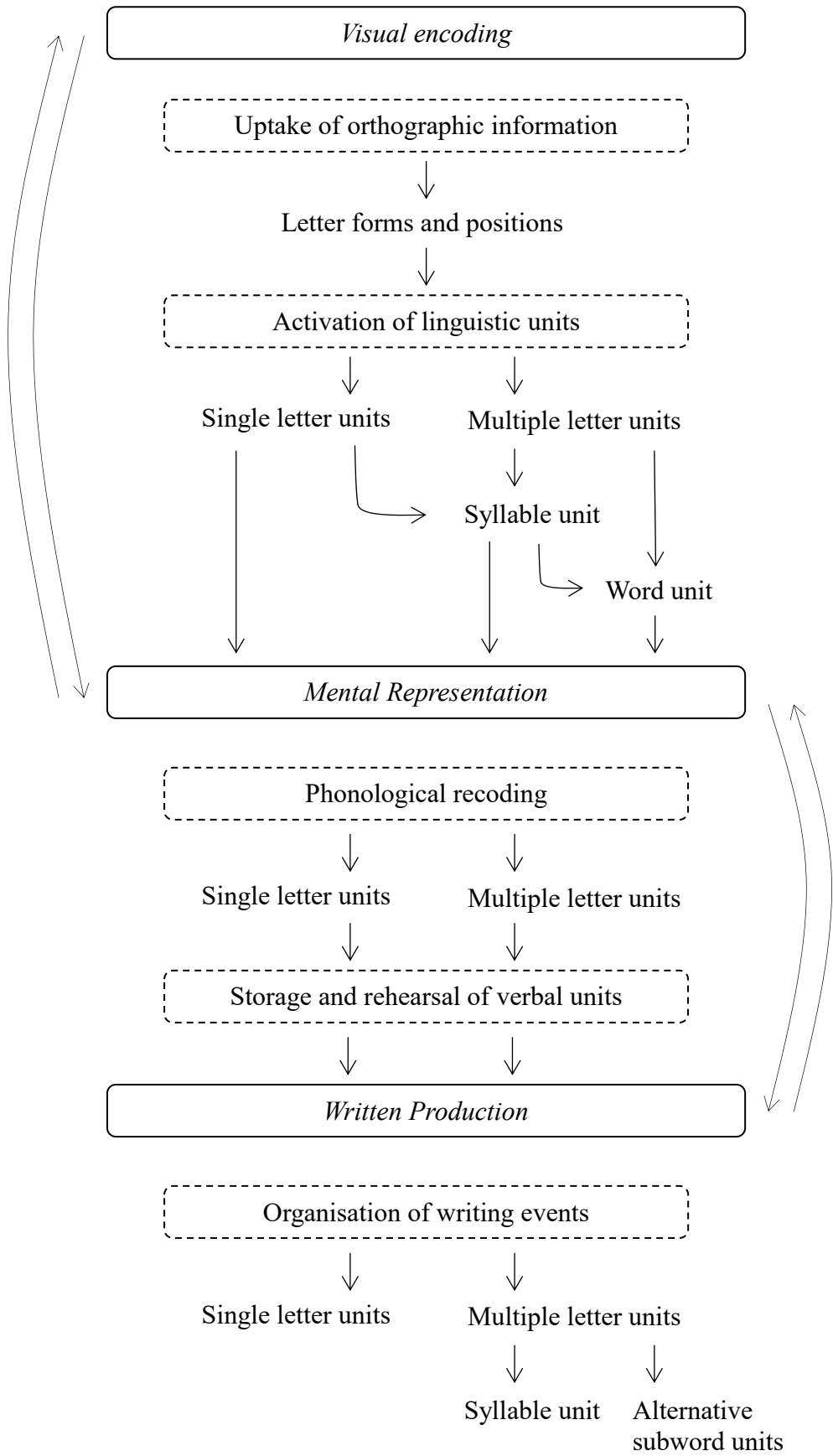


Figure 10. The basis of the framework for a single word copying task.

The nature of cognitive operations is determined by 4 factors. Each factor impacts the task demands of copying; the lower the task demand, the more sophisticated the nature of the operation. Where an operation has multiple routes of processing, relative sophistication of these routes increases from left to right: single letter units are considered less sophisticated than multiple letter units; within multiple letter units, syllable units are considered less sophisticated than word units. It is key to state that sophistication does not necessarily equate to efficiency. Particularly in the case of copiers who are still developing reading ability, their encoding may be more time-efficient overall, and their production may be more accurate if they operated over single letters rather than multiple letter units. Also, the information encoded is dependent on the information so far produced. Even in copiers with fully developed reading ability, in the rare need for a secondary encoding episode, encoding may be more time-efficient if only the letters yet to be written were re-encoded, rather than the entire word.

Three of the key factors that determine the nature of the cognitive operation are characteristics of the copier: their chronological age, reading ability, and memory capacity. Age and reading ability are related in that typically, reading ability progresses as people age, but there may be more variation in reading ability along a developmental trajectory of reading skill in children than in adults. So, reading ability may determine copying behaviour to a different extent for copiers of different ages, being a more important determinant of copying behaviour in children than adults. Overall, the lower the chronological age and reading ability the smaller the unit size on which visual encoding, mental representation and written production operate. Memory capacity is a more complex issue; as stated earlier, verbal short term storage capacity and verbal working storage capacity could relate to both the time-efficiency of representing the information and the amount of information represented. Therefore, it is not possible to only relate greater storage capacities to the use of larger linguistic units than smaller storage capacities. Developing a further understanding of the range of functional linguistic units in between individual letters and whole words would be particularly useful in relating memory capacity to particular units in terms of both their size in letters and linguistic nature. For now, it is clear that memory capacity is an influential factor in relation to children's copying performance, but narrower conclusions cannot be drawn at present.

The fourth factor that influences the cognitive operation is the characteristics of the stimuli: how difficult it is to cognitively process the information. These characteristics can relate to the whole word: how often readers encounter that word in

their reading experience; how many letters there are in the word. Or, these can be sub word characteristics can be related to a chunk unit of information within that word, such as a syllable: how many units there are in the word; how many letters are there in each unit. More cognitively demanding stimuli is more effortful to process, and this effort may be reflected in the time taken during the encoding or production sub-process, or the number of encoding and production cycles required to complete the copy.

Irrespective of the characteristics of the copier or the stimuli, copiers first engage in visual uptake of information, in which they encode letter identity and letter position during visual encoding. As discussed in relation to the ideas of lexical tuning (Castles et al., 2007), children are likely to operate to a lesser extent of specific coding of individual letter positions than adults. With respect to the amount of information encoded, the characteristics of the stimuli determine the extent of cognitive processing that is done on the encoded letters towards activating linguistic units. Encoding for copying can draw on similar operations of lexical retrieval as in single word recognition (as discussed in the context of the DRC model, Coltheart et al., 2001), but not all the time. When the characteristics of the copier and stimuli mean that task demands are very high, such as children copying a word with many letters, encoding for copying may not proceed as in reading. Rather than activating linguistic units to the extent of whole word units, subword units of individual letters or syllable units may have been activated instead. Activation of these linguistic units is still sensitive to the size of the linguistic unit, but the ease of accessing a lexical unit would only modulate the operations in which activation extended to the whole word unit.

Also note that activation of subword units is not merely a compensatory behaviour when whole word units are not activated. Recall from the ideas of Taft (1989) that activating subword units such as syllables occurs during operations such as lexical access of word units. However, syllable units could be accessed by direct retrieval, or by phonological assembly (as drawn from Brown and Watson's (1987) phonological completeness hypothesis).

After activating the linguistic units, this input forms the basis for mental representation. Constructs from Baddeley's seminal model of working memory (Baddeley & Hitch, 1974; Baddeley, 2000; Baddeley, 2003) informed the inclusion of his concepts of phonological recoding, storage and rehearsal of information stored in terms of a verbal form. However, this verbal representation may be stored in terms of individual letter units in short term storage (Salamé & Baddeley, 1982), or copiers

might maintain an imposition of organised structure on a group of information (Cowan, 2008).

Precisely when the mental representation transitions from the verbal representation of letter sounds during encoding to the visual representation of letter forms during production is not defined as of yet. However, written production events are planned on the basis of multiple subword units within a single word. Drawing concepts from both Van Galen's (1991) and Houghton and Zorzi's (2003) model of writing, copiers organise writing events in terms of a range of spelling units, including individual letters and subword units of syllables. Yet these are by no means the only spelling units used, as children often produced in terms of multiple letter unit that did not correspond to the syllable boundaries within a word. For children at least, it is likely that both the orthographic and phonological characteristics of the word drive how much information is written before another encoding episode is needed. Children tend to be able to encode, remember and write about 3-4 letters in a single copying cycle, whereas adults can consistently encode and maintain up to 8 letters throughout production. Finally, after completing all the letters of a written copy, copiers may engage in an optional additional episode of verification encoding, to compare the written copy with the stimuli.

8.4 Challenges in the current research

As outlined from the beginning of the Thesis, the area of copying research is still very new, and this mobile eye tracking paradigm looking at how both adults and children copy individually presented words is the first of its kind. The greatest challenges in the research were of a practical nature. The design of the studies were directly informed from an exceptionally robust literature on word reading, in line with the critical idea that individuals would engage in similar cognitive processing operations during encoding when visually presented with a word in a copying task as in a reading task. Due to this, decisions such as the sample size and age range of the children in Experiment 1 were considered in relation to existing developmental studies employing a sentence reading paradigm, such as the sample of 12 children aged between 7-11 years old in (Blythe et al., 2009). Yet, as discussed above, children did not always encode information in a similar manner during a copying task as in a task in which written production of the mental representation was not required. Behavioural events of gaze lifts arose during copying that do not occur during reading for meaning. Because of these differences, there was a large amount of variation in encoding times and gaze lift

probabilities in Experiment 1, and it might have been that younger and older children within the sample were relying to a different extent on individual letters, and multi-letter partial word representations. To address this, Experiment 3 looked at a narrower age range of 7-8 year old children, and there was much less variation in the number of gaze lifts required during copying between these children. Even so, there were differences between children in the extent to which they produced words syllable-by-syllable with regard to reading age. This variance could potentially be addressed in the future by carefully selecting child participants whose reading age is similar to that expected by their chronological age, rather than also including children with reading abilities beyond that expected in comparison to same age peers.

A related issue is that of selecting a narrow age range in relation to school grades. In Experiment 3, the age range of 7-8 year old children was selected because, as covered in the Literature Review, children seem to have developed the ability to recognise and utilise syllable units in other language tasks using visually presented text. However, as seen in the study by Kandel and Valdois (2006b) who looked at first grade 6-7 year olds and second grade 7-8 year olds, this age group could have potentially spanned 2 school grades. For Experiment 3 which focused on the role of syllable units, this was not a problem, because children's data were collected in the second and third school terms of the year. According to the current National Curriculum (Department of Education, 2013) issued for the next year when the data collection started, English children should be taught to use syllable units in spelling by the end of Year 1 (age 5-6), and revision of this might occur in the first term of Year 2 (age 6-7). This means that in the time period in which data for Experiment 3 were collected, even the youngest 7 year old child should have been taught to recognise and use syllable units.

This then leads to consideration of a practical challenge for upcoming research, that of assessing the preference for functional units of children younger than 7. Physical size of the children was important, as found in the Experiments using mobile eye tracking. As described in Chapter 2, page 53, the Dikablis mobile eye tracker is worn in a similar fashion as spectacles, with a nose rest. During testing sessions with physically small children, the nose rest was sometimes ineffective at stabilising the head unit during trials that contained several gaze lifts. Regular breaks were taken to ensure the children's comfort, and re-calibration was often needed to ensure high quality data. However, the Dikablis eye tracker is likely to be impractical for use with children below the age of 7 years old without an adaptation of the head unit for these physically smaller children.

Once the data was collected, another of the greatest challenges in the Thesis was the extent of hand-coding required. This limited the practicality of sample sizes, and future research, especially in relation to individual difference, would benefit from a much larger sample. As mentioned in Chapter 7, new updates to the software reduce the amount of hand-coding, offering a promising tool for future studies.

8.5 Next Steps for Future Research

The copying paradigm might seem simple, but this Thesis has shown that it is could indeed be a valuable tool to look at an array of exciting topics within cognitive science. Future research using the copying paradigm could branch out in several directions, and some of those directions that arise most apparently from the current research are that of: investigating the co-ordination of visual encoding and written production; assessing the span in which individuals can visually encode useful information during copying; the emergence of a preference for different functional units in relation to the age of copiers, and the language of the stimuli; incorporating time delays and secondary tasks to examine the role of different components of working memory in an experimental approach; and advancing copying research into special populations, in particularly developmental samples such as children with dyslexia. After considering each of these directions, future research will be considered in terms of relating copying performance to additional measures of cognition.

