An fMRI and TMS Investigation of Response, Semantic, and Task Conflict in The Stroop Task

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Abstract

Overcoming Stroop interference (i.e., ignoring the meaning of a word whilst naming the colour it is printed in) requires selective attention which calls upon several different processes. A Stroop stimulus generates cognitive conflict at different stages of the processing stream (i.e., at the task, semantic, and response level). An enduring goal of research investigating attentional control is to establish the point in the processing stream at which information can be selected or ignored, and in turn establish whether dissociable neural networks underpin these different cognitive processes. The anterior cingulate cortex (ACC) and dorsolateral prefrontal cortex (DLPFC) are two regions thought to be central to the circuitry of attentional control, however the precise role that each plays is still widely debated. The present thesis attempts to elucidate the function of these regions in two experiments employing a Stroop paradigm. Experiment 1 (n=20) used high frequency rTMS to stimulate the left DLPFC and observed the behavioural effect on each of the various forms of cognitive conflict. Our results showed a significant main effect of stimulation in reducing response times (RTs) compared to sham-stimulation, however stimulation had no effect on any of the underlying components of interference. In line with previous findings our results were consistent with the role of the left DLPFC in implementing top–down attentional control. Experiment 2 (n=13) employed the same Stroop paradigm while the BOLD response of participants was recorded using fMRI. We demonstrated evidence for hemispheric differences in attentional control, as the right DLPFC appeared more engaged by response conflict, while left DLPFC activation was unique to pre-response conflict. Surprisingly ACC activation was only associated with semantic conflict. We concluded that our results favour multi-stage selection accounts of attentional control but highlight the need for additional neuroimaging studies with more consistent methods before our findings can be validated. While the Stroop effect is one of the most studied phenomena in psychology our findings make clear that there remains a significant amount for future research to address. The results are discussed in context of the limitations of our experiments and directions for future research are proposed.

List of Contents

List of Figures

List of Tables

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Author's Declaration

I hereby declare that the work presented in this thesis has not been and will not be, submitted in whole or in part to another University for the award of any other degree.

Signature:

INTRODUCTION

The Stroop effect refers to a robust finding whereby people are slower to name a colour that a word is printed in when the word spells out a different colour (i.e., incongruent trials- the word 'red' in green) compared to when the word and the print colour are the same (i.e., congruent trials- the word 'red' in red). The effect was first reported in 1935 by John Ridley Stroop, and since then many hundreds of studies have sought to understand this seemingly straightforward phenomenon. As well as being utilised in many models of executive function (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Cohen, Dunbar, & McClelland, 1990; Roelofs, 2003), the Stroop task has also become an important clinical tool and is often referred to as the gold-standard measure of selective attention (MacLeod, 1992). Despite this, the specific neural mechanisms involved in guiding our attention in the Stroop task remains a source of debate. It is important that research attempts to elucidate the neural networks involved in processing and resolving cognitive conflict as this may ultimately lend insight into how failures in these systems are expressed in disorders such as attention deficit-hyperactivity disorder, posttraumatic stress disorder, obsessive compulsive disorder, depression, and schizophrenia (Berggren & Derakshan, 2014).

Interference in the Stroop task is typically measured by recording the response times (RTs) to incongruent stimuli and subtracting the RTs to 'neutral' control items (e.g., colour patches, letter/symbol strings, or pseudo-words). The finding that people respond slower to incongruent stimuli was initially explained as demonstrating the difficulty in overcoming the more practiced behaviour of word reading, which is irrelevant to the task, compared to the relevant, but less practiced behaviour of colour naming (MacLeod & Dunbar, 1988). However, this account offers little in explaining how certain words (e.g., words semantically related to colour) produce slower RTs than others (e.g., neutral words; Sharma & McKenna, 1998). As such, it would appear that the Stroop task involves smaller subcomponents that call upon several different processes (Peterson, et al., 1999). Klein (1964) first suggested that the Stroop effect was made up of interference at multiple levels, and now the research literature tends to agree that response and semantic conflict (together referred to as informational conflict), as well as task conflict all constitute the Stroop effect.

Informational conflict

Informational conflict (or semantic and response conflict) refers to the conflict that arises from the information that the irrelevant word conveys. For semantic conflict this means that the irrelevant word may interfere with the processing of the print colour by activating a competing alternative colour through association (e.g., the word 'sky' in red, may activate competing response options 'blue' and 'red'). Whereas response conflict occurs when the irrelevant word spells out a possible response option (i.e., incongruent trials; the word 'blue' in red where both colours are possible responses).

According to single-stage models of selective attention, information accruing from both dimensions of the Stroop stimulus (word vs. colour) comes together at the output or response module to either converge (facilitation) or compete (interference) (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Cohen, Dunbar, & McClelland, 1990). Botvinick et al.'s (2001) model claims that a task demand unit biases activity in the colour-processing pathway, to ensure that the response is based on colour identity. When biasing is successful there is less information from the word dimension contributing converging and competing information, resulting in reduced facilitation and interference. Alternatively, the WEAVER ++ model proposed by Roelofs (2003) describes a spreading activation of concepts in a network. For example, it suggests that the colour 'blue' is connected to the word 'blue' which also activates the superordinate concept of 'colours' (thus activating concepts such as 'red' and 'green') to a lesser extent. When perceiving a Stroop stimulus, the subsequent selection of an appropriate response is determined by the relative activation of a particular concept. Activation of relevant concepts accumulates throughout the processing stream and is weighed up at the response module such that one eventually wins out. A greater degree of competition between two or more relevant concepts at the response module results in increased interference as more cognitive resources are required to discriminate between correct and incorrect responses. Thus, while conflict at the pre-response level contributes to Stroop interference (by activating competing information that must then be selected against/ignored), single-stage models of Stroop task performance assume that such conflict is only resolved at the response selection stage and not before.

Other accounts assume a multi-stage selection mechanism in which converging and competing information can be resolved at an earlier pre-response level, as well as at the response level. One such model, the Dimensional Overlap model (DO) and

taxonomy developed by Kornblum and his colleagues, describes how aspects of a stimulus set or a response set, may be perceptually, structurally, or conceptually similar (Kornblum, 1992; Kornblum, Hasbroucq, & Osman, 1990; Kornblum & Lee, 1995; Kornblum & Stevens, 2002; Kornblum, Stevens, Whipple, & Requin, 1999). In the Stroop task dimensional overlap exists between the two stimulus dimensions (colour vs. word), one relevant for performing the task and the other non-relevant. Stimulus-stimulus overlap between the two dimensions of the Stroop stimulus results in interference at the pre-response level when the irrelevant dimension gives conflicting information about which is the target stimulus. On the other hand, stimulus-response overlap creates conflict at the response level when the response dimension (i.e., the verbal production of the correct response) conflicts with either of the stimulus dimensions (i.e., relevant or irrelevant). According to the DO taxonomy stimulus-stimulus and stimulus-response conflicts are processed and resolved separately (Kornblum, 1992). Contrary to single-stage models of selective attention, this therefore implies that both pre-response and response conflict recruit inhibitory processes that serve to produce an early and late selection.

In its most common format, conflicts at the semantic and response levels are intertwined in the Stroop task. Since performance of the task requires both semantic processing of the stimulus and a subsequent selection of the appropriate response, these two processes cannot be performed independently of each other. Thus, in order to determine how much semantic and response conflict contribute to Stroop interference research must first find a way of teasing the two apart from one another. This is typically achieved by designing conditions which provide an index of semantic conflict and not response conflict. The difference in performance between this critical condition and a baseline is taken as a measure of semantic conflict, while the difference between the incongruent and the critical condition provides a measure of response conflict. The current literature describes three conditions that can be used as this critical condition to separate semantic and response conflict, *same-response trials, non-response set trials* and *semantic associates*.

Same-response trials

Same-response trials, also referred to as the two-to-one colour-response mapping paradigm, has become the most popular way of indexing semantic and response conflict in recent studies. Here two colour responses are mapped on to the

same response button (see Figure 1), which allows for a distinction between stimulus-stimulus and stimulus-response interference. By mapping two response options onto the same response key (e.g., both 'blue' and 'yellow' are assigned to the 'z' key) it ensures that any interference during same-response trials (e.g., when 'blue' is printed in yellow) contains only semantic conflict. Any additional interference on incongruent trials (e.g., when 'red' is printed in yellow and where both 'red' and 'yellow' are assigned to different response keys) is taken as evidence of response conflict. A congruent trial vs. same-response trail comparison would therefore reveal the interference that can be attributed to semantic conflict, whereas a same-response trial vs. incongruent trial comparison would reveal interference due to response conflict. Thus, the main advantage of using same-response trials as an index of semantic conflict is that it claims to be able to remove all the influence of response competition (De Houwer, 2003).

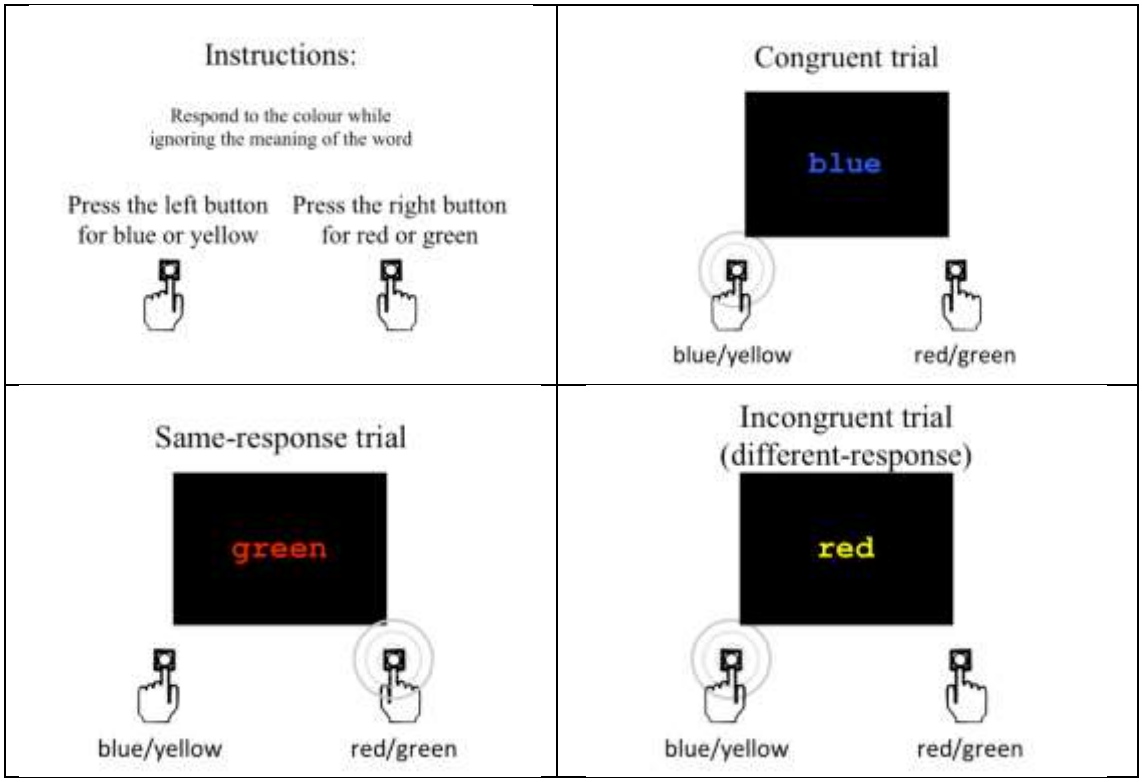

Figure 1. Example instructions and trials in the two-to-one colour-response mapping paradigm.