8.5.1 Investigating the co-ordination of visual encoding and written production.

One conclusion that does emerge from the current copying research is a necessity for time-based measures in future research to aspire towards an equal focus on sub-processes of both visual encoding and production. Though there is a growing number of copying studies focused on written production as discussed in the Literature Review, sometimes these studies are at a disadvantage in terms of relating their detailed measures of written production to less detailed or lack of measures in relation to encoding. In seeking to redress this balance, the current study sought to use the same dependent measure, eye movements, as an indicator of both encoding and written production behaviour. This was most successful in the younger children who regularly produced words in partial word units, so gaze lifts provided an indicator of the units in which writing events were programmed. However, for the older children and adult copiers, a more detailed measure of written production would be beneficial. The Eye

and Pen software (Alamargot et al., 2006) developed with the aim of synchronising eye movement records and pen movement records is so far only compatible with a small range of mobile eye trackers, the Dikablis eye tracker not being one of those compatible eye trackers. As discussed in previous chapters, the methods needed to achieve this co-registration mean that the copying paradigm does not occur in a naturalistic setting. This would perhaps present a practical barrier to quickly and efficiently collecting data within a school without intimidating or unintentionally changing the behaviour of young children. So far, in order to further investigate detailed co-ordination of visual encoding and written production, one direction of research could focus on advancing technology or software so as to synchronise digitised pen movements and eye movements in a mobile copying paradigm.

8.5.1 Assessing the span in which individuals can visually encode useful information during copying.

Another area of uncertainty outlined towards the beginning of this Thesis concerned the amount of information copiers can encode within a single fixation, and how much upcoming information in the parafovea is useful. Recall in relation to the work of Inhoff and colleagues that copiers visually extract far less information around the point of fixation during a copytyping task compared to a sentence reading task. Understanding how much information adults and children extract from each fixation during copying became a critical point in Experiment 1 when thinking about how children could avoid automatic word recognition. In addition, a direct comparison of children's span of effective vision in different visual word processing tasks such as reading, lexical decision, word naming and copying could be another approach towards ranking the task difficulty associated with encoding as a consequence of additional task demands. This was one of the surprising findings from the indirect comparisons between Experiment 1 in Chapter 3 and Experiment 2 in Chapter 4, in which children spent much longer looking at a word during lexical decision than copying. This was attributed to ongoing cognitive operations in the decision process rather than the time-course of visually accessing the information, though this was not experimentally confirmed. In the current mobile eye tracking paradigm required for studying a handwritten mode of production, equivalent gaze contingent moving window paradigms would not be possible. This is because the gaze location is calculated in relation to the areas of interest in the visual environment on a post hoc manner, rather than detecting these areas live on a frame-by-frame basis. In addition, the temporal detail in mobile eye

trackers such as the Dikablis is not yet high enough to conduct these Experiments accurately. However, in a similar vein as the disappearing text paradigm presented in sentence reading research (Liversedge et al., 2004), it could potentially be possible to control the amount of information available to copiers during the initial encoding period, and the time for which this information remains available. In this paradigm, after fixation on a word, the word remains visually available for a limited time period, the idea being that if the limited time period is shorter than that necessary to extract the visual information, reading will be disrupted in comparison to conditions of unlimited visual extraction time in which the word does not disappear. In reading tasks, even children can capture all the visual information needed from a word within 60ms, yet they often spend about 300ms looking at a word when reading (Blythe et al., 2009). Adapting a similar paradigm in a copying task might contribute towards developing an understanding of how much of the initial encoding period is taken up with operations of visually capturing information, and also with performing further cognitive processing operations on the visually encoded information. Furthermore, manipulating the number of letters in the word that disappear might be a way of bridging the disappearing text paradigm of Liversedge et al. (2004) with the seminal moving window paradigm of McConkie and Rayner (1975) used in Inhoff's copytyping research. Upon presentation of the stimulus in initial encoding, there would be a limited time period in which all the letters of a word are visually available, but then an increasing number of letters disappear from the end of the word after a certain time. This would provide an opportunity to examine the exact number of letters adults and children visually extract within a certain time-period during the encoding sub-process of a copying task without requiring gaze contingent methods.

8.5.2 The emergence of a preference for different functional units.

As mentioned several times throughout this Thesis, children develop awareness and efficient use of a range of different linguistic units as they develop print experience and literacy skills. Investigating the extent to which children of different ages are sensitive to these different linguistic units would speak to broader issues in reading development, such as whether preference for small or large linguistic units are developed first. Considering that this Thesis only directly examines children copying in English, there has been a need to continually contextualise the investigation in terms of orthographic grain size (Ziegler & Goswami, 2005; Ziegler et al., 1996). This is primarily because the existing copying literature has predominantly been conducted in

the language of French, with a small handful of studies in Spanish, Catalan, German and Italian. Only three studies examining children's copying have been carried out using English words, none of these provide a direct time-based measure of visual encoding. Therefore, this continuously necessitated estimations of cross-linguistic differences. As argued by Frost (2012), establishing commonalities how individuals process and represent printed text is a core aspect of developing meaningful understanding. Now that the basis of a theoretical framework into a copying task has been systematically built up in this Thesis, directly conducting cross-linguistic research into functional units within each sub-process would be a remarkable way of expanding this understanding in more detail. This would allow an examination of underlying processing mechanisms that develop at a different rate for children learning different languages. For instance, recall how letter position coding develops specificity earlier for children learning English compared to French owing to the need for more precise representations of spelling (Castles et al., 1999; Lete & Fayol, 2013). However, while this would be perhaps one of the most interesting future directions, there are inherent difficulties in cross-linguistic research, practically in creating controlled, comparable stimuli. More fundamental challenges would emerge in establishing an international collaboration within a very new, small field consisting of academics approaching the same paradigm with different opinions on prioritising particular sub-processes, and variation in preferred methods of collecting data.

8.5.3 Incorporating time delays and secondary tasks to examine the role of different components of working memory in an experimental approach.

As brought up in Chapter 7, one of the least specified topics so far has been an understanding of the nature of copiers' mental representations and the mechanisms of memory that are engaged in order to temporarily hold these mental representations in an accessible state. To date, researchers have only adopted an individual differences perspective in looking into the role of short term and working memory during written production in a copying task. This is perhaps one of the areas within the copying literature that has remained in its infancy, despite the existence of a robust understanding of memory mechanisms within the exceptionally well documented area of memory research. One of the obstacles so far in really developing this individual differences approach within such a multi-faceted copying task that consists of multiple sub-processes is that sample size and amount of data needed to make strong claims. However, within a less naturalistic copying task, experimental approaches designed to

prevent some aspect of memory needed for successful copying could advance understanding of the way in which individuals rely on specific memory mechanisms in a copying task. For instance time delays between encoding and production, and secondary tasks alongside a copying task would enable research to quantify how both time and resource management contribute towards efficient copying performance, and the particular components of working memory that are required for success within each sub-process of copying.

8.5.4 Advancing copying research into special populations.

Perhaps one of the hottest topics of future directions might be to consider cognitive processing during copying in relation to both typical populations and special populations. While this might enable a bridging of links between research and practice, it might be ambitious immediate step. The research in this Thesis has really highlighted the need for caution in drawing assumptions from the way in which reading, mental representation and written production processes operate in isolation, and applying these assumptions to the way in which these sub-processes operate in co-ordination. With an expanded understanding of what happens, cognitively, when an individual copies a word, it would indeed be fascinating to identify the nature of cognitive processing in individuals who struggle to read, remember and write information. At the forefront of this investigation into special populations, children with dyslexia are clearly appropriate.

However, one of the critical issues in research comparing typically developing children and children with dyslexia is the notion of differentiating a quantitative, fundamental difference in performance that is beyond that of developmental lag (as reviewed in Velluntino, Fletcher, Jack, Snowling, & Scanlon, 2004). Until more is understood about the development of functional units in typically developing children, concrete next steps towards expectations in atypically developing children cannot be determined.

8.5.5 Relating copying performance to additional measures of cognition.

The research in this Thesis had a primary focus of investigating the encoding sub-process of the copying task in most detail, in contrast to the majority of existing research that primarily studied the written production sub-processes. While children's copying performance was examined in relation to their reading ability and working memory ability, future research might benefit from considering children's writing

ability, in terms of individual tests of spelling ability and handwriting skills. There was wide variation in the time taken to write each word in Experiment 1 and Experiment 3, even between children of a similar age. By understanding how much variance can be accounted for by spelling ability and handwriting fluency, research can speak to explaining differential sensitivity to unit size even in typically developing children. For instance, do children avoid programming writing events in syllable units because they have not yet developed robust long term memory representations of those syllable units for spelling retrieval? Alternatively, is it that some children cannot programme those large writing events because the lack of fluency in their handwriting movements results in syllable rime information being forgotten while initial onset letters are being written?

As seen in Chapter 7 that looked into the extent to which different children consistently operate over syllable sized units, there was differential sensitivity to unit size between children. Children's reading ability and verbal working memory capacity predicted the proportion of gaze lifts that consistently occurred at syllable boundaries. For instance, sound-based units of syllables were more functional as children's reading age increased. To further examine why some phonetic units may be functional for some children, but not others, future research might consider looking at children's copying behaviour in relation to their levels of phonological awareness. It might be that even within a typically developing population, preference for different linguistic units is determined by the extent to which different children are consistently able to identify units of phonemes, onsets, rimes and syllables.

8.6 Final Summary

To summarise, 3 large scale developmental experimental studies have been completed, showing encoding measures, combined with gaze transfer patterns, are very sensitive measures during a copying paradigm. This offered a useful way of investigating the nature of sub word encoding underpinning children's copying. Children seem to employ a flexible range of copying units, and the primary factor that determines the nature of their encoding behaviour, and in turn their production behaviour, is the length of the linguistic unit. Children behave differently when copying long compared to short words, and even within long words, the length of the sub word units further modulates copying behaviour.

In addressing the original research aims, the experiments presented identified the circumstances in which whole word units were functional, over different sub-tasks of a word copying task, for adults and children, and began to identify functional sub word

units as well. The research clarified the relationship between visual encoding and written production, in that written production depended on visual encoding, they may operate on different functional units. Furthermore, for the first time, evidence was presented showing how working memory capacity constrained both encoding and production behaviour. Finally, differences between populations with developing and developed reading abilities were qualified, in that children, still developing reading abilities, relied to a greater extent on assembling a written copy through encoding and producing piecemeal partial word representations.

8.6.1 Concluding comments.

At the very outset of this Thesis, the overarching aim involved developing an understanding of what happens, cognitively, when an individual makes a handwritten copy of a word. This was contextualised within the importance of efficient classroom performance. The paradigm adapted a naturalistic classroom task that required the involvement of the three core aspects that underlie classroom literacy activities: reading, memory and writing. Reflecting on that, perhaps these initial thoughts underestimated the power of a simple copying task. After the surprising results that children do not consistently read word units when they are copied, future research using the paradigm could potentially reach out to informing fundamental on-going cognitive debates, such as the units of linguistic information children employ, and the pace at which this functionality develops. That is not to say the project was without its challenges, and while mobile eye tracking during a single word copying task generated a valuable paradigm to start the basis of a promising technique, perhaps the use of eye movements to measure written production behaviour is limited in its application to populations of copiers that need multiple episodes of encoding for a single word.

From the initial investigation that planned to quantify the role of working memory in efficient classroom performance, the research presented in this Thesis addressed three core topics within cognitive science of reading, mental representation and written production. Some findings questioned the fundamental assumption that it is working memory and not short term memory that is the mechanism by which mental representations of text are held in a temporarily accessible state when encoding information in readiness for written production. The differences between the ways in which children operate in comparison to adults were surprising, as children used qualitatively different processing mechanisms during the encoding period, and relied on behavioural gaze lifts to compensate for forgetting. This led to conceptualising

efficiency not only in terms of time, as first thought, but also in terms of the nature of processing and how compensatory behavioural tools might bridge efficient and successful copying. Indeed, is perhaps success a more relevant concept than efficiency? Finally, the research presented here suggests the use of adapting the copying paradigm to an investigation of more than just classroom performance. The paradigm presented here has the potential to be an exceptionally flexible tool that could be applied to a range of different questions within cognitive, and develop an understanding of how language and memory operate in co-ordination with each other, as in real world tasks, rather than occur in isolation.