Despite providing us with a seemingly convenient measure of semantic and response conflict, the studies which have employed the two-to-one colour-response mapping paradigm share one major flaw. Since the same-response trials require the use of congruent trials as a baseline control condition it could be that the difference between

same-response and congruent trials is simply facilitation and not semantic interference, a criticism De Houwer (2003) alluded to in his original paper. Hasshim and Parris (2014) explored this possibility in their study by comparing performance on same-response trials to non-colour word neutral trials. Faster RTs to same-response trials would have provided evidence for response facilitation, whereas faster RTs to non-colour word neutral trials would have provided evidence for semantic interference. However, they found no statistical difference between the RTs of the two trial types and reported Bayes Factors indicating strong evidence in favour of the null hypothesis of no difference. This would suggest that, when using reaction time as the index of performance, same-response trials cannot be attributed with revealing semantic conflict since same-response trials are not different from neutral trials.

In a later study the researchers investigated whether the two-to-one colour mapping paradigm could still be used to reveal semantic conflict when using a more sensitive measure of performance than RT (Hasshim & Parris, 2015). They attempted to provide evidence for semantic conflict using an oculomotor Stroop task and an early, pre-response pupillometric measure of effort, which had previously been shown to provide a reliable alternative measure of the potential differences between conditions (Hodgson, Parris, Gregory, & Jarvis, 2009). However, in line with their previous findings they reported Bayes Factors indicating strong evidence for no statistical difference between two-to-one response-mapping trials and neutral trials. These findings therefore support the notion that the difference between same-response and congruent trials indexes facilitation on congruent trials, and thus same-response trials are not a reliable measure of semantic conflict. They therefore argue that the findings from studies which have utilised the two-to-one colour mapping paradigm may have to be re-evaluated.

Non-response set trials

An alternative method of indexing semantic conflict is through the use of non-response set trials. This is where the irrelevant colour word used is not part of the response set (e.g., the word ‘orange’ in blue, where orange is not a possible response option and blue is). Since the non-response set colour word will activate colour-processing systems, interference on such trials can be taken as evidence for conflict occurring at the semantic level. These trials should in theory remove the influence of response conflict, as the irrelevant colour-word is not a possible response option, and

thus conflict at the response level is not present. However, this assumption is problematic given that interference is greater when colours are closer to each other on the electromagnetic spectrum (Klopfer, 1996). For instance, Klopfer (1996) demonstrated that when blue, purple and orange were all possible response options RTs were slower when both colour dimensions are closely related (e.g., 'blue' in purple) compared to when the colours were distantly related (e.g., 'blue' in orange). Therefore, non-response set trials may still index response conflict to some extent when the irrelevant colour word used is closely related to a possible response option (e.g., the non-response colour-word 'purple' in yellow may activate competing response options 'blue' and 'yellow').

The difference in performance between the non-response set trials and a neutral word baseline condition (e.g., the word 'table' in red) is taken as evidence of interference caused by the semantic processing of the irrelevant colour word. Whereas response conflict can be isolated by comparing the difference between the performance on incongruent trials and the non-response set trials. This index of response conflict is referred to as the response set membership effect and describes the interference that is a result of the irrelevant word denoting a colour that is also a possible response option. Although this provides us with a useful measure of response conflict it is worth noting that the magnitude of the response set effect varies between studies according to the methods employed.

Noting this, Hasshim and Parris (2017) conducted two within-subjects experiments in which the trial types (e.g., response set, non-response set, neutral) were presented either in separate blocks (pure) or in blocks containing all trial types in a random order (mixed). In their first experiment they found a decrease in RTs to response set trials when trials were presented in mixed blocks when compared to the RTs to response set trials in pure blocks. The findings demonstrate that presentation format modulates the magnitude of the response set effect, substantially reducing it when trials are presented in mixed blocks. In their second experiment Hasshim and Parris (2017) manipulated the number of colour-words that make up the non-response set of distractors. They found that increasing the number of non-response set colour concepts reduced the response set effect. It is important for studies to consider how these manipulations may be used to maximise the detection of a response set effect (response conflict). Hasshim and Parris' (2017) results suggests that the use of pure blocks will enable a better index of response conflict.

Semantic-associative trials

A final method that has been used to tease apart semantic and response conflict, is the use of semantic associates. In these trials the irrelevant words used are semantically related to each of the response colours (e.g., sky – blue, grass – green). This method of isolating semantic conflict was first introduced by Klein (1964) and has since been used in many studies investigating Stroop interference (e.g., Glaser & Glaser, 1989; Risko, Schmidt, & Besner, 2006; Stirling, 1979). However, research has found that the interference observed when using semantic associates tends to be smaller than when using non-response set trials (Sharma & McKenna, 1998). Sharma and McKenna (1998) postulate that this is because non-response set trials involve an additional level of semantic processing, semantic relevance (as the irrelevant words denote colours), and thus semantic associates may not capture semantic interference in its entirety. Furthermore, it is unclear whether semantic associates exclude the influence of response competition (Roelofs, 2003). Since semantic-associate interference is the result of activation of the related response set colours, it does not allow for a clear distinction between semantic and response processes. Thus, semantic associates may still index response competition to some extent (for instance when 'sky' in red activates competing response set options blue and red).

While semantic associates and non-response set trials provide useful ways of dissociating semantic and response conflict, recent research would suggest that same-response trials cannot be used as a valid measure of semantic conflict when using response times and pupil size as dependent variables (Hasshim & Parris, 2014; Hasshim & Parris, 2015). Instead it is argued that the slower RTs for same-response trials compared to congruent trials is an index of response facilitation on congruent trials where both dimensions of the stimulus point towards the same response. As such, future studies should consider the utility the two-to-one response mapping paradigm before employing it as an index of sematic conflict since other methods may potentially provide a better alternative. Furthermore, given the effect of trial type mixing on the magnitude of response conflict (Hasshim & Parris, 2017), future studies would do better to use pure block presentation of the different Stroop conditions when assessing different components of informational conflict.

Task conflict

MacLeod and MacDonald (2000) proposed that performance in the Stroop task reflects two types of conflict, informational conflict and task conflict. Task conflict refers to a situation whereby participants perform an additional irrelevant task that they are not supposed to, and thus which interferes with the task goal (i.e., colour naming). The presentation of a coloured letter string may evoke a number of irrelevant tasks to be performed (e.g., reading, letter counting, word association). Reading seems most likely to interfere with the task goal since we associate words more closely to reading than to colour naming (Rogers & Monsell, 1995). The expectation of these two types of stimulus is thought to activate competing neural systems responsible for word reading and colour naming. Thus, interference at this level derives from the simultaneous preparation of two task sets which creates conflict even before the identity of the Stroop stimulus has been revealed. Consequently, task conflict is resolved by biasing attention away from automatic word reading and directing it towards the less practised task of colour naming. Task conflict in the Stroop task therefore reflects the initial interference that arises from anticipating the presentation of both a word and a colour and the subsequent attempt to resolve this competition by imposing an attentional set or biasing information.

Since task conflict is produced by the automatic tendency to read, interference at this level occurs regardless of whether the resulting Stroop stimulus is congruent or incongruent. Recent work has supported the long-standing notion that all readable stimuli trigger an automatic and unavoidable reading process (Augustinova & Ferrand, 2014). In line with this any readable letter string should produce more interference than any unreadable, non-word letter string. This is because the mere presence of a readable stimulus, regardless of its meaning, will activate involuntary word reading processes which in turn makes processing information about the goal relevant stimulus (i.e., colour) slower. Previous studies have used this logic in order to isolate task conflict from informational conflict (e.g., Entel & Tzelgov, 2016). Since both congruent and incongruent trials produce task conflict, trials consisting of neutral non-word stimuli (e.g., xxxx or ####) must be introduced as a baseline. The common behavioural finding in such experiments is that incongruent trials produce slower RTs than neutral non-word stimuli, while congruent stimuli produce the fastest RTs (Entel, Tzelgov, Bereby-Meyer, & Shahar, 2015). The latency difference between the incongruent trials and non-word neutral trials is referred to as the inhibition effect, while the difference between

neutral and congruent trials is what is known as the facilitation effect (MacLeod, 1991). However, the notion of task conflict posits that readable stimuli should interfere more with colour naming than unreadable stimuli, therefore resulting in faster RTs to the non-word neutral trials compared to congruent trials. As such task conflict can be identified by the detection of a reversed or negative facilitation effect, whereby the RTs of congruent trials are slower than that of neutral trials.