REFERENCES

9.1 References

- Abbott, R. D., Berninger, V. W., & Fayol, M. (2010). Longitudinal relationships of levels of language in writing and between writing and reading in grades 1 to 7. *Journal of Educational Psychology, 102*(2), 281–298.
- Afonso, O., & Álvarez, C. J. (2011). Syllable frequency effects in Spanish handwriting production. *Revista de Logopedia Foniatría Y Audiología, 31*(1), 33–38.
- Afonso, O., Alvarez, C. J., & Kandel, S. (2014). Effects of grapheme-to-phoneme probability on writing durations. *Memory & Cognition, 43*(4), 579–592.
- Afonso, O., Suárez-Coalla, P., & Cuetos, F. (2015). Spelling impairments in Spanish dyslexic adults. *Frontiers in Psychology, 6*, 466.
- Alamargot, D., Caporossi, G., Chesnet, D., & Ros, C. (2011). What makes a skilled writer: Working memory and audience awareness during text composition. *Learning and Individual Differences, 21*(5), 505–516.
- Alamargot, D., Chesnet, D., Dansac, C., & Ros, C. (2006). Eye and pen: A new device for studying reading during writing. *Behavior Research Methods, 38*(2), 287–299.
- Alloway, T. P. (2006). How does working memory work in the classroom? *Educational Research, 1*(4), 134–139.
- Alloway, T. P. (2007). *Automated Working Memory Assessment*. London: Pearson.
- Alvarez, C., Garcia-Saavedra, G., Luque, J. L., & Taft, M. (2016). Syllabic parsing in children: A developmental study using visual word-spotting in Spanish. *Journal of Child Language, In Press*, 1–22.
- Alvarez, C. J., Carreiras, M., & Taft, M. (2001). Syllables and morphemes: Contrasting frequency effects in Spanish. *Journal of Experimental Psychology: Learning Memory and Cognition, 27*(2), 545–555.
- Araújo, S., Faísca, L., Bramão, I., Petersson, K. M., & Reis, A. (2014). Lexical and phonological processes in dyslexic readers: Evidence from a visual lexical decision task. *Dyslexia, 20*(1), 38–53.
- Atkinson, R. C., & Shiffrin, R. (1968). Human memory: A proposed system and its control processes. In K. W. Spence & J. T. Spence (Eds.), *The Psychology of Learning and Motivation: Advances in Research and Theory* (Volume 2, pp. 89–195). New York: Academic Press.

- Baddeley, A. (1996). Exploring the central executive. *The Quarterly Journal of Experimental Psychology A*, 49(1), 5–28.
- Baddeley, A. (2003a). Working memory: Looking back and looking forward. *Nature Reviews Neuroscience*, 4(10), 829–839.
- Baddeley, A. (2003b). Working memory and language: An overview. *Journal of Communication Disorders*, 36, 189–208.
- Baddeley, A. D. (1992). Working memory. *Science*, 255(5044), 556–559.
- Baddeley, A. D. (2000). Short Term and Working Memory. In E. Tulving & F. I. M. Craik (Eds.), *The Oxford Handbook of Memory* (pp. 77–92). NY: Oxford University Press.
- Baddeley, A. D., & Hitch, G. J. (1974). Working Memory. *Psychology of Learning and Motivation*, 8, 47–89.
- Baddeley, A., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning And Verbal Behavior*, 14(6), 575–589.
- Balota, D. A., Cortese, M. J., Sergent-Marshall, S. D., Spieler, D. H., & Yap, M. (2004). Visual word recognition of single-syllable words. *Journal of Experimental Psychology*, 133(2), 283–316.
- Balota, D. A., & Neely, J. H. (1980). Test-expectancy and word-frequency effects in recall and recognition. *Journal of Experimental Psychology: Human Learning & Memory*, 6(5), 576–587.
- Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, 68(3), 255–278.
- Barrouillet, P., Gavens, N., Vergauwe, E., Gaillard, V., & Camos, V. (2009). Working memory span development: A time-based resource-sharing model account. *Developmental Psychology*, 45(2), 477–490.
- Bates, D., Maechler, M., Bolker, B., & Walker, S. (2014). *lme4: Linear mixed-effects models using Eigen and S4*, R package version 1.1-7. Retrieved from <http://cran.r-project.org/package=lme4>.
- Berninger, V. W., & Amtmann, D. (2003). Preventing written expression disabilities through early and continuing assessment and intervention for handwriting and/or spelling problems: Research into practice. In H. Swanson, K. Harris, & S. Graham (Eds.) *Handbook of Learning Disabilities* (pp. 345-363). New York: Guilford Press.

- Berninger, V. W., & Winn, W. D. (2006). Implications of advancements in brain research and technology for writing development, writing instruction, and educational evolution. In C. MacArthur, S. Graham, & J. Fitzgerald (Eds.), *Handbook of Writing Research* (pp. 96-114). New York: Guilford Press.
- Blythe, H. I., Häikiö, T., Bertam, R., Liversedge, S. P., & Hyönä, J. (2011). Reading disappearing text: Why do children refixate words? *Vision Research*, *51*(1), 84–92.
- Blythe, H. I., & Joseph, H. S. S. L. (2011). Children's eye movements during reading. In S. P. Liversedge, I. Gilchrist, & S. Everling (Eds.), *The Oxford Handbook of Eye Movements* (pp. 643–662). Oxford, England: Oxford University Press.
- Blythe, H. I., Liversedge, S. P., Joseph, H. S. S. L., White, S. J., Findlay, J. M., & Rayner, K. (2006). The binocular coordination of eye movements during reading in children and adults. *Vision Research*, *46*(22), 3898–3908.
- Blythe, H. I., Liversedge, S. P., Joseph, H. S. S. L., White, S. J., & Rayner, K. (2009). Visual information capture during fixations in reading for children and adults. *Vision Research*, *49*(12), 1583–1591.
- Borgwaldt, S. R., Hellwig, F. M., & De Groot, A. M. B. (2005). Onset entropy matters: Letter-to-phoneme mappings in seven languages. *Reading and Writing*, *18*(3), 211–229.
- Borzone de Manrique, A. M., & Signorini, A. (1994). Phonological awareness, spelling and reading abilities in Spanish-speaking children. *British Journal of Psychology*, *64*(3), 429–439.
- Bosman, E. A. (1993). Age-related differences in the motoric aspects of transcription typing skill. *Psychology and Aging*, *8*(1), 87–102.
- Bosse, M.-L., Kandel, S., Prado, C., & Valdois, S. (2014). Does visual attention span relate to eye movements during reading and copying? *International Journal of Behavioral Development*, *38*(1), 81–85.
- Bosse, M.-L., & Valdois, S. (2009). Influence of the visual attention span on child reading performance: a cross-sectional study. *Journal of Research in Reading*, *32*(2), 230–253.
- Bowey, J. A. (1990). Orthographic onsets and rimes as functional units of reading. *Memory Cognition*, *18*(4), 419–427.
- Bowey, J. A. (1996). Orthographic onsets as functional units of adult word recognition. *Journal of Psycholinguistic Research*, *25*(5), 571–595.

- Brown, C. M. "Lin." (1988). Comparison of Typing and Handwriting in "Two-Finger Typists." *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 32(5), 381–385.
- Brown, G. D. A., & Watson, F. L. (1987). First in, first out: Word learning age and spoken word frequency as predictors of word familiarity and word naming latency. *Memory & Cognition*, 15(3), 208–216.
- Brysbart, M., & Nazir, T. (2005). Visual constraints in written word recognition: Evidence from the optimal viewing-position effect. *Journal of Research in Reading*, 28(3), 216–228.
- Bub, D. N., Masson, M. E. J., & Lalonde, C. E. (2006). Cognitive control in children: Stroop interference and suppression of word reading. *Psychological Science*, 17(4), 351–357.
- Butler, B., & Hains, S. (1979). Individual differences in word recognition latency. *Memory & Cognition*, 7(2), 68–76.
- Cain, K., Oakhill, J., & Bryant, P. (2004). Children's reading comprehension ability: Concurrent prediction by working memory, verbal ability, and component skills. *Journal of Educational Psychology*, 96(1), 31–42.
- Cantor, J., Engle, R. W., & Hamilton, G. (1991). Short-term memory, working memory and verbal abilities: How do they relate? *Intelligence*, 15, 229–246.
- Caramazza, A., & Hillis, A. E. (1990). Levels of representation, co-ordinate frames, and unilateral neglect. *Cognitive Neuropsychology*, 7(5), 391–445.
- Carreiras, M., Alvarez, C. J., & de Vega, M. (1993). Syllable frequency and visual word recognition in Spanish. *Journal of Memory and Language*, 32, 766–780.
- Carreiras, M., & Perea, M. (2002). Masked priming effects with syllabic neighbors in a lexical decision task. *Journal of Experimental Psychology: Human Perception and Performance*, 28(5), 1228–1242.
- Carroll, J. M., Snowling, M. J., Hulme, C., & Stevenson, J. (2003). The development of phonological awareness in preschool children. *Developmental Psychology*, 39(5), 913–923.
- Case, R., Kurland, D. M., & Goldberg, J. (1982). Operational efficiency and the growth of short-term memory span. *Journal of Experimental Child Psychology*, 33, 386–404.
- Castles, A., Davis, C., Cavalot, P., & Forster, K. (2007). Tracking the acquisition of orthographic skills in developing readers: Masked priming effects. *Journal of Experimental Child Psychology*, 97(3), 165–182.

- Castles, A., Davis, C., & Letcher, T. (1999). Neighbourhood effects on masked form priming in developing readers. *Language & Cognitive Processes, 14*(2), 201–224.
- Chall, J. S. (1983). *Stages of reading development*. New York: McGraw-Hill.
- Clifton, C., Ferreira, F., Henderson, J. M., Inhoff, A. W., Liversedge, S. P., Reichle, E. D., & Schotter, E. R. (2015). Eye movements in reading and information processing: Keith Rayner's 40year legacy. *Journal of Memory and Language, 86*, 1-19.
- Clifton, C., Staub, A., & Rayner, K. (2007). Eye movements in reading words and sentences. In R. van Gompel, M. H. Fischer, W. S. Murray, & R. L. Hill (Eds.), *Eye Movements: A Window on Mind and Brain* (pp. 341–372). Elsevier Ltd.
- Colé, P., Magnan, A., & Grainger, J. (1994). The development of orthographic rimes as units of word recognition. *Journal of Experimental Child Psychology, 58*(3), 465–488.
- Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review, 108*(1), 204–56.
- Coltheart, V., Avons, S. E., & Trollope, J. (1990). Articulatory suppression and phonological codes in reading for meaning. *The Quarterly Journal of Experimental Psychology, 42*(2), 375–399.
- Cowan, N. (2008). What are the differences between long-term, short-term, and working memory? *Progress in Brain Research, 169*(7), 323–338.
- Cowan, N., & Alloway, T. P. (2009). The development of working memory in childhood. In N. Cowan & M. Courage (Eds.), *The development of memory in infancy and childhood*. (pp. 303–342). United Kingdom: Psychology Press.
- Cronbach, L. J. (1957). The two disciplines of scientific psychology. *American Psychologist, 12*(11), 671–684.
- Crump, M. J. C., & Logan, G. D. (2010). Hierarchical control and skilled typing: evidence for word-level control over the execution of individual keystrokes. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*(6), 1369–1380.
- Cutler, A., Hawkins, J. A., & Gilligan, G. (1985). The suffixing preference: A processing explanation. *Linguistics, 23*(5), 723–758.

- Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory during reading. *Journal of Verbal Learning And Verbal Behavior*, 19(4), 450–466.
- Davis, C. J. (2010). The spatial coding model of visual word identification. *Psychological Review*, 117(3), 713–758.
- de Zeeuw, M., Schreuder, R., & Verhoeven, L. T. W. (2014). Lexical processing of nominal compounds in first- and second-language learners across primary grades. *Writing Systems Research*, 7(2), 133–156.
- Devonshire, V., Morris, P., & Fluck, M. (2013). Spelling and reading development: The effect of teaching children multiple levels of representation in their orthography. *Learning and Instruction*, 25, 85–94.
- Department for Education. (2013). *The national curriculum in England*.
- Department for Education and Skills. (2014). *Department for Education 'Evidence check' memorandum: Phonics policy*.
- Di Filippo, G., de Luca, M., Judica, A., Spinelli, D., & Zoccolotti, P. (2006). Lexicality and stimulus length effects in Italian dyslexics: Role of the overadditivity effect. *Child Neuropsychology: A Journal on Normal and Abnormal Development in Childhood and Adolescence*, 12(2), 141–9.
- Drewnowski, A., & Healy, A. F. (1980). Missing -ing in reading: Letter detection errors on word endings. *Journal of Verbal Learning and Verbal Behavior*, 19(3), 247–262.
- Duchowski, A. T. (2007). *Eye tracking methodology: Theory and practice* (2nd ed.). London: Springer-Verlag.
- Ducrot, S., Pynte, J., Ghio, A., & Lété, B. (2013). Visual and linguistic determinants of the eyes' initial fixation position in reading development. *Acta Psychologica*, 142(3), 287–298.
- Education Standards Research Team. (2012). *What is the research evidence on writing?*
- Ehri, L. C. (1991). Development of the ability to read words. In M. L. Barr, P. Kamil, P. B. Mosenthal, & P. D. Pearson (Eds.), *Handbook of reading research* (Vol. II, pp. 383–417). NY: Longman.
- Ehri, L. C. (2000). Learning to read and learning to spell: Two sides of a coin. *Topics in Language Disorders*, 20(3), 19–36.
- Ehri, L. C. (2010). Development of Sight Word Reading: Phases and Findings. In M. Snowling & C. Hulme (Eds.) *The Science of Reading: A Handbook* (pp. 135–155). Malden, MA: Blackwell Publishing Ltd.