A negative facilitation effect in the Stroop task was first reported in a study by Goldfarb and Henik (2007; see also Kalanthroff et al., 2013) as evidence for the presence of task conflict. In the study the researchers reduced the task conflict control by increasing the proportion of non-word neutral trials to 75%. Additionally, on half of the trials participants received cues that indicated whether the following stimulus would be a non-word or a colour word. This manipulation allowed for the detection of task conflict in the non-cued, low task control condition. For non-cued trials RTs were slower for congruent trials than for neutral trials (negative facilitation effect), and RTs for congruent trials were slower when the stimuli were non-cued as opposed to cued. These findings were interpreted as being due to increased task conflict in the absence of a cue as participants were unable to prepare appropriate focus to the colour naming goal. Goldfarb and Henik (2007) suggested that previous studies had not detected a negative facilitation effect because resolving task conflict for congruent stimuli does not take long, and thus the effects of facilitation had meant that the RTs for congruent trials had remained shorter than that of neutral trials. Thus, by reducing the task control both globally (by increasing the proportion of neutral trials) and locally (by adding cues to half of the trials) they were able to demonstrate a negative facilitation effect, providing evidence for the presence of task conflict. Similarly, Steinhauser and Hübner (2009) manipulated task conflict control by combining the Stroop task with a task switching paradigm (where participants switch between colour naming and reading). They found that when combined with the task switching paradigm participants performed worse in the congruent and incongruent trials than they did in the neutral trials, thus reaffirming Goldfarb and Henik's (2007) previous findings.

Recent studies have built upon the work of Goldfarb and Henik (2007) by demonstrating that it is possible for experimental manipulations of task conflict to affect interference whilst leaving facilitation untouched (e.g., Parris, 2014). This challenges single mechanism accounts of Stroop task performance which suggest that information about the print colour and word meaning come together at the response output to either

converge (facilitation) or compete (interference) (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Cohen, Dunbar, & McClelland, 1990). Such an account predicts that experimental manipulations of Stroop task conflict should affect both facilitation and interference equally and in the same direction. However, Parris (2014) demonstrated that manipulating the response-stimulus interval (RSI) to induce greater goal focus affects facilitation and interference independently, and in opposing directions. The study found that compared to long RSIs (3500 ms) short RSIs (200 ms) resulted in RTs decreasing for congruent and incongruent trials, compared to neutral trials; such that interference decreased as facilitation increased. These findings provide yet more evidence for the presence of task conflict and challenge single mechanism models that predict that interference and facilitation should be affected in tandem.

The presence of task conflict was first proposed in MacLeod and MacDonald's (2000) review of brain imaging studies since the anterior cingulate cortex (ACC) appeared to be more activated by incongruent and congruent stimuli compared to neutral stimuli. They suggest that increased ACC activation by congruent and incongruent stimuli is likely an expression of the task conflict caused by the automatic, irrelevant reading task. Whereas the reduced activation of the ACC during non-word neutral trials reflects the absence of competition between word reading and colour naming processes, resulting in the faster attainment of the task goal. Models of control of the Stroop effect (e.g., Botvinick et al., 2001) often suggest that control is regulated by a module referred to as the conflict-monitoring unit (located within the ACC) that detects conflicts in information processing. The unit is thought to calculate the amount of conflict at the response layer, and consequently increase the input from the relevant task-demand units when high levels of conflict are detected. Botvinick et al. (2001) claim that the conflict detected by this unit arises due to the preparation of two different response options caused by incongruent stimuli. Whereby a reduced proportion of incongruent trials would result in a lower level of calculated conflict, thus reducing the amount of cognitive control being used to supress any irrelevant information processing (Goldfarb & Henik, 2007).

According to Entel and Tzelgov's (2016) interpretation of this framework, only task conflict is directly controlled by the ACC, whereas informational conflict is only monitored. Yet this begs the question of whether task conflict can still be monitored and controlled for in the absence of informational conflict. Entel and Tzelgov (2016) attempted to address this issue in their study by manipulating the congruent-to-neutral

trial ratio. In their first experiment no incongruent trials were included, and their results revealed a large facilitation effect when the stimuli were mainly congruent, and a smaller but significant facilitation when the stimuli were mainly neutral. The lack of negative facilitation indicating no task conflict detection. In the second experiment participants were exposed to incongruent trials in a pre-experimental practise, but not during the actual experimental blocks. They found that exposing participants to incongruent trials before the experiment slowed down RTs to congruent stimuli, resulting in a reduced facilitation effect when the stimuli were mainly congruent and a negative facilitation effect (evidencing task conflict) in the mostly neutral condition. These findings demonstrate that in the absence of any informational conflict (i.e., incongruent trials) task conflict is not detected. Thus, the ACC may only monitor and control conflict when experiencing, or at least expecting informational conflict. However, this is something that neuroimaging studies have so far failed to clarify.

Neuroimaging the Stroop task

The neural basis of attention has been proposed to involve a network of brain structures that form two distinct systems, one anterior and one posterior (Posner & Dehaene, 1994). While the anterior system is thought to be responsible for executive aspects of attention, the posterior system is responsible for the selection of information based on the perceptual characteristics and/or spatial location of a stimulus. This is supported by neuroimaging studies which show increased activity in the prefrontal regions when an executive or decision-making component is involved in attentional control, and increased activity in the posterior regions that are specialised at detecting a particular goal-relevant attribute (e.g., increased activation in V5 when focussing attention on an object's movement; Corbetta et al., 1991). Banich et al.'s (2000) fMRI investigation of the Stroop task attempted to reveal the roles of both the anterior and posterior systems by varying the task-relevant (colour vs. spatial location) and task-irrelevant information (word vs. object) in two experiments. The study found that distinct subdivisions of the dorsolateral prefrontal cortex were activated during tasks that differed in the task-relevant information, but not the task-irrelevant information. In contrast, little activation was observed in these regions when the tasks varied in task-irrelevant information, but not task-relevant information. Instead, for this manipulation greater activation was observed in posterior regions. They suggest that attentional selection in tasks which contain multiple sources of potentially relevant information (e.g., word vs. print colour), acts more by modulating the processing of task-irrelevant

information than by modulating processing of task-relevant information (Banich, et al., 2000).

The brain region often associated with being responsible for selecting between viable response options is the anterior cingulate cortex (ACC; Barch, et al., 2000). Its role, according to the 'conflict monitoring hypothesis' (Botvinick, Braver, Barch, Carter, & Cohen, 2001), is to detect conflict between competing neural systems and consequently determine the extent to which attentional control needs to be exerted. In situations where more sources of task relevant information are identified (e.g., colour-word naming vs. colour-print naming) a greater level of attentional control is required. While many neuroimaging studies of the Stroop task would agree that the ACC plays a vital role in conflict monitoring (Li, Zheng, Wang, Gui, & Li, 2009; Milham, et al., 2002; van Veen & Carter, 2002) there is still disagreement when it comes to distinguishing the types of conflict the ACC is responsible for resolving.

Van Veen et al. (2001) recorded ACC activation using fMRI whilst participants completed the flanker task (Eriksen & Eriksen, 1974), which is similar to the Stroop task in that it allows for stimuli to be congruent, incongruent at the level of stimulus identification, and incongruent at the response level. Although both incongruent trial types caused greater RT interference the ACC was only activated as a result of response conflict. The researchers claim that this is evidence that the ACC is only responsible for the detection of conflicts occurring at later or response-related levels of processing. These findings are supported by Milham et al. (2001) who also used fMRI to investigate the role of the ACC in detecting conflict in a Stroop task. Their findings suggested that the involvement of the ACC in attentional control is limited to situations containing response conflict, while the left prefrontal cortex extends to situations involving conflict at non-response levels. Such findings are therefore consistent with the conflict monitoring hypothesis (Botvinick, Braver, Barch, Carter, & Cohen, 2001) and are supported by research which shows that ACC conflict-related activity predicts both greater prefrontal cortex activity and adjustments in behaviour (Kerns, et al., 2004). Therefore, implying that ACC activity only reflects the detection of response conflict, and not semantic or task conflict.

Some researchers however have challenged this view, suggesting instead that the ACC continues to play a role in regulating attentional control in the absence of response competition (Roelofs, van Turennout, & Coles, 2006). In their study Roelofs et al.

(2006) used an arrow-word Stroop task (e.g., responding to the word 'left' whilst ignoring the mismatched arrow '→') in which participants responded to incongruent, congruent, and neutral stimuli. They suggest that if the involvement of the ACC is limited to situations of response conflict then ACC activity should be increased only when conflicting response alternatives are present (i.e., incongruent trials). Whereas in fact they found that ACC responses were larger for neutral compared to congruent stimuli, thus demonstrating the engagement of the ACC in the absence of response conflict. While the conflict monitoring theory suggests that once the ACC has detected conflict it engages other brain regions to regulate attentional control, Roelofs et al.'s (2006) findings imply that the ACC has a role in regulation itself. The conflict monitoring theory is also compounded by the knowledge that ACC lesions do not consistently impair the cognitive control adjustments that, according to the theory, should follow conflict detection (Boschin, Brkic, Simons, & Buckley, 2017; Swick & Jovanovic, 2002).

Other neuroimaging studies have suggested that two distinct subregions within the ACC are functionally specialized for detecting conflict occurring at pre-response and response levels. Milham and Banich (2005) showed that the rostral dorsal region of the ACC (rdACC) was activated by conflict, whereas the caudal dorsal region (cdACC) was not related to conflict in general but instead was responsive to specific perceptual competition between colour information. Similarly van Veen and Carter (2005) found greater rdACC activation in an incongruent vs. semantic condition comparison (representing response conflict) and increased cdACC activation in a semantic vs. congruent condition comparison (representing semantic conflict). They claim that while the rdACC is sensitive to conflict at the response level, cdACC activation is specific to competition occurring at an earlier pre-response level. This claim is reaffirmed by more recent work that demonstrates that the rdACC and cdACC are involved in conflict tasks and are dissociated by the source of conflict (Kim, Kroger, & Kim, 2011). In their fMRI study Kim et al. (2011) employed a Stroop matching task in which the response set was either composed of two coloured rectangles (colour-response condition) or two words in black ink (word-response condition). During the colour-response condition participants could select the correct response by perceptual comparison, matching the stimulus colour to the colour of the response patch. Since the translation of colour information into a verbal response was not required, response competition was minimized in this condition. Conversely for the word-response condition response competition was

maximized as participants had to convert the colour of the Stroop stimulus into a verbal response option whilst inhibiting information from the word dimension (Sugg & McDonald, 1994). The results showed that the cdACC was more activated during the colour-response condition, whereas the rdACC showed greater activation in the word-response condition. Kim et al. (2011) suggest that this is evidence of functionally dissociable networks for conflict processing whereby perceptual conflict recruits cdACC and response conflict recruits rdACC. In which case pre-response conflict (i.e., semantic conflict) can be expected to activate the cdACC whereas response conflict should activate the rdACC. Yet despite this, some studies have failed to find evidence for ACC dissociation between semantic and response conflict (e.g., van Veen et al., 2001) and thus the exact nature of ACC function remains a source of debate.

While greater activation of the ACC during congruent and incongruent trials, compared to neutral trials has been taken as evidence of task conflict (MacLeod & MacDonald, 2000), others have suggested that this increased activation represents something else (Grinband, et al., 2011). Grinband et al. (2011) argue that the conflict monitoring model fails to predict the relationship between error likelihood and RT. Instead they argue that the ACC is actually responsive to time-on-task and not conflict. Yet Yeung, Cohen and Botvinick (2011) dispute their claims and instead suggest that flaws in their methods and conclusions mean that their findings are in fact consistent with the previously published predictions of the conflict monitoring theory. Conversely, Zysset et al. (2001) argue that ACC activation reflects its involvement in motor preparation processes rather than the detection of conflict. In their fMRI investigation of the Stroop task no substantial activation was detected in the ACC when motor preparation processes were controlled for. As such, it is clear that there is disagreement within the research literature as to whether task conflict is monitored and controlled for by the ACC. Thus, highlighting the need for additional neuroimaging research in order to clarify the role that the ACC plays in identifying and resolving different types of conflict.

Few studies have employed transcranial magnetic stimulation (TMS) as a technique to isolate the neural regions involved in the detection and resolution of conflict. By using TMS to inhibit or facilitate brain regions thought to be responsible for identifying conflict, one could observe the effect on errors and RTs in different conditions and in theory determine whether specific regions are essential for resolving different types of conflict. In practise however reliably targeting specific neural regions

such as the ACC, which is located deeper within the brain, can prove challenging. Nonetheless one study which attempted to use high frequency TMS in order facilitate ACC activity was able to abolish the Stroop interference effect (Hayward, Goodwin, & Harmer, 2004). The study found that reaction times and response errors were significantly greater when TMS was applied over the control area rather than the ACC site, suggesting that the ACC is central to the processes underlying the Stroop task. Other TMS studies have shown that stimulation over the left DLPFC has a positive effect on the reaction times to both congruent and incongruent trials whilst having no effect on the Stroop interference effect (Vanderhasselt, De Raedt, Baeken, Leyman, & D'haenen, 2006). The researchers claim that such findings are consistent with the role of the left DLPFC in implementing top-down attentional control, by representing context and imposing an attentional set. Although such studies are useful in confirming the importance of the ACC and DLPFC in conflict monitoring, research which combines TMS with functional brain imaging is needed in order to establish the differential involvement of these two regions in exerting attentional control.

Electroencephalography (EEG) is another brain imaging technique that offers a unique advantage over fMRI in that it is able to measure electrophysiological changes with high temporal resolution. One study that employed this technique examined the event-related potentials (ERPs) of the ACC between congruent-control and incongruent-control comparisons (Badzakova-Trajkov, Barnett, Waldie, & Kirk, 2009). The study found that congruent-control and incongruent-control differences have a similar timeframe and cingulate source. They claim that this is evidence that the ACC is detecting two sources of information (colour name vs. print colour) and selectively attending to one. They also suggest that a later peak in the incongruent-congruent comparison reflects the detection (and subsequent resolution) of conflict in the two sources of information. These findings would therefore imply that the ACC monitors task relevant information in both congruent and incongruent trials, and later identifies response conflict in incongruent trials. Other EEG studies have also supported the theory that the ACC is responsible for detecting conflict and engaging other brain regions to exert attention control (Hanslmayr, et al., 2008). In their study Hanslmayr et al. (2008) demonstrated that ACC activation increased linearly with increasing interference and that phase coupling between the ACC and the left prefrontal cortex was more persistent for incongruent stimuli compared to congruent and neutral stimuli. Thus, providing evidence for the role the ACC plays in engaging brain regions thought

to be responsible for imposing attentional control. While this suggests that the left prefrontal cortex is involved in conflict resolution processes rather than conflict detection processes, the precise role it plays in conflict resolution is still unclear.

Neuroimaging the Stroop task has proved useful in revealing types of conflict that had previously gone undetected in behavioural studies (MacLeod & MacDonald, 2000). Such studies have enabled us to identify the dorsolateral prefrontal cortex (DLPFC), anterior cingulate cortex (ACC), and posterior parietal cortex (PPC) as being central to overcoming interference. The DLPFC is thought to select the relevant information by biasing information and representing context (Miller & Cohen, 2001), while the ACC is often thought to detect the presence of conflict and alert other systems to exert control (van Veen & Carter, 2002), whereas the PPC is thought to be involved in the visuospatial selection of relevant stimuli (Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002). Although some psychologists have claimed that neuroimaging has revealed that the types of conflict experienced in the Stroop task are underpinned by separate neural networks (e.g., van Veen & Carter, 2005) others have criticized the methods used to isolate stimulus-stimulus (semantic) from stimulus-response conflict, namely the two-to-one colour mapping technique (Hasshim & Parris, 2014). Thus, the important question that still remains is whether the different types of conflict experienced in the Stroop task are resolved by neurologically dissociable regions, or whether conflict resolution is not specific?

Response time distributional analysis

Research on Stroop task performance often uses chronometric analyses which are restricted to mean RTs. However, Heathcote, Popiel and Mewhort (1991) point out that such analyses may obscure certain aspects of performance since they do not take the shape of the distribution into account. Although popular models of Stroop task performance (e.g., Cohen, Dunbar, & McClelland, 1990) are able to successfully predict changes in mean response latencies between conditions, research has demonstrated that such models are inadequate in predicting changes in the shape of the latency distributions, despite the fact that these changes are responsible for the differences between mean RTs (Mewhort, Braun, & Heathcote, 1992). Thus, a better method of analysing RT distributions is to fit a theoretical distribution to the data that describes the cumulative probability of the range of possible RTs as a function of a set of parameters. These parameters can then be analysed in the same way as mean RT, and as such one

can reveal how experimental variables affect the specific feature of the RT distribution represented by each of these parameters (Steinhauser & Hübner, 2009).

A popular theoretical distribution that provides a good fit to RT distributions is the ex-Gaussian distribution (Hohle, 1965; Ratcliff, 1979). Here the data is partitioned into quantiles and three parameters are generated that correspond to different characteristics of the distribution; Mu (μ), Sigma (σ), and Tau (τ). Where μ and σ represent the mean and standard deviation of the normal distribution respectively, and τ denotes the mean and standard deviation of the exponential component of the distribution. Through generating these ex-Gaussian parameters, more information can be obtained about changes in RT distribution that go unheeded in chronometric analyses of mean RTs. Mathematically the ex-Gaussian equation can be written as:

$$f(t) = \frac{1}{\tau} \exp\left\{-\frac{(t-\mu)}{\tau} + \frac{\sigma^2}{\tau^2}\right\}$$

$$\times \Phi\left\{\frac{t-\mu}{\sigma} - \frac{\sigma}{\tau}\right\}$$

Where t is time and ϕ is the normal cumulative distribution function.

The ex-Gaussian distribution provides an appealing method of RT analysis because of its ability to capture regularities in the skewness of RT distributions (Dawson, 1988; Plourde & Besner, 1997; Spieler, Balota, & Faust, 2000). In order to fit an ex-Gaussian distribution to empirical data, two steps must first be considered. Firstly, the empirical RT data must be summarized so that the distributional properties are revealed. Vincentization, originally described by Ratcliff (1979), has become the standard method for averaging RT data as it permits the creation of an average data set while preserving the shapes of the individual distributions. Here the RT data is ranked in ascending order for each subject. Then the desired number of quantiles is selected to describe the data and performance of subjects at each quantile is summed and then averaged. When the quantiles have been calculated for each subject, each quantile is averaged across subjects to give group quantiles. Secondly, an ex-Gaussian distribution is fitted to the Vincentized data. Estimates of the three parameters of the ex-Gaussian distribution are calculated by minimizing the chi-squared fit between the data and the model. The large number of possible combinations of parameters makes finding the optimal combination problematic. However, programs such as the QMPE algorithm (Heathcote, Brown, & Cousineau, 2004) can be used as a robust method of optimisation

(see Dawson, 1988, for a review of fitting the ex-Gaussian distribution). Having estimated the best fitting parameters, one can then assess the fit by overlaying the ex-Gaussian distribution on a histogram of the empirical data.

When applied to the Stroop paradigm the ex-Gaussian function has revealed consistent and replicable changes in the three parameters between conditions (Heathcote, Popiel, & Mewhort, 1991; Spieler, Balota, & Faust, 1996; Spieler, Balota, & Faust, 2000). In such studies the incongruent condition showed increases for all parameters (i.e., μ, σ, and τ) compared to the neutral condition. Whereas for the congruent condition a reduction in μ and an increase in τ was observed (see Figure 2). Steinhauser and Hübner (2009) suggest that this decrease in the exponential parameter τ in the neutral condition relative to the congruent and incongruent conditions may evidence task conflict where the non-lexical neutral condition is selected against at an earlier perceptual level. This would imply that the ex-Gaussian parameters represent different stages of processing. For instance, some psychologists have claimed that the time taken to perceive a stimulus and make a response (transduction component) is normally distributed (with a mean of μ and standard deviation of σ) whereas the time taken to decide on a response (decision component) is distributed exponentially (with a mean of τ; Gordon & Carson, 1990; Hohle, 1965). Thus, on neutral trials where the decision component requires less time, τ should be smaller compared to trials where task conflict is present. On this assumption that τ is reflective of a more central processing component, one can infer that a decline in inhibitory processes should be represented by an increase in τ on incongruent trials due to the additional time needed to resolve conflict between the colour and word dimensions. In support of this notion Spieler, Balota and Faust (1996) demonstrated that the increased interference on incongruent trials observed in older adults (who exhibit a reduction in inhibitory control) compared to younger adults was due to an increase in the tail of the distribution (represented by the parameter τ).