- Engbert, R., Longtin, A., & Kliegl, R. (2002). A dynamical model of saccade generation in reading based on spatially distributed lexical processing. *Vision Research*, *42*, 621–636.
- Fischer-Baum, S., Charny, J., & McCloskey, M. (2011). Both-edges representation of letter position in reading. *Psychonomic Bulletin Review*, *18*(6), 1083–1089.
- Fox, B., & Routh, D. K. (1975). Analyzing spoken language into words, syllables, and phonemes: A developmental study. *Journal of Psycholinguistic Research*, *4*(4), 331–342.
- Frazier, L., & Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology*, *14*(2), 178–210.
- Frith, U. (1985). Beneath the surface of developmental dyslexia. In K. Patterson, J. Marshall, & M. Coltheart (Eds.), *Surface dyslexia: Neuropsychological and cognitive studies of phonological reading* (pp. 301–330). London: Erlbaum.
- Frost, R. (2012). Towards a universal model of reading. *Behavioral and Brain Sciences*, *35*(5), 263–279.
- Gathercole, S. E., & Adams, A.-M. (1994). Children's phonological working memory: Contributions of long-term knowledge and rehearsal. *Journal of Memory and Language*, *33*, 672–688.
- Gathercole, S. E., Pickering, S. J., Ambridge, B., & Wearing, H. (2004). The structure of working memory from 4 to 15 years of age. *Developmental Psychology*, *40*(2), 177–190.
- Gentner, D. R., Larochelle, S., & Grudin, J. (1988). Lexical, sublexical, and peripheral effects in skilled typewriting. *Cognitive Psychology*, *20*(4), 524–548.
- Goldstein, D. M. (1976). Cognitive-linguistic functioning and learning to read in preschoolers. *Journal of Educational Psychology*, *68*(6), 680–688.
- Gomez, P., Ratcliff, R., & Perea, M. (2008). The overlap model: A model of letter position coding. *Psychological Review*, *115*(3), 577–600.
- Goswami, U. (2008). The development of reading across languages. *Annals of the New York Academy of Sciences*, *1145*, 1–12.
- Goswami, U., Ziegler, J. C., Dalton, L., & Schneider, W. (2003). Nonword reading across orthographies: How flexible is the choice of reading units? *Applied Psycholinguistics*, *24*(2), 235–247.

- Grabowski, J., Weinzierl, C., & Schmitt, M. (2010). Second and fourth graders' copying ability: From graphical to linguistic processing. *Journal of Research in Reading, 33*(1), 39–53.
- Graham, S., Berninger, V., Weintraub, N., & Schafer, W. (1998). Development of handwriting speed and legibility in grades 1-9. *The Journal of Educational Research, 92*(1), 42–52.
- Graham, S., Weintraub, N., & Berninger, V. (2001). Which manuscript letters do primary grade children write legibly. *Journal of Educational Psychology, 93*(3), 488–497.
- Grainger, J., & Ziegler, J. C. (2011). A Dual-Route Approach to Orthographic Processing. *Frontiers in Psychology, 2*(54), doi: 10.3389/fpsyg.2011.00054.
- Grudin, J. T. (1983). Error Patterns in Novice and Skilled Transcription Typing. In W. E. Cooper (Ed.), *Cognitive aspects of skilled typewriting* (pp. 121–143). New York: Springer-Verlag.
- Hale, S., Bronik, M. D., & Fry, A. F. (1997). Verbal and spatial working memory in school-age children: Developmental differences in susceptibility to interference. *Developmental Psychology, 33*(2), 364–371.
- Hardiess, G., Gillner, S., & Mallot, H. A. (2008). Head and eye movements and the role of memory limitations in a visual search paradigm. *Journal of Vision, 8*(1), 1–13.
- Hautala, J., Hyönä, J., Aro, M., & Lyytinen, H. (2011). Sublexical effects on eye movements during repeated reading of words and pseudowords in Finnish. *Psychology of Language and Communication, 15*(2), 129–149.
- Hayes, J. R. (1996). A new framework for understanding cognition and affect in writing. In C. M. Levy & S. Ransdell (Eds.), *The science of writing: Theories, methods, individual differences, and applications* (pp. 1–27). Mahwah, NJ: Lawrence Erlbaum.
- Hayes, J. R., & Chenoweth, N. A. (2006). Is working memory involved in the transcribing and editing of texts. *Written Communication, 23*(2), 135–149.
- Hayes, J. R., & Flower, L. S. (1980). Identifying the organization of writing processes. In L. W. Gregg & E. R. Steinberg (Eds.), *Cognitive Processes in Writing* (pp. 3–30). Hillsdale, NJ: Erlbaum.
- Henderson, J. M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control.

- Journal of Experimental Psychology: Learning, Memory, and Cognition*, 16(3), 417–429.
- Hoedemaker, R. S., & Gordon, P. C. (2014). It takes time to prime: Semantic priming in the ocular lexical decision task. *Journal of Experimental Psychology: Human Perception and Performance*, 40(6), 2179–2197.
- Houghton, G., & Zorzi, M. (2003). Normal and impaired spelling in a connectionist dual-route architecture. *Cognitive Neuropsychology*, 20(2), 115–62.
- Hudson, P. T. W., & Bergman, M. W. (1985). Lexical knowledge in word recognition: Word length and word frequency in naming and lexical decision tasks. *Journal of Memory and Language*, 24(1), 46–58.
- Huestegge, L., Radach, R., Corbic, D., & Huestegge, S. M. (2009). Oculomotor and linguistic determinants of reading development: A longitudinal study. *Vision Research*, 49(24), 2948–2959.
- Huey, E. B. (1898). Preliminary experiments in the physiology and psychology of reading. *The American Journal of Psychology*, 9(4), 575–586.
- Hyönä, J., & Olson, R. K. (1995). Eye fixation patterns among dyslexic and normal readers: effects of word length and word frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 21(6), 1430–1440.
- Inhoff, A. W. (1984). Two stages of word processing during eye fixations in the reading of prose. *Journal of Verbal Learning and Verbal Behavior*, 23(5), 612–624.
- Inhoff, A. W. (1991). Word frequency during copytyping. *Journal of Experimental Psychology: Human Perception and Performance*, 17(2), 478–487.
- Inhoff, A. W., Briehl, D., Bohemier, G., & Wang, J. (1992). Eye-hand span and coding of text during copytyping. *Journal of Experimental Psychology Learning Memory and Cognition*, 18(2), 298–306.
- Inhoff, A. W., & Gordon, A. M. (1997). Eye movements and eye-hand coordination during typing. *Current Directions in Psychological Science*, 6(6), 153–157.
- Inhoff, A. W., Morris, R., & Calabrese, J. (1986). Eye movements in skilled transcription typing. *Bulletin of the Psychonomic Society*, 24(2), 113–114.
- Inhoff, A. W., & Wang, J. (1992). Encoding of text, manual movement planning, and eye-hand coordination during copytyping. *Journal of Experimental Psychology: Human Perception and Performance*, 18(2), 437–448.
- Joseph, H. S. S. L., Liversedge, S. P., Blythe, H. I., White, S. J., & Rayner, K. (2009). Word length and landing position effects during reading in children and adults. *Vision Research*, 49(16), 2078–2086.

- Joseph, H. S. S. L., Nation, K., & Liversedge, S. P. (2013). Using eye movements to investigate word frequency effects in children's sentence reading. *School Psychology Review, 42*(2), 207–222.
- Just, M. A., & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review, 87*, 329–354.
- Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review, 99*(1), 122–149.
- Kail, R. (1997). Phonological skill and articulation time independently contribute to the development of memory span. *Journal of Experimental Child Psychology, 67*, 57–68.
- Kail, R., & Park, Y.-S. (1994). Processing time, articulation time, and memory span. *Journal of Experimental Child Psychology, 57*, 281–291.
- Kandel, S., Alvarez, C. J., & Vallée, N. (2006). Syllables as processing units in handwriting production. *Journal of Experimental Psychology: Human Perception and Performance, 32*(1), 18–31.
- Kandel, S., Alvarez, C. J., & Vallée, N. (2008). Morphemes also serve as processing units in handwriting production. In M. Baciú (Ed.), *Neuropsychology and cognition of language: Behavioural, neuropsychological and neuroimaging studies of spoken and written language* (pp. 87–100). Kerala, India: Research Signpost.
- Kandel, S., Hérault, L., Grosjacques, G., Lambert, E., & Fayol, M. (2009). Orthographic vs. phonologic syllables in handwriting production. *Cognition, 110*(3), 440–444.
- Kandel, S., Peereman, R., & Ghimenton, A. (2014). How do we code the letters of a word when we have to write it? Investigating double letter representation in French. *Acta Psychologica, 148*, 56–62.
- Kandel, S., Peereman, R., Grosjacques, G., & Fayol, M. (2011). For a psycholinguistic model of handwriting production: Testing the syllable-bigram controversy. *Journal of Experimental Psychology: Human Perception and Performance, 37*(4), 1310–1322.
- Kandel, S., & Perret, C. (2015). How does the interaction between spelling and motor processes build up during writing acquisition? *Cognition, 136*, 325–336.
- Kandel, S., & Soler, O. (2010). Differential syllable effects when learning to write French and Catalan words. *Current Psychology Letters, 25*(3), 1–12.
- Kandel, S., Soler, O., Valdois, S., & Gros, C. (2006). Graphemes as motor units in the acquisition of writing skills. *Reading and Writing, 19*(3), 313–337.

- Kandel, S., & Spinelli, E. (2010). Processing complex graphemes in handwriting production. *Memory & Cognition*, 38(6), 762–770.
- Kandel, S., Spinelli, E., Tremblay, A., Guerassimovitch, H., & Alvarez, C. J. (2012). Processing prefixes and suffixes in handwriting production. *Acta Psychologica*, 140(3), 187–195.
- Kandel, S., & Valdois, S. (2005). The effect of orthographic regularity on children's organisation of handwriting production. *Current Psychology Letters: Behavior, Brain and Cognition*, 17(3), 1–11.
- Kandel, S., & Valdois, S. (2006a). French and Spanish-speaking children use different visual and motor units during spelling acquisition. *Language & Cognitive Processes*, 21(5), 531–561.
- Kandel, S., & Valdois, S. (2006b). Syllables as functional units in a copying task. *Language & Cognitive Processes*, 21(4), 432–452.
- Kellogg, R. T. (1999). Components of working memory in text production. In M. Torrance & G. C. Jeffery (Eds.), *The cognitive demands of writing: Processing capacity and working memory in text production* (pp. 42–61). Amsterdam, The Netherlands: Amsterdam University Press.
- Kennedy, A., Radach, R., Heller, D., & Pynte, J. (Eds.). (2000). *Reading as a Perceptual Process*. Oxford, England: Elsevier Science.
- Kennedy, E., Dunphy, E., Dwyer, B., Hayes, G., McPhillips, T., Marsh, J., ... Shiel, G. (2012). *Literacy in Early Childhood and Primary Education*. Dublin: National Council for Curriculum and Assessment.
- Kirkby, J., Webster, L., Blythe, H., & Liversedge, S. (2008). Binocular coordination during reading and non-reading tasks. *Psychological Bulletin*, 134(5), 742–763.
- Kuperman, V., Stadthagen-Gonzalez, H., & Brysbaert, M. (2012). Age-of-acquisition ratings for 30 thousand English words. *Behavior Research Methods*, 44(4), 978–990.
- Kwon, M., Legge, G. E., & Dubbels, B. R. (2007). Developmental changes in the visual span for reading. *Vision Research*, 47(22), 2889–2900.
- Lambert, E., Alamargot, D., Larocque, D., & Caporossi, G. (2011). Dynamics of the spelling process during a copy task: Effects of regularity and frequency. *Canadian Journal of Experimental Psychology*, 65(3), 141–150.
- Lambert, E., Kandel, S., Fayol, M., & Espéret, E. (2008). The effect of the number of syllables on handwriting production. *Reading and Writing*, 21(9), 859–883.

- Lambert, E., Sausset, S., & Rigalleau, F. (2015). The ortho-syllable as a processing unit in handwriting: The mute e effect. *Reading and Writing, 28*, 683–698.
- Leigh, R. J., & Zee, D. S. (1991). *The neurology of eye movements* (5th ed.). New York: Oxford University Press.
- Lete, B., & Fayol, M. (2013). Substituted-letter and transposed-letter effects in a masked priming paradigm with French developing readers and dyslexics. *Journal of Experimental Child Psychology, 114*(1), 47–62.
- Lewellen, M. J., Goldinger, S. D., Pisoni, D. B., & Greene, B. G. (1993). Lexical familiarity and processing efficiency: Individual differences in naming, lexical decision, and semantic categorization. *Journal of Experimental Psychology: General, 122*(3), 316–330.
- Liversedge, S. P., & Findlay, J. . M. (2000). Saccadic eye movements and cognition. *Trends in Cognitive Sciences, 4*(1), 6–14.
- Liversedge, S. P., Rayner, K., White, S. J., Vergilino-Perez, D., Findlay, J. M., & Kentridge, R. W. (2004). Eye movements when reading disappearing text: is there a gap effect in reading? *Vision Research, 44*(10), 1013–1024.
- Locke, J. (1689). *An essay concerning human understanding*. (P. Nidditch, Ed.). Oxford: Clarendon Press, 1975.
- Luque, J. L., López-Zamora, M., Alvarez, C. J., & Bordoy, S. (2013). Beyond decoding deficit: Inhibitory effect of positional syllable frequency in dyslexic Spanish children. *Annals of Dyslexia, 63*(3–4), 239–52.
- Maïonchi-Pino, N., Magnan, A., & Écalle, J. (2010). Syllable frequency effects in visual word recognition: Developmental approach in French children. *Journal of Applied Developmental Psychology, 31*(1), 70–82.
- Martens, V. E. G., & de Jong, P. F. (2006). The effect of word length on lexical decision in dyslexic and normal reading children. *Brain and Language, 98*(2), 140–149.
- Martlew, M. (1992). Handwriting and spelling: Dyslexic children's abilities compared with children of the same chronological age and younger children of the same spelling level. *British Journal of Educational Psychology, 62*(2), 375–390.
- Masterson, J., Stuart, M., Dixon, M., & Lovejoy, S. (2010). Children's printed word database: Continuities and changes over time in children's early reading vocabulary. *British Journal of Psychology, 101*(Pt 2), 221–242.

- McBride-Chang, C., Chung, K. K. H., & Tong, X. (2011). Copying skills in relation to word reading and writing in Chinese children with and without dyslexia. *Journal of Experimental Child Psychology*, *110*(3), 422–433.
- McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics*, *17*, 578–586.
- McConkie, G. W., Rayner, K., & Wilson, S. J. (1973). Experimental manipulation of reading strategies. *Journal of Educational Psychology*, *65*(1), 1–8.
- Mccutchen, D. (2011). From novice to expert: Implications of language skills and writing-relevant knowledge for memory during the development of writing skill. *Journal of Writing Research*, *3*(1), 51–68.
- Medler, D. A., & Binder, J. R. (2005). MCWord: *An on-line orthographic database of the English language*. Retrieved from <http://www.neuro.mcw.edu/mcword/>
- Miellat, S., O'Donnell, P. J., & Sereno, S. C. (2009). Parafoveal magnification: Visual acuity does not modulate the perceptual span in reading. *Psychological Science*, *20*(6), 721–728.
- Miller, G. A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological Review*, *101*(2), 343–352.
- Miller, G. A., Galanter, E., & Pribram, K. H. (1960). *Plans and the structure of behavior*. New York, Holt: Rinehart & Winston.
- Morrison, C. M., & Ellis, A. W. (1995). Roles of word frequency and age of acquisition in word naming and lexical decision. *Journal Of Experimental Psychology: Learning Memory And Cognition*, *21*(1), 116–133.
- Morrison, R. E., & Rayner, K. (1981). Saccade size in reading depends upon character spaces and not visual angle. *Perception & Psychophysics*, *30*(4), 395–396.
- Murray, D. J. (1968). Articulation and acoustic confusability in short-term memory. *Journal of Experimental Psychology*, *78*(4), 679–684.
- Nairne, J. S. (1990). A feature model of immediate memory. *Memory & Cognition*, *18*(3), 251–269.
- Nation, K., & Snowling, M. J. (2004). Beyond phonological skills: Broader language skills contribute to the development of reading. *Journal of Research in Reading*, *27*(4), 342–356.
- Nelson, J. D., Cottrell, G. W., Movellan, J. R., & Sereno, M. I. (2004). Yarbus lives: A foveated exploration of how task influences saccadic eye movement. *Journal of Vision*, *4*(8), 741.

- Oberauer, K., & Kliegl, R. (2001). Beyond resources: Formal models of complexity effects and age differences in working memory. *European Journal of Cognitive Psychology, 13*(1–2), 187–215.
- Orsini, A., D. G., E. C., M. L., Papagno, C., & Vallar, G. (1987). Verbal and spatial immediate memory span: Normative data from 1355 adults and 1112 children. *The Italian Journal of Neurological Sciences, 8*(6), 537–548.
- Ostry, D. J. (1983). Determinants of interkey times in typing. In W. E. Cooper (Ed.), *Cognitive aspects of skilled typewriting* (pp. 225–246). Heidelberg, Berlin: Springer Verlag.
- Pammer, K., Lavis, R., Hansen, P., & Cornelissen, P. L. (2004). Symbol-string sensitivity and children's reading. *Brain and Language, 89*, 601–610.
- Paterson, K., Liversedge, S. P., Rowland, C., & Filik, R. (2003). Children's comprehension of sentences with focus particles. *Cognition, 89*, 263–294.
- Perfetti, C. A., & Hart, L. (2002). The lexical quality hypothesis. In L. Verhoeven, C. Elbro, & P. Reitsma (Eds.), *Precursors of functional literacy* (pp. 189–213). Amsterdam and Philadelphia, PA: John Benjamins.
- Plaut, D. C., McClelland, J. L., & Seidenberg, M. S. (1996). Understanding normal and impaired word reading: Computational principles in quasi-regular domains. *Psychological Bulletin, 103*(1), 56–115.
- Pollatsek, A., Juhasz, B. J., Reichle, E. D., Machacek, D., & Rayner, K. (2008). Immediate and delayed effects of word frequency and word length on eye movements in reading: A reversed delayed effect of word length. *Journal of Experimental Psychology: Human Perception and Performance, 34*(3), 726–750.
- Prinzmetal, W., Treiman, R., & Rho, S. H. (1986). How to see a reading unit. *Journal of Memory and Language, 25*(4), 461–475.
- Pufpaff, L. A. (2009). A developmental continuum of phonological sensitivity skills. *Psychology in the Schools, 46*(7), 679–691.
- Rastle, K., & Coltheart, M. (1998). Whammies and double whammies: The effect of length on nonword reading. *Psychonomic Bulletin & Review, 5*(2), 277–282.
- Rayner, K. (1978). Eye movements in reading and information processing. *Psychological Bulletin, 85*(3), 618–660.
- Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology, 41*(2), 211–236.

- Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*(3), 372–422.
- Rayner, K., & Bertera, J. H. (1979). Reading without a fovea. *Science*, *206*(4417), 468–469.
- Rayner, K., Carlson, M., & Frazier, L. (1983). The interaction of syntax and semantics during sentence processing: Eye movements in the analysis of semantically biased sentences. *Journal of Verbal Learning and Verbal Behavior*, *22*(3), 358–374.
- Rayner, K., & Duffy, S. A. (1986). Lexical complexity and fixation times in reading: effects of word frequency, verb complexity, and lexical ambiguity. *Memory & Cognition*, *14*(3), 191–201.
- Rayner, K., Foorman, B. R., Perfetti, C. A., Pesetsky, D., & Seidenberg, M. S. (2001). How psychological science informs the teaching of reading. *Psychological Science*, *2*, 31–74.
- Rayner, K., Inhoff, A. W., Morrison, R. E., Slowiaczek, M. L., & Bertera, J. H. (1981). Masking of foveal and parafoveal vision during eye fixations in reading. *Journal of Experimental Psychology. Human Perception and Performance*, *7*(1), 167–179.
- Rayner, K., & McConkie, G. W. (1976). What guides a reader's eye movements? *Vision Research*, *16*(8), 829–837.
- Rayner, K., Sereno, S. C., Morris, R. K., Schmauder, A. R., & Clifton, C. (1989). Eye movements and on-line language comprehension processes. *Language and Cognitive Processes*, *4*(3–4), SI21-SI49.
- Rayner, K., Sereno, S. C., & Raney, G. E. (1996). Eye movement control in reading: a comparison of two types of models. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(5), 1188–1200.
- Rayner, K., Well, A. D., & Pollatsek, A. (1980). Asymmetry of the effective visual field in reading. *Perception and Psychophysics*, *27*(6), 537–544.
- RCoreTeam. (2015). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from <http://www.r-project.org/>
- Re, A. M., & Cornoldi, C. (2015). Spelling errors in text copying by children with dyslexia and ADHD Symptoms. *Journal of Learning Disabilities*, *48*(1), 73–82.
- Reichle, E. D., Pollatsek, A., Fisher, D. L., & Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological Review*, *105*(1), 125–157.

- Reichle, E. D., Pollatsek, A., & Rayner, K. (2006). E-Z Reader: A cognitive-control, serial-attention model of eye-movement behavior during reading. *Cognitive Systems Research*, 7, 4–22.
- Reichle, E. D., Tokowicz, N., Liu, Y., & Perfetti, C. a. (2011). Testing an assumption of the E-Z Reader model of eye-movement control during reading: Using event-related potentials to examine the familiarity check. *Psychophysiology*, 48(7), 993–1003.
- Reilhac, C., Jucla, M., Iannuzzi, S., Valdois, S., & Demonet, J.-F. (2012). Effect of orthographic processes on letter identity and letter-position encoding in dyslexic children. *Frontiers in Psychology*, 3, (154) doi: 10.3389/fpsyg.2012.00154.
- Rey, A., Ziegler, J. C., & Jacobs, A. M. (2000). Graphemes are perceptual reading units. *Cognition*, 75(1), B1–B12.
- Richter, E. M., Engbert, R., & Kliegl, R. (2006). Current advances in SWIFT. *Psychological Review*, 112, 777–813.
- Rieben, L., & Saada-Robert, M. (1991). Developmental patterns and individual differences in the word-search strategies of beginning readers. *Learning and Instruction*, 1(1), 67–87.
- Rieben, L., & Saada-Robert, M. (1997). Relation between word-search strategies and word-copying strategies in children aged 5-6 years old. In C. A. Perfetti, L. Rieben, & M. Fayol (Eds.), *Learning to Spell: Research, Theory, and Practice Across Languages* (pp. 295–318). New Jersey: Lawrence Erlbaum.
- Rieben, L., Saada-Robert, M., & Moro, C. (1997). Word-search strategies and stages of word recognition. *Learning and Instruction*, 7(2), 137–159.
- Salamé, P., & Baddeley, A. (1982). Disruption of short-term memory by unattended speech: Implications for the structure of working memory. *Journal of Verbal Learning And Verbal Behavior*, 21(2), 150–164.
- Salthouse, T. A. (1984). Effects of age and skill in typing. *Journal of Experimental Psychology: General*, 113(3), 345–371.
- Salthouse, T. A. (1986). Perceptual, cognitive, and motoric aspects of transcription typing. *Psychological Bulletin*, 99(3), 303–319.
- Sampson, G. (1978). Linguistic universals as evidence for empiricism. *Journal of Linguistics*, 14(2), 183–206.
- Sausset, S., Lambert, E., & Olive, T. (2013). Flexibility of orthographic and graphomotor coordination during a handwritten copy task: Effect of time pressure. *Frontiers in Psychology*, 4(NOV), 1–9.