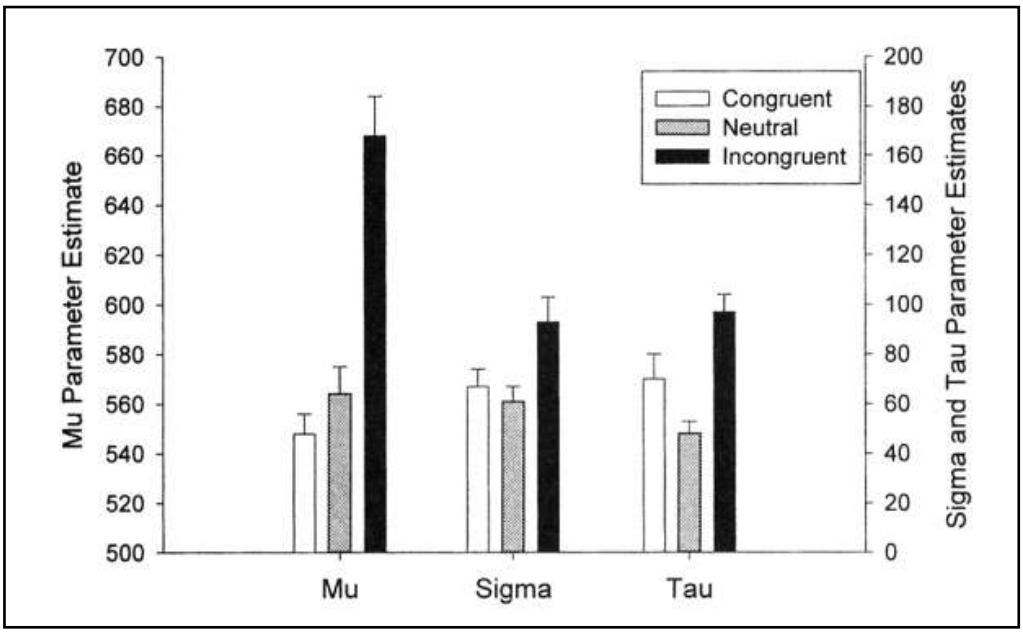

Figure 2. Mean ex-Gaussian parameter estimates from the Stroop task as a function of condition. From "Levels of selective attention revealed through analyses of response time distributions" by D. H. Spieler, D. A. Balota, and M. E. Faust, 2000, *Journal of Experimental Psychology: Human Perception and Performance, 26*, p. 508. Copyright 2000 by the American Psychological Association.

More recently research has applied the ex-Gaussian analysis to the semantic Stroop effect. White, Risko and Besner (2016) postulate that if the increase in τ on incongruent trials is associated with greater response competition (Spieler, Balota, & Faust, 1996) then little or no semantic Stroop effect should be observed in this parameter. In their study they conducted four semantic Stroop experiments using colour-associated words (e.g., sky, frog, lemon and tomato). Across all of their experiments they found a consistent semantic Stroop effect in the mean RTs, however an ex-Gaussian analysis revealed that this effect was only present in μ, and absent from σ and τ. They claim that this is because interference associated with response competition on incongruent trials in τ is absent in the semantic Stroop effect. Therefore, reaffirming the notion that there is a clear difference in the source of semantic and response interference when distinguishing between informational conflict (White, Risko, & Besner, 2016). Such inferences could not be made through the analysis of mean RTs alone, and thus demonstrates the utility of the ex-Gaussian distribution in revealing additional informational about the nature of interference in the Stroop task. The present study will therefore conduct an ex-Gaussian analysis of the RT data to better investigate the presence of each conflict type in Stroop interference.

Planned comparisons

In order to attribute the contribution of each conflict type to Stroop interference we will run a number of planned pairwise comparisons between conditions (see Table 1). Rather than running these comparisons on mean RTs alone we will conduct our analyses on each of the ex-Gaussian parameter estimates individually. For each comparison we take the condition that permits the purest measure of the relevant conflict type and compare this critical condition to a suitable baseline in which the relevant conflict is assumed to be absent. For example, to index response conflict we will take incongruent trials (containing task, semantic and response conflict) as our critical condition, and non-response set trials (containing task and semantic conflict) as our baseline comparison. Additionally, the present study used two independent measures of semantic conflict (semantic associates and non-response set trials).

Table 1. Planned comparisons between conditions and their index of conflict.

Comparison conditions	**Index**
Neutral words – Baseline shapes	Task conflict
Semantic associates – Neutral words	Semantic conflict
Non-response set – Neutral words	Semantic conflict
Incongruent – Non-response set	Response conflict
Incongruent – Baseline shapes	Stroop interference

Nonetheless, such an approach to analysing the various components of interference has recently been criticized (Levin & Tzelgov, 2016). Levin and Tzelgov (2016) suggest that the use of non-orthogonal contrasts do not allow for correct estimation of each of the components because they use the same information multiple times. As is shown above, when indexing the different types of conflict, neutral word trials and non-response set trials are used in more than one comparison. What is argued is that if RTs to incongruent trials, for example, remain constant but RTs to non-response set trials increase then inevitably estimates of response conflict decrease since the difference between incongruent and non-response set trials is now smaller. Thus, when the same condition is used as a critical condition for one measure and a baseline condition for another, it does not permit for an entirely clean estimation since the information used is not unique (Brown, 2011).

Instead, Levin and Tzelgov (2016) propose an integrated framework in which they use a set of independent contrasts by averaging across different trial types. For instance, when indexing semantic conflict, they average RTs across high and low frequency colour-associative word trials and generate a baseline by averaging RTs across high and low frequency neutral word trials. By contrast, response conflict is measured by taking incongruent trials as the critical condition and averaging across all other trials to produce a baseline. Yet while this approach offers a solution to the problem of orthogonality when indexing the different types of conflict, it is not without problems of its own. Since the approach assumes a similarity in the averaged-over trial types it is easy to see how such contrasts might result in the over- or under-estimation of a given component of interference. Thus, if we were to index response conflict by taking incongruent trials as the critical condition and averaging across multiple other trials (each containing varying levels of conflict themselves) to produce a baseline, it is likely to result in the mean decreasing in the baseline which would consequently yield an overestimation of response conflict. Hence, when the averaged-across trials do not contain some or all of the components of interference required for the desired comparison it will inevitably decrease the probability that the resulting estimate is a pure representation of its intended measure (see Roelofs, 2012, for a similar argument).

Therefore, despite Levin and Tzelgov's (2016) suggestion of creating orthogonal comparisons to index each conflict type, our study uses multiple pairwise comparisons in which some information overlaps with other measures. Whilst we acknowledge that these comparisons might not permit the cleanest estimates of the various components of interference, we suggest that their use is more appropriate than assuming similarity between conditions and averaging across different trial types to produce orthogonal contrasts. We note however that future studies might do well to employ a number of conditions for each level of conflict so that independent contrasts can be generated for each index of conflict, allowing for a more stable estimation of the underlying interference components (Levin & Tzelgov, 2016).

Rationale for the present studies

As previously discussed, research to date is yet to clarify the neural networks involved in processing and resolving task, semantic and response conflict. The aim of the present studies is to add to the longstanding debate on the specific nature of ACC and DLPFC function in conflict resolution. In Experiment 1 we use TMS to stimulate

left DLPFC activation and observe the behavioural effect of interference for each conflict type. In Experiment 2 we use fMRI to record the involvement of each putative brain region in resolving these different types of conflict. A novel approach of these studies was to use irregular shapes as our baseline control condition. Previous studies have tended to use non-word letter/symbol strings (e.g., xxxx or ####) as their baseline (e.g., Entel & Tzelgov, 2016; Kalanthroff, Avnit, Henik, Davelaar, & Usher, 2015; Monsell, Taylor, & Murphy, 2001), however these stimuli are likely to activate letter reading processes or at the least they can still be attributed to meaning. Given this we suggest that the use of irregular shapes that are difficult to name should provide us with a better baseline control when indexing task conflict. Furthermore, most of the current neuroimaging studies of conflict in the Stroop task have tended to use same-response trials as an index of semantic conflict (e.g., Chen, Lei, Ding, Li, & Chen, 2013; Jiang, Zhang, & Van Gaal, 2015; van Veen & Carter, 2005), however as previously highlighted recent work has questioned the validity of this measure (Hasshim & Parris, 2014; Hasshim & Parris, 2015). Instead the present studies use non-response set trials and semantic-associative trials as two separate indexes of semantic conflict.

EXPERIMENT 1

Method

Participants

20 participants (12 female, M_{age} = 26.15, SD = 7.1) recruited from the Bournemouth University student and staff population completed the study. One participant was replaced as they withdrew from the experiment. All participants were 18-45 years old, fluent in English and had normal or corrected-to-normal vision, as well as normal colour vision. Participants were screened for potential risk factors associated with rTMS according to published guidelines (Rossi, Hallett, Rossini, & Pascual-Leone, 2009). Each participant was tested individually across two testing sessions and received £10 for participating.

Materials and measures

Stimuli

12 unique stimuli were used for each of our 5 conditions (baseline shape trials, neutral word trials, semantic-associative trials, non-response set trials and incongruent trials). All items were matched for length and frequency with the colours in the response set (red, green, blue, and yellow) using the English Lexicon Project (Balota, et al., 2007). Items were presented individually in uppercase Courier New font, size 42, on a black background (for a full list of stimuli see Figure 3). All items were presented in the centre of the screen in one of four colours: red (RGB; 255; 0; 0), blue (RGB: 0; 32; 96), green (RGB: 0; 176; 80), and yellow (255; 255; 0), with colour-associated words always being presented in an incongruent colour (e.g., 'grass' would be presented in red, as opposed to green).

Baseline shapes	Neutral words	Semantic associates	Non-response set words	Incongruent
	CAR	SKY	PURPLE	BLUE
	CHIEF	GRASS	GREY	GREEN
	CLUB	LEMON	GOLD	YELLOW
	CAR	TOMATO	WHITE	RED
	CHIEF	GRASS	GREY	GREEN
	STAGE	LEMON	GOLD	YELLOW
	CAR	TOMATO	WHITE	RED
	CLUB	SKY	PURPLE	BLUE
	STAGE	LEMON	GOLD	YELLOW
	CHIEF	TOMATO	WHITE	RED
	CLUB	SKY	PURPLE	BLUE
	STAGE	GRASS	GREY	GREEN

Figure 3. List of stimuli for each condition.

OpenSesame 3.2 software (Mathôt, Schreij, & Theeuwes, 2012) was used to administer the Stroop task. The stimuli were presented in pure blocks containing all 12 stimuli for each condition. Each run contained the 5 conditions, with each condition presented in a random order for each new run. Each run was repeated 5 times, meaning that each participant completed a total of 300 trials (60 trials per condition). Each stimulus presentation began with a fixation cross for 300 ms. The stimuli were presented for 1 s and an inter-stimulus interval of 1 s occurred after each stimulus presentation, during which a black screen was shown (see Figure 4). After each block of 12 stimuli participants could take a break. Manual responses were recorded with a Cedrus response box.

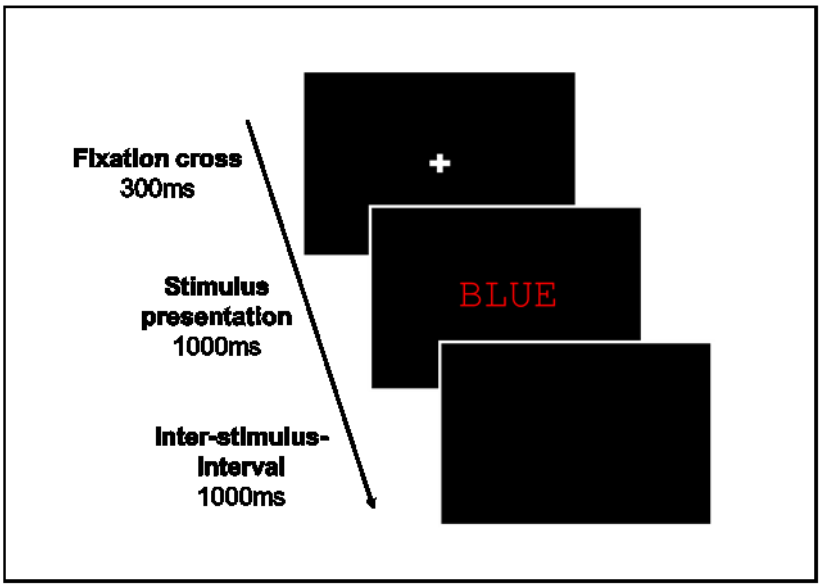

Figure 4. Trial sequence in the Stroop task with example of incongruent stimulus.

TMS

The study used a within subjects design with counterbalanced sham vs. active rTMS crossover. Before beginning the Stroop task high frequency rTMS was performed over the left DLPFC. All stimulations were performed using a DuoMAG XT stimulator (Rogue Resolutions Ltd, Cardiff, UK) with a figure 8-shaped coil. The EMG was recorded using two pregelled Deymed Diagnostic 22 × 30 mm^2 Ag–AgCl disposable electrodes placed over the region of the abductor pollicus brevis (APB) belly and associated tendon of the right hand, and a Velcro wraparound Ground Electrode on the right wrist. The motor threshold (MT) of each participant was determined before real or sham stimulation by establishing the lowest setting at which ≥5 out of 10 stimulations of the left motor cortex resulted in a minimum MEP amplitude of 50 μV elicited at a

given stimulation intensity. Stimulation intensity was set at 110% of the established MT for each individual. The study used the parameters previously set by Vanderhasselt et al. (2006), with a stimulation frequency of 10 HZ and intertrain interval of 26 s. Forty trains were applied in a 20 min period (1,560 pulses per session). The left DLPFC was defined as the F3 location given by the International 10–20 system and was identified for each participant using the Beam F3 system (Beam, Borckardt, Reeves, & George, 2009). Both real and sham stimulation were performed at the same location on the scull, but for sham stimulation the coil was pointed away from the scalp at a 90° angle.

Overall procedure

Before beginning the experiment, participants were asked to read the experiment information sheet (Appendix A) and TMS information sheet (Appendix B). Once participants had confirmed their eligibility for the study by completing the screening questionnaire (Appendix C) and had been given the opportunity to ask questions they were asked to sign a consent form (Appendix D).

After informed consent had been obtained participants were randomly allocated to either a TMS (experimental) or sham-TMS (control) condition (counterbalanced between two testing sessions). Participants in the experimental condition received high frequency rTMS to the left DLPFC for 20 minutes and for sham stimulation the figure 8-shaped coil was positioned at an angle of 90° with one edge resting on the scalp. Participants were told to inform the researcher if they began to feel uncomfortable or experienced adverse effects.

After TMS or sham-TMS had been applied participants completed a manual Stroop task. Participants made responses by pressing the corresponding key on a Cedrus response box and were given the opportunity to practice making responses before beginning the experimental trials. Participants were instructed to respond to the print colour of each stimulus as quickly and as accurately as possible. During the experimental trials no feedback was given about the accuracy of responses. This phase lasted approximately 15 minutes. Each testing session lasted approximately 45-60 minutes. The order of the testing sessions was counterbalanced such that 10 participants received active TMS and 10 participants received sham TMS on the first session. During the second session participants completed the same procedure except that they were assigned to the opposite condition (sham or active TMS). The two testing sessions were separated by a delay of at least 24 hours. After completing the experiment

participants were fully debriefed (Appendix E) and thanked for their time. This study was approved by the Bournemouth University Research Ethics Committee (Appendix F).

Results

TMS was generally well tolerated by participants and there were no reports of any serious adverse effects. Participants had previously been informed about contractions of facial muscles. Other side effects such as seizures, headache, tinnitus, dizziness, or nausea, which have been observed during rTMS studies in the literature, were not reported in our study group. One participant withdrew because they found the TMS stimulation uncomfortable, but they reported no other side effects. This participant was later replaced.

Manipulation check

In the introduction we outlined a series of planned comparisons that we reasoned permitted the most appropriate index of each of the individual components of interference. In order to index task conflict (the conflict that arises from reading the irrelevant word dimension of a Stroop stimulus) we proposed that unreadable irregular shapes should provide us with the most suitable baseline condition to compare against readable neutral word trials. Unexpectedly we consistently showed that the baseline shape trials produced longer RTs than neutral word trials and thus we were unable to demonstrate evidence for the effect of task conflict using this comparison (reported below). Because of this finding it was no longer appropriate to use the irregular shape trials as our baseline to index the overall Stroop interference effect. Instead we used an incongruent – neutral word comparison which better captures the range of interference observed in the experiment. Since incongruent – neutral word comparisons are commonly used to index Stroop interference in the literature (e.g., Milham, et al., 2001) we did not find it necessary to make post hoc corrections.

Analysis of errors

Errors, including incorrect responses and no-responses, accounted on average for 6.48% of the trials in the sham condition and 4.95% of the trials in the TMS condition (error rates for each condition are displayed in Figure 5). An analysis of variance (ANOVA) for repeated measurements was used to analyse differences in error

rates. We used a 2 × 5 within subjects ANOVA with stimulation (sham vs. TMS) and trial type (baseline shapes vs. neutral words vs. semantic associates vs. non-response set vs. incongruent) as within-factors and error rate as the dependent variable. The results showed that there was a significant effect of trial type $F(4, 76) = 3.77$, $p = .008$, $\eta_p^2 = .166$ on error rate. However the effect of stimulation was non-significant $F(1, 19) = 3.65$, $p = .071$, $\eta_p^2 = .161$, as was the interaction between stimulation and trial type $F(4, 76) = 1.05$, $p = .389$, $\eta_p^2 = .052$.

Therefore, although we observed that errors decreased in every trial type after receiving real TMS stimulation compared to sham stimulation, these differences were not significant at the significance level (α) of 0.05. Follow up pairwise comparisons on the error rates between trial types revealed that incongruent trials (8.42%) produced significantly more errors than neutral word trials (5.5%) in the sham stimulation condition $t(19) = 2.62$, $p = .017$. Thus, providing evidence for a Stroop interference effect in the error data after sham stimulation. However, the comparison between incongruent trials (5.83%) and neutral word trials (4.92%) in the real TMS stimulation condition was shown to be non-significantly different $t(19) = 0.88$, $p = .388$. No significant differences in error rates were observed in the planned comparisons between other trial types.

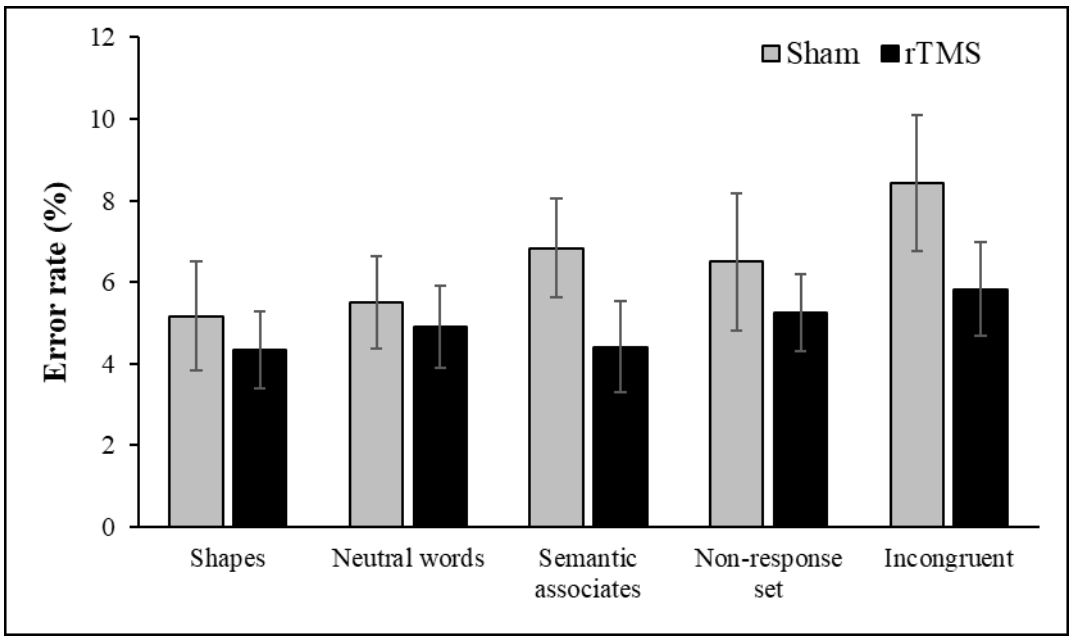

Figure 5. Error rates (%) per trial type as a function of stimulation condition. Error bars represent SE.

Analysis of mean response times

The mean RTs of correct responses for each participant in each condition were subjected to a 2 × 5 (stimulation vs trial type) repeated measures ANOVA. All RT outliers (RTs < 200 ms) were excluded from the analysis. The ANOVA revealed both a significant main effect of stimulation $F(1, 19) = 5.17$, $p = .035$, $\eta_p^2 = .214$ and trial type $F(4, 76) = 6.46$, $p = .001$, $\eta_p^2 = .254$. However, the interaction between stimulation and trial type was non-significant $F(4, 76) = 0.38$, $p = .821$, $\eta_p^2 = .02$.