- Sausset, S., Lambert, E., Olive, T., & Larocque, D. (2012). Processing of syllables during handwriting: Effects of graphomotor constraints. *The Quarterly Journal of Experimental Psychology*, *65*(10), 1872–1879.
- Savage, R. S., Deault, L., Daki, J., & Aouad, J. (2011). Orthographic analogies and early reading: Evidence from a multiple clue word paradigm. *Journal of Educational Psychology*, *103*(1), 190–205.
- Schmalz, X., Marinus, E., & Castles, A. (2013). Phonological decoding or direct access? Regularity effects in lexical decisions of Grade 3 and 4 children. *The Quarterly Journal of Experimental Psychology*, *66*(2), 338–346.
- Schoonbaert, S., & Grainger, J. (2004). Letter position coding in printed word perception: Effects of repeated and transposed letters. *Language & Cognitive Processes*, *19*(3), 333–367.
- Seidenberg, M. S., & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review*, *96*(4), 523–568.
- Service, E., & Turpeinen, R. (2001). Working memory in spelling: Evidence from backward typing. *Memory*, *9*, 395–421.
- Seymour, P. H. K., Aro, M., & Erskine, J. M. (2003). Foundation literacy acquisition in European orthographies. *British Journal of Psychology*, *94*(Pt 2), 143–174.
- Seymour, P. H. K., & Duncan, L. G. (1997). Small versus large unit theories of reading acquisition. *Dyslexia*, *3*(3), 125–134.
- Shaffer, L. H. (1978). Timing in the motor programming of typing. *The Quarterly Journal of Experimental Psychology*, *30*(2), 333–345.
- Shaffer, L. H., & Hardwick, J. (1968). Typing performance as a function of text. *The Quarterly Journal of Experimental Psychology*, *20*, 360–369.
- Shaffer, L. H., & Hardwick, J. (1969). Reading and typing. *The Quarterly Journal of Experimental Psychology*, *21*(4), 381–383.
- Share, D. L. (1995). Phonological recoding and self-teaching: Sine qua non of reading acquisition. *Cognition*, *55*(2), 151-218-226.
- Shillcock, R., Ellison, T. M., & Monaghan, P. (2000). Eye-fixation behavior, lexical storage, and visual word recognition in a split processing model. *Psychological Review*, *107*(4), 824–851.
- Siegel, L. S., & Linder, B. A. (1984). Short-term memory processes in children with reading and arithmetic learning disabilities. *Developmental Psychology*, *20*(2), 200–207.

- Smith, F. (1973). *Psycholinguistics and reading*. New York: Holt, Reinhart and Winston.
- Soler, O., & Kandel, S. (2009). Linguistic factors on stroke programming in children's writing: The importance of syllabic structure. *Infancia Y Aprendizaje*, *32*(2), 189–198.
- Soler, O., & Kandel, S. (2012). A longitudinal study of handwriting skills in pre-schoolers: The acquisition of syllable oriented programming strategies. *Reading and Writing*, *25*, 151–162.
- Stanovich, K. E. (2000). *Progress in Understanding Reading: Scientific Foundations and New Frontiers*. New York: The Guilford Press.
- Staub, A., & Rayner, K. (2007). Eye movements and on-line comprehension processes. In M. Gaskell (Ed.), *The Oxford Handbook of Psycholinguistics* (pp. 327–342). Oxford University Press.
- Sternberg, S., Knoll, R. L., & Wright, C. E. (1978). Experiments on temporal aspects of keyboard entry. In D. J. P (Ed.), *Getting it together: Research and applications in human factors* (pp. 28–50). Santa Monica, CA: Human Factors Society.
- Stromquist, N. (1995). Romancing the state: Gender and power in education. *Comparative Education Review*, *39*(4), 423–454.
- Sumner, E., Connelly, V., & Barnett, A. L. (2014). The influence of spelling ability on handwriting production: Children with and without dyslexia. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(5), 1441–1447.
- Swanson, H. L., & Berninger, V. W. (1996). Individual differences in children's working memory and writing skill. *Journal of Experimental Child Psychology*, *63*(2), 358–385.
- Taft, M. (1979). Lexical access via an orthographic code: The basic orthographic syllable structure. *Journal of Verbal Learning and Verbal Behavior*, *18*, 21–39.
- Taft, M., & Forster, K. I. (1975). Lexical storage and retrieval of prefixed words. *Journal of Verbal Learning And Verbal Behavior*, *14*(6), 638–647.
- Terzuolo, C. A., & Viviani, P. (1980). Determinants and characteristics of motor patterns used for typing. *Neuroscience*, *5*(6), 1085–1103.
- Tinker, M. A. (1936). Eye movement, perception and legibility in reading. *Psychological Bulletin*, *33*(4), 275–290.
- Tinker, M. A. (1946). The study of eye movements in reading. *Psychological Bulletin*, *43*(2), 93–120.

- Tinker, M. A. (1958). Recent studies of eye movements in reading. *Psychological Bulletin*, 55(4), 215–231.
- Transler, C., Leybaert, J., & Gombert, J. (1999). Do deaf children use phonological syllables as reading units? *Journal of Deaf Studies and Deaf Education*, 4, 124–43.
- Treiman, R., Mullennix, J., Bijeljac-Babic, R., & Richmond-Welty, E. D. (1995). The special role of rimes in the description, use, and acquisition of English orthography. *Journal of Experimental Psychology: General*, 124(2), 107–136.
- Underwood, B. J. (1975). Individual differences as a crucible in theory construction. *American Psychologist*, 30, 128–134.
- Underwood, N. R., & McConkie, G. W. (1985). Perceptual span for letter distinctions during reading. *Reading Research Quarterly*, 20(2), 153–162.
- Unsworth, N., & Engle, R. W. (2007). The nature of individual differences in working memory capacity: Active maintenance in primary memory and controlled search from secondary memory. *Psychological Review*, 114(1), 104–132.
- van den Boer, M., de Jong, P. F., & Haentjens-van Meeteren, M. M. (2012). Lexical decision in children: Sublexical processing or lexical search. *Quarterly Journal of Experimental Psychology*, 65(6), 1214–1228.
- Van Galen, G. P. (1991). Handwriting: Issues for a psychomotor theory. *Human Movement Science*, 10(2–3), 165–191.
- Velluntino, F. R., Fletcher, Jack, M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): what have we learned in the past four decades. *The Journal of Child Psychology and Psychiatry*, 45(1), 2–40.
- Wechsler, D. (2005). *Wechsler Individual Achievement Test: Second UK Edition*. London: Pearson.
- Wechsler, D. (2011). *Wechsler Abbreviated Scale of Intelligence*. London: Pearson.
- Weingarten, R., Nottbusch, G., & Will, U. (2004). Morphemes, syllables and graphemes in written word production. In T. Pechmann & C. Hable (Eds.), *Multidisciplinary Approaches to Language Production* (pp. 529–572). Berlin, Germany: Mouton de Gruyter.
- West, L. J., & Sabban, Y. (1982). Hierarchy of stroking habits at the typewriter. *Journal of Applied Psychology*, 67(3), 370–376.
- Whitney, C. (2001). How the brain encodes the order of letters in a printed word: the SERIOL model and selective literature review. *Psychonomic Bulletin Review*, 8(2), 221–243.

- Wood, C., & Farrington-Flint, L. (2001). Orthographic analogy use and phonological priming effects in non-word reading. *Cognitive Development, 16*(4), 951–963.
- Zesiger, P., Mounoud, P., & Hauert, C. A. (1993). Effects of lexicality and trigram frequency on handwriting production in children and adults. *Acta Psychologica, 82*(1–3), 353–365.
- Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin, 131*(1), 3–29.
- Ziegler, J. C., Jacobs, A. M., & Stone, G. O. (1996). Statistical analysis of the bidirectional inconsistency of spelling and sound in French. *Behavior Research Methods, Instruments, & Computers, 28*(4), 504–515.
- Ziegler, J. C., Stone, G. O., & Jacobs, A. M. (1997). What's the pronunciation for –ough and the spelling for /u/? A database for computing feedforward and feedback inconsistency in English. *Behavior Research Methods, Instruments, & Computers, 29*(4), 600–618.

APPENDICES

APPENDIX A

10.1 Ethical information for Experiment 1: Information sheet for adults

Information Sheet (Version 1 – 25/10/12)

Study title: The role of working memory in a copying task

Researcher name: Abby Laishley

My name is Abby Laishley and I am a postgraduate student in the psychology department at the Bournemouth University. I am requesting your participation in a study about how our memory works when we copy words from a board. In order to participate, it is necessary for you to have normal or corrected to normal vision, be a native speaker of English and to not be diagnosed with any reading difficulties. Please tell the experimenter now if this is not the case.

This research will involve you being seated at a table in front of a whiteboard screen. At the beginning of the study you will be adjusted into the eyetracker, which will be secured firmly in a comfortable position on your head. The camera will be moved in front of your left eye until it is in the correct place to track where your eye is looking. Once comfortable, you will be asked to look at four circles that appear on the screen in front of you to calibrate the eye tracker. The eye tracker will be tracking your eyes throughout this study and you are asked to remain as still as possible during the calibration to minimise head movements which can affect the quality of the eye tracking data. Once calibrated, you are free to move your head during the rest of the experiment.

The study involves copying words from the board at your own pace using a pen and paper. You will first complete a practice trial to make you familiar with the process. Before each trial is presented, a cross will appear on the centre of the screen, you will need to look at this to start the trial. Once you look at the cross, the next set of words will appear. If you need a break or feel uncomfortable please alert the experimenter. You can take as many breaks as you need during the study. The entire session will last no longer than 30 minutes and you will receive ½ a course credit for your participation.

Personal information will not be released to or viewed by anyone other than researchers involved in this project. Results of this study will not include your name or any other identifying characteristics. Your participation is voluntary and you may withdraw your participation at any time. If you choose not to participate there will be no consequences to your grade or to your treatment as a student in the psychology department. This study is being carried out under the supervision of Dr Julie Kirkby. If you have any questions or require further information, please ask me now or contact me at alaishley@bournemouth.ac.uk or Julie Kirkby at jkirkby@bournemouth.ac.uk.

APPENDIX B

10.2 Ethical information for Experiment 1: Information sheet for children

Information Sheet (Version 1.2 – 08/04/13)

Study title: The role of working memory in a copying task

Researcher name: Abby Laishley

Firstly, thank you for taking the time to come in today – welcome to Bournemouth University. My name is Abby Laishley, I am a postgraduate student in the psychology department at the Bournemouth University. I am requesting your child's participation in a study about how our language processing works when we read. In order to participate, it is necessary for your child to have normal or corrected to normal vision (glasses are fine!), be learning English as a first language and to not be diagnosed with any reading difficulties. Please tell me now if this is not the case.

This research will involve your child being seated at in front of our eyetracker, which will record the movement of your child's eyes as they read words presented on the computer screen. Sometimes there will be a short question about what they have read. Your child is allowed to take as many rest breaks as they wish throughout their session, and can immediately stop the study at any time.

Personal information will not be released to or viewed by anyone other than researchers involved in this project. Results of this study will not include your child's name or any other identifying characteristics. Your child's participation is voluntary and he/she may withdraw their participation at any time. This study is being carried out under the supervision of Dr Julie Kirkby. If you have any questions or require further information, please ask me now or contact me at alashley@bournemouth.ac.uk or Julie Kirkby at jkirkby@bournemouth.ac.uk.

APPENDIX C

10.3 Ethical information for Experiment 1: Consent form for adults

The role of working memory in a copying task

Consent Form (Version 1 – 25/10/12)

Your continued participation in this research will be taken as evidence of your giving informed consent to participate in this study and for your data to be used for the purposes of research, and that you understand that published results of this research project will maintain your confidentiality. Your participation is voluntary and you may withdraw your participation at any time. If you choose not to participate there will be no consequences to your grade or to your treatment as a student in the psychology department. If you have any questions please ask them now.

If you have questions about your rights as a participant in this research, or if you feel that you have been placed at risk, you may contact the Ethics Committee, Psychology, School of DEC, Bournemouth University.

Please initial the box(es) if you agree with the statement(s):

I have read and understood the information sheet (Version 1 – 25/10/12) and have had the opportunity to ask questions about the study

I agree to take part in this research project and agree for my data to be used for the purpose of this study

I understand my participation is voluntary and I may withdraw at any time without my legal rights being affected

Name of participant (print name).....

Signature of participant.....

Date.....

APPENDIX D

10.4 Ethical information for Experiment 1: Consent form for children

The role of working memory in a copying task

Consent Form (Version 1.2 – 08/04/13)

Your continued participation in this research will be taken as evidence of your giving informed consent for your child to participate in this study and for his/her data to be used for the purposes of research, and that you understand that published results of this research project will maintain confidentiality. Your child's participation is voluntary and may be withdrawn at any time. If you have any questions please ask them now.

If you have questions about your rights as a participant in this research, or if you feel that you have been placed at risk, you may contact the Ethics Committee, Psychology, School of DEC, Bournemouth University.

Please initial the box(es) if you agree with the statement(s):

I have read and understood the information sheet (Version 1.2 – 08/04/13) and have had the opportunity to ask questions about the study

I agree that my child may take part in this research project the data may be used for the purpose of this study

I understand participation is voluntary and can be withdrawn at any time without my legal rights being affected

Name of child (print name)

Name of parent/guardian (print name).....

Signature of parent/guardian

Date.....