The mean RTs for sham vs active rTMS were compared for each condition and are summarized in Table 3. Comparisons of each trial type after real and sham TMS revealed that RTs were faster for all trials after real TMS. However, these differences were only significant for neutral word trials $t(19) = 2.13$, $p = .047$, and incongruent trials $t(19) = 2.25$, $p = .036$.

Table 2. Comparison of mean RTs (ms) for each condition after sham and active rTMS.

	Sham	**TMS**	***t***	***p***
Baseline shapes	611.99 (16.88)	594.35 (15.98)	1.69	.107
Neutral words	607.67 (15.11)	587.93 (14.95)	2.13	**.047**
Semantic associates	609.41 (13.00)	595.57 (14.01)	1.57	.134
Non-response set	615.91 (14.68)	597.55 (13.83)	1.86	.078
Incongruent	632.95 (13.14)	608.82 (14.30)	2.25	**.036**

Note. SE is presented between parentheses.

Planned comparisons

In order to determine whether TMS had an effect on the individual components of interference we subjected the data to a series of planned comparisons. Comparisons for each measure of conflict were made independently for the sham and real TMS conditions and the mean differences were then compared between the two stimulation conditions. Comparisons in the sham stimulation condition revealed that RTs for incongruent trials were significantly greater than neutral word trials $t(19) = 3.24$, $p = .004$, providing evidence for an overall Stroop interference effect. The incongruent – non-response set trial comparison in the sham stimulation condition revealed a significant effect of response conflict $t(19) = 2.09$, $p = .050$. All other comparisons in the sham condition were non-significantly different, thus we were unable to demonstrate an effect of task or semantic conflict in this condition. Similarly, the

planned comparisons in the TMS simulation condition revealed a Stroop interference effect in the incongruent – neutral word comparison $t(19) = 3.54$, $p = .002$. However, the comparison for response conflict (incongruent – non-response set) just missed the threshold for significance $t(19) = 2.07$, $p = .052$. We therefore found no evidence for task, semantic or response conflict in the TMS stimulation condition.

We compared mean differences for each comparison between the sham and real TMS stimulation conditions and the findings are summarized in Table 4. The mean differences in the Stroop interference comparison (incongruent – neutral words) between the two stimulation conditions were non-significantly different $t(19) = 0.50$, $p = .625$, suggesting that the Stroop interference effect was unaffected by the stimulation. All other comparisons between the two stimulation conditions were also non-significant.

Table 3. Planned pairwise comparisons between conditions in the arithmetic mean RT data for sham vs. active rTMS.

Comparison	**Sham**	**TMS**	***t***	***p***
NW – BS	-4.31 (6.85)	-6.43 (5.01)	0.32	.750
SA – NW	1.74 (4.95)	7.64 (5.84)	-0.90	.381
NRS – NW	8.24 (6.16)	9.63 (5.87)	-0.19	.850
I – NRS	17.03 (8.15)*	11.27 (5.44)	0.60	.554
I – NW	25.27 (7.80)**	20.89 (5.91)**	0.50	.625

Note. SE is presented between parentheses. 'BS' refers to baseline shapes. 'NW' refers to neutral words. 'SA' refers to semantic associates. 'NRS' refers to non-response set. 'I' refers to incongruent. * $p < 0.05$ ** $p < 0.01$

ex-Gaussian analysis of response times

QMPE software (Heathcote, Brown, & Cousineau, 2004) was used to generate parameter estimates for μ, σ, and τ for each trial type in both the sham and real TMS conditions. All error trials were excluded from the analysis as were any RT outliers (RTs < 200 ms). Each of the ex-Gaussian parameter estimates were subjected to a 2×5 (stimulation vs trial type) repeated measure ANOVA. μ, σ, and τ were entered independently. The mean ex-Gaussian parameter estimates for each condition are displayed in Figure 6.

For the parameter μ the results showed that there was a significant main effect of trial type on μ parameter estimates of RT $F(2.89, 54.83) = 2.89$, $p = .045$, $\eta_p^2 = .132$. However the main effect of stimulation $F(1, 19) = 1.89$, $p = .185$, $\eta_p^2 = .091$, and the interaction effect of stimulation and trial type $F(4, 76) = 0.19$, $p = .945$, $\eta_p^2 = .01$, were both non-significant. For σ the results showed that both the main effect of trial type $F(4, 76) = 2.03$, $p = .099$, $\eta_p^2 = .097$ and stimulation $F(1, 19) = 0.47$, $p = .503$, $\eta_p^2 = .024$, were non-significant. The interaction effect was also non-significant $F(2.67, 50.73) = 1.06$, $p = .370$, $\eta_p^2 = .053$. Similarly for τ the main effect of trial type $F(4, 76) = 0.52$, $p = .722$, $\eta_p^2 = .027$, and stimulation $F(1, 19) = 2.03$, $p = .170$, $\eta_p^2 = .009$, as well as the interaction effect $F(4, 76) = 0.43$, $p = .787$, $\eta_p^2 = .022$, were all non-significant. We were therefore only able to demonstrate a significant main effect of trial type in the parameter μ.

Planned comparisons

As with the arithmetic mean RT data we also subjected each of the ex-Gaussian parameter estimates to a series of planned comparisons. Comparisons for each measure of conflict were made independently for the sham and real TMS conditions and the mean differences were then compared between the two stimulation conditions. Comparisons in the sham stimulation condition revealed a significant effect of semantic conflict in the parameter σ for both the semantic associates – neutral words comparison $t(19) = 2.35$, $p = .030$, and the non-response set – neutral words comparison $t(19) = 2.4$, $p = .027$. The incongruent – neutral words comparison in the sham condition also revealed a significant Stroop interference effect in the parameter μ $t(19) = 2.71$, $p = .014$. All other comparisons in the sham stimulation condition were non-significant. Comparisons in the TMS stimulation condition revealed a significant Stroop interference effect in both the parameter μ $t(19) = 2.49$, $p = .022$, and the parameter σ $t(19) = 2.88$, $p = .010$. All other comparisons in the TMS stimulation condition were non-significant.

We compared mean differences for each comparison between the sham and real TMS stimulation conditions and the findings are summarized in Table 5. No significant differences between the comparisons in the sham and TMS conditions were found in any of the parameters. Thus, TMS did not significantly reduce any of the components of interference in any of the ex-Gaussian parameter estimates.

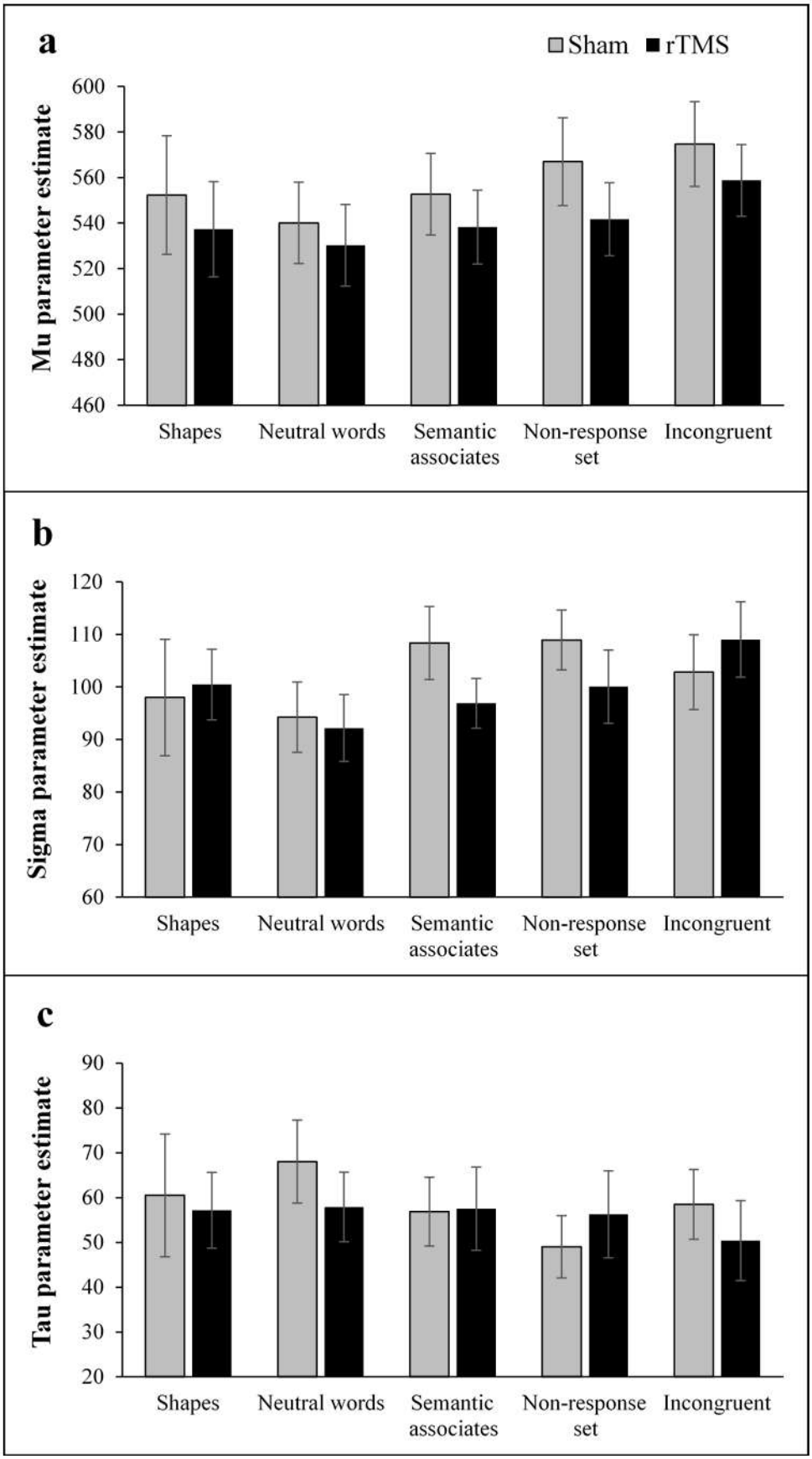

Figure 6. ex-Gaussian parameter estimates for Mu (a) Sigma (b) and Tau (c) in milliseconds for each trial type as a function of stimulation type. Error bars represent SE.

Table 4. Planned pairwise comparisons between conditions in each of the ex-Gaussian parameter estimates for sham vs. active rTMS.