APPENDIX E

10.5 Ethical information for Experiment 1: Debriefing statement

The role of working memory in a copying task

Debriefing Statement (Version 1 – 25/10/12)

The aim of this research was to assess how certain properties of words influence how difficult it is to process them. On the basis of many eyetracking studies using just a reading task, we expect certain characteristics of words to influence how long readers need to look at that word in order to process it. In order to do this, we manipulated the word length and word frequency of the words to manipulate how difficult they were to process.

Our study aims to explore how word processing difficulty subsequently impacts how memory is used and how people change their strategies in copying the words. In summary, your data will help our understanding of word processing and working memory during a copying task.

If you have any further questions please contact me, Abby Laishley, at alashley@bournemouth.ac.uk. Thank you for your participation in this research. If you have questions about your rights as a participant in this research, or if you feel that you have been placed at risk, you may contact the Ethics Committee, Psychology, School of DEC, Bournemouth University.

APPENDIX F

10.6 Ethical information for Experiment 2: Information sheet for children

Language processing during children's reading

(Version 1.1 – 10/12/13)

Study title: Language processing during children's reading

Researcher name: Abby Laishley

Firstly, thank you for taking the time to come in today – welcome to Bournemouth University. My name is Abby Laishley, I am a postgraduate student in the psychology department at the Bournemouth University. I am requesting your child's participation in a study about how our language processing works when we read. In order to participate, it is necessary for your child to have normal or corrected to normal vision (glasses are fine!), be learning English as a first language and to not be diagnosed with any reading difficulties. Please tell me now if this is not the case.

This research will involve your child being seated at in front of our eyetracker, which will record the movement of your child's eyes as they read words presented on the computer screen. Sometimes there will be a short question about what they have read. Your child is allowed to take as many rest breaks as they wish throughout their session, and can immediately stop the study at any time.

Personal information will not be released to or viewed by anyone other than researchers involved in this project. Results of this study will not include your child's name or any other identifying characteristics. Your child's participation is voluntary and he/she may withdraw their participation at any time. This study is being carried out under the supervision of Dr Julie Kirkby. If you have any questions or require further information, please ask me now or contact me at alaishley@bournemouth.ac.uk or Julie Kirkby at jkirkby@bournemouth.ac.uk.

APPENDIX G

10.7 Ethical information for Experiment 2: Consent form for children

Language processing during children's reading

Consent Form (Version 1.1 – 10/12/13)

Your continued participation in this research will be taken as evidence of your giving informed consent for your child to participate in this study and for his/her data to be used for the purposes of research, and that you understand that published results of this research project will maintain confidentiality. Your child's participation is voluntary and may be withdrawn at any time. If you have any questions please ask them now.

If you have questions about your rights as a participant in this research, or if you feel that you have been placed at risk, you may contact the Ethics Committee, Psychology, School of DEC, Bournemouth University.

Please initial the box(es) if you agree with the statement(s):

I have read and understood the information sheet (Version 1.1 – 10/12/13) and have had the opportunity to ask questions about the study

I agree that my child may take part in this research project the data may be used for the purpose of this study

I understand participation is voluntary and can be withdrawn at any time without my legal rights being affected

Name of parent/guardian (print name).....

Signature of parent/guardian

Date.....

APPENDIX H

10.8 Ethical information for Experiment 3: Information sheet for adults

Information Sheet (Version 1.1 – 05/01/14)

Study title: How do people read and write words in the classroom?

Researcher names: Abby Laishley

Firstly, thank you for taking the time to come in today – welcome to Bournemouth University. My name is Abby Laishley, I am a postgraduate student in the psychology department at the Bournemouth University. I am requesting your participation in a study about how our memory works when we copy words from a board. In order to participate, it is necessary for you to have normal or corrected to normal vision (glasses are fine!), speak English as a first language and to not be diagnosed with any reading difficulties. Please tell me now if this is not the case.

This research will involve you being seated at a table in front of a whiteboard screen. At the beginning of the study you will be adjusted comfortably into the eyetracker, which is like a pair of glasses that will track your eye movements as you read and write. You will be shown a series of words, and asked to copy them down one at a time using a pen and paper, with as many breaks as you would like. The entire session will last no longer than one hour.

Personal information will not be released to or viewed by anyone other than researchers involved in this project. Results of this study will not include your name or any other identifying characteristics. Your participation is voluntary and he/she may withdraw their participation at any time. This study is being carried out under the supervision of Dr Julie Kirkby. If you have any questions or require further information, please ask me now or contact me at alashley@bournemouth.ac.uk or Julie Kirkby at jkirkby@bournemouth.ac.uk.

APPENDIX I

10.9 Ethical information for Experiment 3: Information sheet for children

Information Sheet Version 1.3 – 24/03/15

Do children use sound and stress patterns of words during classroom tasks?

Researchers: Abby Laishley, Postgraduate Researcher, alaishley@bournemouth.ac.uk
Dr Julie Kirkby, Senior Lecturer,
jkirkby@bournemouth.ac.uk

Firstly, thank you for taking the time to come in today – welcome to Bournemouth University. My name is Abby Laishley, I am a postgraduate student in the psychology department at the Bournemouth University.

What is the purpose of the project: I am requesting your child’s participation in a study about how our memory works when we copy words from a board. We are hoping to find out more about the different ways children encode and produce information in a typical literacy task.

Why have I been chosen: In order to participate, it is necessary for your child to have normal or corrected to normal vision (glasses are fine!), be learning English as a first language and to not be diagnosed with any reading difficulties. Please tell me now if this is not the case.

What happens in the project: This research will involve your child being seated at a table in front of a whiteboard screen. At the beginning of the study your child will be adjusted comfortably into the eyetracker, which is like a pair of glasses that will track your child’s eye movements as they read and write.

Your child will be shown a series of words, and asked to copy them down one at a time using a pen and paper, with as many rests as they would like.

We also ask your child to take a short test of reading ability, and we play some “memory games” to find the capacity of your child’s working memory. We take lots of breaks, and we can have as many separate sessions as you would like. Normally we arrange about one or two sessions that each last about an hour including breaks. If you would like to attend the first session, you can still change your mind about coming back for the second session.

What are the costs and benefits: All children who have participated so far have greatly enjoyed the novelty of wearing the eyetracker, and playing some fun memory



games, and we take lots of breaks to make sure your child will not get tired. While we cannot give any reports of individual performance, after we have finished the study, we like to send you a small letter about what we found out overall about how children read and write information in typical literacy tasks.

What will happen to the results: Personal information will not be released to or viewed by anyone other than researchers involved in this project. Results of this study will not include your child's name or any other identifying characteristics. Your child's participation is voluntary and he/she may withdraw their participation at any time within the study session.

Contact for further information: This study is being carried out under the supervision of Dr Julie Kirkby. If you have any questions or require further information, please ask me now or contact me at alaishley@bournemouth.ac.uk or Julie Kirkby at jkirkby@bournemouth.ac.uk. In the event of any complaints, Matt Bentley, the Deputy Dean of Research and Professional Practice, can be contacted by email: mbentley@bournemouth.ac.uk; or telephone: 01202 962203.

APPENDIX J

10.10 Ethical information for Experiment 3: Consent form for adults

How do people read and write words in the classroom?

Consent Form (Version 1.1 – 05/01/14)

Your continued participation in this research will be taken as evidence of your giving informed consent to participate in this study and for your data to be used for the purposes of research, and that you understand that published results of this research project will maintain your confidentiality. Your participation is voluntary and you may withdraw your participation at any time. If you choose not to participate there will be no consequences to your grade or to your treatment as a student in the psychology department. If you have any questions please ask them now.

If you have questions about your rights as a participant in this research, or if you feel that you have been placed at risk, you may contact the Ethics Committee, Psychology, Faculty of Science and Technology, Bournemouth University.

Please initial the box(es) if you agree with the statement(s):

I have read and understood the information sheet (Version 1.1 – 05/01/14) and have had the opportunity to ask questions about the study

I agree to take part in this research project and agree for my data to be used for the purpose of this study

I understand my participation is voluntary and I may withdraw at any time without my legal rights being affected

Name of participant (print name).....

Signature of participant.....

Date.....

APPENDIX K

10.11 Ethical information for Experiment 3: Consent form for parental guardians

Parental Consent Form

Do children use sound and stress patterns of words during classroom tasks?

Researchers: Abby Laishley, Postgraduate Researcher,
alaishley@bournemouth.ac.uk
Dr Julie Kirkby, Senior Lecturer,
jkirkby@bournemouth.ac.uk

Your continued participation in this research will be taken as evidence of your giving informed consent for your child to participate in this study and for his/her data to be used for the purposes of research, and stored for up to 5 years.

If you have questions about your rights as a participant in this research, or if you feel that you have been placed at risk, you may contact Matt Bentley, the Deputy Dean of Research and Professional Practice, by email mbentley@bournemouth.ac.uk, or telephone 01202 962203.

Please initial below

I have read and understood the information sheet and have had the opportunity to ask questions about the study.

I understand that my child's participation is voluntary and that he/she is free to withdraw until the end of the session, without giving reason and without any negative consequences. Should he/she not wish to answer any particular question(s), he/she is free to decline.

I give permission for members of the research team to access my child's anonymised responses. I understand that their name will not be linked with the research materials, and will not be identifiable in reports that result from the research.

I agree to my child taking part in the above research project.

Parental Consent Form (continued)

Name of child (print name).....

Name of parent/guardian (print name)

Signature of parent/guardian

Date

Name of researcher

Date

APPENDIX L

10.12 Ethical information for Experiment 3: Consent form for children

Children's Assent Form

Do children use sound and stress patterns of words during classroom tasks?

Researchers: Abby Laishley, Postgraduate Researcher,
alaishley@bournemouth.ac.uk

Dr Julie Kirkby, Senior Lecturer,
jkirkby@bournemouth.ac.uk

Hello, my name is Abby.

I'm doing a project to find out about how children read and write words, and I hope that you'll be able to help me.

If you agree to be in our project, we will ask you to do some reading and writing, and then we will play some fun memory games together.

You can ask us questions about the project and have a break if you feel tired.

If you want to take part, write your name below.

.....

Name of researcher

Date

APPENDIX M

10.13 Ethical information for Experiment 3: Debriefing statement

How do people read and write words in the classroom?

Debrief Form (Version 1.1 – 05/01/14)

The aim of this research was to assess how certain properties of words influence how difficult it is to process them. On the basis of previous studies looking at how children and adults process words during a copying task, we expected certain characteristics related to the structure of the word to influence how long readers need to look at that word in order to process it, and how that word might be “chunked” into sub-word units in working memory. In order to do this, we manipulated how many syllables the words contained to manipulate how difficult they were to process.

Our study aims to explore how word processing difficulty subsequently impacts how memory is used and how people change their strategies in copying the words. In summary, your data will help our understanding of word processing and working memory during a copying task.

If you have any further questions please contact me, Abby Laishley, at alashley@bournemouth.ac.uk. Thank you for your participation in this research. If you have questions about your rights as a participant in this research, or if you feel that you have been placed at risk, you may contact the Ethics Committee, Psychology, Faculty of Science and Technology, Bournemouth University.

APPENDIX N

10.14 Materials in Experiment 1 for adult participants

List of stimuli created for adult participants in Experiment 1, with words manipulated orthogonally for word length and frequency.

Word characteristics	4 letters	8 letters
High frequency	tree	daughter
	suit	hospital
	deep	attention
	seat	surprise
	gold	situation
	bank	marriage
	ring	position
	boat	government
	ship	experience
road	president	
Low frequency	oboe	flotilla
	dolt	wainscot
	tusk	apostate
	aloe	chancery
	serf	alkaloid
	tarn	oratorio
	toga	fruition
	moot	tomahawk
	kiln	misnomer
bard	vanguard	

APPENDIX O

10.15 Materials in Experiment 1 for child participants

List of stimuli created for child participants in Experiment 1, with words manipulated orthogonally for word length and frequency.

Word characteristics	4 letters	8 letters
High frequency	busy	surprise
	tiny	treasure
	body	mountain
	oven	squirrel
	cafe	tortoise
	rose	porridge
	ugly	concrete
	hero	daughter
Low frequency	axle	blizzard
	ruin	fountain
	dire	gargoyle
	neon	patience
	liar	portrait
	riot	splinter
	obey	struggle
	dozy	approach

APPENDIX P

10.16 Materials in Experiment 2 for child participants

List of stimuli created for child participants in Experiment 2, with words manipulated orthogonally for word length and frequency, and pseudowords match for length with words.

4 letter items		8 letter items	
Words	Nonwords	Words	Nonwords
busy	kiry	surprise	seachace
tiny	gily	treasure	combaire
body	goet	mountain	foudrell
oven	moen	squirrel	seppougs
cafe	asem	tortoise	vaudlere
rose	sazy	porridge	shilyors
ugly	juor	concrete	chytench
hero	tery	daughter	reeazlen
axle	tyel	blizzard	ourweays
ruin	aram	fountain	absplict
dire	liey	gargoyle	symparch
neon	amur	patience	preliet
liar	yoem	portrait	chysosts
riot	tyek	splinter	sterise
obey	tomy	struggle	mollurle
dozy	dede	approach	plourful

10.17 Structure of linear mixed models for Experiment 2, reported in Chapter 4

The structures of linear mixed models are presented in relation to fixed and random effects for Experiment 2, reported in Chapter 4. Data for word reading age and pseudoword decoding age were centred (each score minus the mean) so that a score of 0 corresponded to a meaningful value, the mean of each predictor.

10.17.1 Models on the whole dataset of word and pseudoword items.

Measures in relation to response accuracy.

Accuracy. Fixed effects were: length, lexical status, the interaction between length and lexical status; word reading age, and pseudoword decoding age. The random effects structure included random intercepts for participants and items.

Measures in relation to response time.

First fixation duration. Fixed effects were: length, lexical status, the interaction between length and lexical status; word reading age, and pseudoword decoding age. The random effects structure included random intercepts for participants and items; random slopes for each participant for length and lexical status; and random slopes for each item for pseudoword decoding age.

Gaze duration. Fixed effects were: length, lexical status, the interaction between length and lexical status; word reading age, and pseudoword decoding age. The random effects structure included random intercepts for participants and items; random slopes for each participant for length, lexical status and the interaction between length and lexical status; and random slopes for each item for word reading age and pseudoword decoding age.

Total time. Fixed effects were: length, lexical status, the interaction between length and lexical status; word reading age, and pseudoword decoding age. The random effects structure included random intercepts for participants and items; random slopes for each participant for length, lexical status and the interaction between length and lexical status; and random slopes for each item for word reading age and pseudoword decoding age.

First run fixation count. Fixed effects were: length, lexical status, the interaction between length and lexical status; word reading age, and pseudoword decoding age. The random effects structure included random intercepts for participants and items;

random slopes for each participant for length, lexical status and the interaction between length and lexical status; and random slopes for each item for word reading age and pseudoword decoding age.

Total fixation count. Fixed effects were: length, lexical status, the interaction between length and lexical status; word reading age, and pseudoword decoding age. The random effects structure included random intercepts for participants and items; random slopes for each participant for length and lexical status; and random slopes for each item for word reading age and pseudoword decoding age.

10.17.2 Models on the subset of word items.

Measures in relation to response accuracy.

Accuracy. Fixed effects were: length, frequency, the interaction between length and frequency; word reading age, and pseudoword decoding age. The random effects structure included random intercepts for participants and items; and random slopes for each participant for length and frequency.

Measures in relation to response time.

First fixation duration. Fixed effects were: length, frequency, the interaction between length and frequency; word reading age, and pseudoword decoding age. The random effects structure included random intercepts for participants and items; and random slopes for each item for word reading age and pseudoword decoding age.

Gaze duration. Fixed effects were: length, frequency, the interaction between length and frequency; word reading age, and pseudoword decoding age. The random effects structure included random intercepts for participants and items; random slopes for each participant for length; and random slopes for each item for word reading age and pseudoword decoding age.

Total time. Fixed effects were: length, frequency, the interaction between length and frequency; word reading age, and pseudoword decoding age. The random effects structure included random intercepts for participants and words; random slopes for each participant for length, frequency, and the interaction of length and frequency; and random slopes for each word for word reading age and pseudoword decoding age.

First run fixation count. Fixed effects were: length, frequency, the interaction between length and frequency; word reading age, and pseudoword decoding age. The random effects structure included random intercepts for participants and words; and random slopes for each participant for length and frequency.

Total fixation count. Fixed effects were: length, frequency, the interaction between length and frequency; word reading age, and pseudoword decoding age. The random effects structure included random intercepts for participants and words; random slopes for each participant for length, frequency, and the interaction of length and frequency; and random slopes for each word for word reading age and pseudoword decoding age.

10.18 Structure of linear mixed models for Experiment 1, reported in Chapter 5

The structures of linear mixed models are presented in relation to fixed and random effects for Experiment 1, reported in Chapter 5. Data were centred for word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity and spatial processing capacity.

10.18.1 Measures in relation to encoding.

Initial encoding. Fixed effects were: length, frequency, the interaction between length and frequency; word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity, and spatial processing capacity. The random effects structure included random intercepts for participants and words; random slopes for each participant for length; and random slopes for each word for word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity, and spatial processing capacity.

Writing onset. Fixed effects were: length, frequency, the interaction between length and frequency; word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity, and spatial processing capacity. The random effects structure included random intercepts for participants and words; and random slopes for each word for word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity, and spatial processing capacity.

Total encoding. Fixed effects were: length, frequency, the interaction between length and frequency; word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity, and spatial processing capacity. The random effects structure included random intercepts for participants and words; and random slopes for each word for word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity, and spatial processing capacity.

Total secondary encoding. Fixed effects were: length, frequency, the interaction between length and frequency; word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity, and spatial processing capacity. The random effects structure included random intercepts for

participants and words; and random slopes for each word for word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity, and spatial processing capacity.

10.18.2 Measures in relation to written production.

Gaze time associated with written production. Fixed effects were: length, frequency, the interaction between length and frequency; word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity, and spatial processing capacity. The random effects structure included random intercepts for participants and words; random slopes for each participant for length, frequency and the interaction between length and frequency; and random slopes for each word for word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity, and spatial processing capacity.

Written production duration. Fixed effects were: length, frequency, the interaction between length and frequency; word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity, and spatial processing capacity. The random effects structure included random intercepts for participants and words; and random slopes for each word for word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity, and spatial processing capacity.

10.18.3 Measures in relation to gaze lifts.

Number of gaze lifts. Fixed effects were: length, frequency, the interaction between length and frequency; word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity, and spatial processing capacity. The random effects structure included random intercepts for participants and words; and random slopes for each word for word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity, and spatial processing capacity.

Probability of making a gaze lift. Fixed effects were: length, frequency, the interaction between length and frequency; word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity, and spatial processing capacity. The random effects structure included random intercepts for participants and words; random slopes for each participant for length; and random slopes for each word for word reading age, pseudoword decoding age, verbal storage capacity, verbal processing capacity, spatial storage capacity, and spatial processing capacity.

APPENDIX S

10.19 Materials in Experiment 3 for adult and child participants

List of stimuli created for adult and child participants in Experiment 3, with words manipulated for number of syllables. The syllable boundaries are denoted here in bold.

	1 syllable	2 syllables	3 syllables
Adults' stimuli	brusque	vul.ture	so.lic.it
	screech	blem.ish	sar.ca.sm
	staunch	mun.dane	in.fer.no
	stealth	for.feit	tor.na.do
	breadth	sal.vage	tor.pe.do
	scourge	phan.tom	mo.sa.ic
	sprite	flur.ry	leg.a.cy
	flaunt	wiz.ard	pac.i.fy
	wretch	bam.bo	e.nig.ma
	scroll	cym.bal	ver.i.fy
	crunch	wal.rus	de.vou.r
	sleigh	rus.tic	so.lic.it
	splooch	crum.ble	vol.ca.no
	draught	tan.trum	o.pe.rate
	scrunch	blan.ket	e.la.stic
Children's stimuli	stretch	pump.kin	ad.mi.ral
	scratch	or.chard	ca.ra.van
	breathe	grum.ble	ma.je.sty
	flight	pu.nish	po.ta.to
	length	sig.nal	to.ma.to
	shrank	cre.ate	ba.na.na
	freeze	che.rry	ci.ne.ma
switch	da.mage	ce.le.ry	
	scream	stu.pid	fi.as.co

10.20 Structure of linear mixed models for Experiment 3, reported in Chapter 6

The structures of linear mixed models are presented in relation to fixed and random effects for Experiment 3, reported in Chapter 6.

10.20.1 Measures in relation to encoding.

Initial encoding time. Fixed effects were: age group in relation to each stimuli set, number of syllables, and the interaction between age group in relation to each stimuli set and number of syllables. The random effects structure included random intercepts for participants and words.

Writing onset. Fixed effects were: age group in relation to each stimuli set, number of syllables, and the interaction between age group in relation to each stimuli set and number of syllables. The random effects structure included random intercepts for participants and words.

Total encoding time. Fixed effects were: age group in relation to each stimuli set, number of syllables, and the interaction between age group in relation to each stimuli set and number of syllables. The random effects structure included random intercepts for participants and words; and random slopes for each participant for number of syllables.

Total secondary encoding time. Fixed effects were: number of syllables. The random effects structure included random intercepts for participants and words; and random slopes for each participant for number of syllables.

First return secondary encoding time. Fixed effects were: number of syllables. The random effects structure included random intercepts for participants and words; and random slopes for each participant for number of syllables.

Second return secondary encoding time. Fixed effects were: number of syllables. The random effects structure included random intercepts for participants and words; and random slopes for each participant for number of syllables.

Third return secondary encoding time. Fixed effects were: number of syllables. The random effects structure included random intercepts for participants and words; and random slopes for each participant for number of syllables.

10.20.2 Measures in relation to written production.

Gaze time associated with written production. Fixed effects were: age group in relation to each stimuli set, number of syllables, and the interaction between age group in relation to each stimuli set and number of syllables. The random effects structure included random intercepts for participants and words; and random slopes for each participant for number of syllables.

Written production duration. Fixed effects were: age group in relation to each stimuli set, number of syllables, and the interaction between age group in relation to each stimuli set and number of syllables. The random effects structure included random intercepts for participants and words; and random slopes for each participant for number of syllables.

10.20.3 Measures in relation to gaze lifts.

Number of gaze lifts. Fixed effects were: number of syllables. The random effects structure included random intercepts for participants and words; and random slopes for each participant for number of syllables.

Number of letters written before first gaze lift. Fixed effects were: number of syllables. The random effects structure included random intercepts for participants and words; and random slopes for each participant for number of syllables.

Number of letters written before second gaze lift. Fixed effects were: number of syllables. The random effects structure included random intercepts for participants and words.

Number of letters written before third gaze lift. Fixed effects were: number of syllables. The random effects structure included random intercepts for participants and words.

Probability of making a gaze lift. Fixed effects were: number of syllables. The random effects structure included random intercepts for participants and words.

Probability of making a gaze lift on at least one syllable boundary. Fixed effects were: number of syllables. The random effects structure included random intercepts for participants and words.

Proportion of gaze lifts on syllable boundaries. Fixed effects were: number of syllables. The random effects structure included random intercepts for participants and words; and random slopes for each participant for number of syllables.

10.21 Structure of linear mixed models for Experiment 3, reported in Chapter 7

The structures of linear mixed models are presented in relation to fixed and random effects for Experiment 3, reported in Chapter 7. Data were centred for word reading age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity.

10.21.1 Measures in relation to encoding.

Total secondary encoding time. Fixed effects were: number of syllables, word reading age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity. The random effects structure included random intercepts for participants and words; random slopes for each participant for number of syllables; and random slopes for each word for word reading age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity.

First return secondary encoding time. Fixed effects were: number of syllables, word reading age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity. The random effects structure included random intercepts for participants and words; random slopes for each participant for number of syllables; and random slopes for each word for word reading age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity.

Second return secondary encoding time. Fixed effects were: number of syllables, word reading age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity. The random effects structure included random intercepts for participants and words; random slopes for each participant for number of syllables; and random slopes for each word for word reading age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity.

Third return secondary encoding time. Fixed effects were: number of syllables, word reading age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity. The random effects structure included random intercepts for participants and words; and random slopes for each word for word reading

age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity.

10.21.2 Measures in relation to written production.

Gaze time associated with written production. Fixed effects were: number of syllables, word reading age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity. The random effects structure included random intercepts for participants and words; random slopes for each participant for number of syllables; and random slopes for each word for word reading age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity.

Written production duration. Fixed effects were: number of syllables, word reading age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity. The random effects structure included random intercepts for participants and words; random slopes for each participant for number of syllables; and random slopes for each word for word reading age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity.

10.21.3 Measures in relation to gaze lifts.

Number of gaze lifts. Fixed effects were: number of syllables, word reading age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity. The random effects structure included random intercepts for participants and words; random slopes for each participant for number of syllables; and random slopes for each word for word reading age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity.

Proportion of gaze lifts on syllable boundaries. Fixed effects were: number of syllables, word reading age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity. The random effects structure included random intercepts for participants and words; and random slopes for each word for word reading age, verbal short term storage capacity, verbal working storage capacity and verbal working processing capacity.