Comparison	Sham	TMS	*t*	*p*
NW – BS				
μ	-12.23 (17.53)	-7.03 (14.17)	-0.25	.805
σ	-3.75 (9.19)	-8.31 (6.34)	0.45	.658
τ	7.53 (13.57)	0.75 (11.28)	0.41	.686
SA – NW				
μ	12.54 (8.92)	7.97 (11.54)	0.30	.768
σ	14.11 (6.01)*	4.71 (5.35)	1.08	.293
τ	-11.17 (8.54)	-0.38 (9.86)	-0.81	.428
NRS – NW				
μ	26.9 (13.90)	11.41 (16.37)	0.76	.457
σ	14.69 (6.12)*	7.89 (7.81)	0.76	.455
τ	-18.98 (12.33)	-1.66 (12.85)	-1.07	.299
I – NRS				
μ	7.71 (13.88)	17.09 (13.66)	-0.47	.646
σ	-6.13 (5.89)	9.00 (7.98)	-1.51	.148
τ	9.44 (8.06)	-5.84 (12.02)	1.05	.306
I – NW				
μ	34.61 (12.78)*	28.50 (11.43)*	0.41	.686
σ	8.56 (6.31)	16.89 (5.87)*	-0.94	.359
τ	-9.55 (10.78)	-7.50 (9.15)	-0.16	.871

Note. Mean standard errors are presented between parentheses. 'BS' refers to baseline shapes. 'NW' refers to neutral words. 'SA' refers to semantic associates. 'NRS' refers to non-response set. 'I' refers to incongruent. * $p < .05$

Discussion

Relatively few studies have employed TMS to target specific neural regions and observe the effect on Stroop interference. In the present study we used rTMS to stimulate left DLPFC activation and measured its effect on each of the individual components of interference (task, semantic, and response conflict). Because the order of rTMS and sham stimulation was counterbalanced and, in addition, the same persons

were used in the two stimulation conditions it was appropriate to compare differences in performance between these two conditions.

Response errors were analysed because increased conflict during Stroop tasks usually manifests itself as an increase in action slips (i.e., fast erroneous responses) or timeout errors (van Veen & Carter, 2005). We observed a significant effect of trial type on response errors. Follow up analyses revealed an overall Stroop interference effect in the sham stimulation condition as errors on incongruent trials were significantly greater than on neutral word trials, however this difference was not observed in the TMS stimulation condition. Although we observed that errors decreased for all trial types after TMS compared to sham, the main effect of stimulation and the interaction effect were both shown to be non-significant. We therefore found that stimulation of the left DLPFC did not significantly affect the accuracy of responses.

Analysis of the arithmetic mean RT data revealed both a significant main effect of trial type and stimulation type. However, the interaction effect was non-significant, suggesting that the effect of TMS did not significantly differ for one trial type compared to another. Planned comparisons between trial types revealed evidence for a significant effect of response conflict in the sham condition, and this effect was almost significant in the TMS condition. No evidence was found for an effect of task or semantic conflict in either stimulation condition in the mean RT data. Because our study was concerned with investigating the differential involvement of the left DLPFC in resolving each of the underlying components of interference we compared each index of conflict between the two stimulation conditions. We observed that for each index of conflict, interference was not significantly reduced after TMS compared to sham. Thus, our findings are consistent with previous research which suggests that high frequency stimulation of the left DLPFC decreases RTs in the Stroop task whilst having no consequences as to the Stroop interference effect (Vanderhasselt, De Raedt, Baeken, Leyman, & D'haenen, 2006).

Whilst recent investigations of the Stroop task have suggested that distributional analysis of the RT data increases the sensitivity of detecting effects on underlying processes (Parris, Dienes, & Hodgson, 2013), the ex-Gaussian analysis in the present study was unable to detect the presence of task or response conflict in any of the parameters. We were however able to detect the presence of semantic conflict in the parameter σ in both indexes in the sham stimulation condition. Because a significant

difference was observed in both the semantic associates – neutral words and non-response set – neutral words comparisons this provides strong evidence that the additional semantic information in semantic associate and non-response set trials results in an increase in the standard deviation of the RTs. Since this effect in σ was not observed for either comparison in the TMS stimulation condition it might indicate that TMS had reduced the influence of semantic conflict. However, comparisons between the two stimulation conditions revealed that the reduction in semantic conflict after TMS was non-significant.

Surprisingly all comparisons in the parameter τ were non-significant. Previous research has shown with some consistency that trials containing a greater degree of response competition tend to produce a greater skew in the RT distribution, reflected by an increase in τ (Heathcote, Popiel, & Mewhort, 1991; Spieler, Balota, & Faust, 2000). In the first application of the ex-Gaussian function to the Stroop task Heathcote, Popiel, and Mewhort (1991) demonstrated that both incongruent and congruent trials produced significantly greater τ estimates than neutral non-word trials (e.g., xxxx). If then decreases in τ for neutral non-word trials do indeed reflect the absence of any response competition, then we might expect τ estimates in the present study to be lowest in the baseline shapes condition and highest in the incongruent condition. Similarly, if the increase in τ for congruent stimuli relative to neutral non-word stimuli is reflective of task conflict (as suggested by Steinhauser & Hübner, 2009) then we would also expect greater τ values in the neutral word condition (containing task conflict) compared to the baseline shapes condition. However, our results revealed that comparisons between all trial types in the τ parameter were not significantly different. Such findings bring into question whether the previously reported increase in τ for readable compared to unreadable stimuli truly represents an increase in task conflict (Heathcote, Popiel, & Mewhort, 1991; Steinhauser & Hübner, 2009).

Less surprising however was the absence of semantic conflict in the τ parameter. Previous studies that have applied an ex-Gaussian analysis to the semantic Stroop effect have reported that the effect was only present in μ, and absent from σ and τ (Steinhauser & Hübner, 2009; White, Risko, & Besner, 2016). Our findings are therefore partially consistent with these previous studies in reporting no semantic Stroop effect in τ, however contradict the claim that semantic conflict is unique to μ, as we observed its presence in σ only. Once again, these findings question the reliability of the ex-Gaussian function in dissociating the different components of interference. Although

some researchers have claimed that the ex-Gaussian parameters uniquely correspond to specific cognitive processes (Hohle, 1965; Steinhauser & Hübner, 2009; Roelofs, 2012), others have suggested that such interpretations are not substantiated by empirical evidence (Matzke & Wagenmakers, 2009). Thus, while an ex-Gaussian analysis provides us with a more descriptive overview of the RT data, what is less clear is whether changes in the parameter estimates can be reliably attributed to different cognitive processes. The lack of clarity on this point in the current literature highlights the need for more research in order to determine whether the underlying components of interference are associated with particular ex-Gaussian parameters.

An interesting finding from the present experiment was that the baseline shape trials produced longer RTs than neutral word trials in the arithmetic mean data as well as in the μ and σ ex-Gaussian parameters (although not statistically significant). Furthermore, no significant difference was observed in the τ parameter between these two conditions, and thus no evidence was found for the presence of task conflict. In the introduction we noted that most previous studies had used non-word letter strings (e.g., xxxx) as their baseline condition when indexing task conflict (Entel & Tzelgov, 2016; Kalanthroff, Avnit, Henik, Davelaar, & Usher, 2015; Monsell, Taylor, & Murphy, 2001). However, we reasoned that since each individual letter in the string can still be read, such trials may still activate reading processes which ultimately interferes with the task goal. Therefore, non-word letter strings may still produce some task conflict but only to a lesser extent. Accounting for this we suggested that unreadable and difficult to name shapes might provide a better baseline in order to capture the entire effect of task conflict. However, no significant difference was observed between the shape trials and neutral word trials in both the arithmetic mean and ex-Gaussian analyses. Because previous research has been able to show a significant increase in the RTs to neutral word trials compared to neutral non-word trials (Levin & Tzelgov, 2016) this might indicate that the irregular shapes used in our experiment were not an appropriate baseline. One possible explanation for this, which we discuss further in the general discussion, is that the unfamiliarity of these irregular shapes distracts attention away from the task goal. Identifying the most appropriate baseline condition for which to index task conflict remains a significant challenge for future research.

While the significant reduction in RTs after TMS compared to sham stimulation supports previous research in suggesting that the role of the DLPFC is to implement cognitive control (Hanslmayr, et al., 2008; MacDonald & Angus, 2000), there are

limitations with the present study that we must also take into consideration. One limitation of the present experimental design, highlighted by Vanderhasselt, et al. (2006) is the potential that non-cortical effects such as an increased alertness after painful stimulation may have influenced the results. Since active rTMS may cause more discomfort than sham, where the coil is positioned at a 90° angle to the scalp (Loo, et al., 2000), it is possible that these different sensations between the two conditions may produce a behavioural effect that is unrelated to cortical activation. For instance, the different somato-sensory effects between the two conditions (e.g., muscle twitches) may lead the participant to change their beliefs about the effectiveness of the stimulation, potentially resulting in a placebo or nocebo effect. Some researchers have argued that sham TMS is useful for controlling for the sensory side effects of TMS on behaviour but is ultimately insufficient as a full-fledged control paradigm (Duecker & Sack, 2015). Future research may wish to control for this by stimulating a control site thought to be unrelated to the processes involved in performing the task (Boschin, Mars, & Buckley, 2017; Hayward, Goodwin, & Harmer, 2004). A popular control site for TMS studies is the vertex, located at position Cz of the International 10-20 System, as it is assumed to have no functional significance in task performance. Recent work which investigated fMRI BOLD signal changes across the whole brain linked to vertex stimulation showed that stimulation did not induce significant increases in activation at any voxels (Jung, Bungert, Bowtell, & Jackson, 2016). This provides support for the use of the vertex as a control site, which might therefore provide the best control condition for future research.

Another potential confound is that the delay between sessions and time of day were not controlled for in this experiment. Previous studies have controlled for this by comparing performance between pre- and post-stimulation tests (Vanderhasselt, De Raedt, Baeken, Leyman, & D'haenen, 2006; Vanderhasselt, et al., 2007). However, the drawback of such a design is that performance on the post-test may be influenced by practice effects or fatigue effects. Nevertheless, future studies may wish to include pre-tests to limit the effect of extraneous variables such as the day of testing, as post-test performance between the two stimulation conditions can still be reliably compared. Since the present study counterbalanced the order of the TMS and sham conditions and because each participant acted as their own control it was still appropriate to compare performance between the two conditions in this experiment.

In sum, the present study was able to demonstrate evidence for the presence of response conflict in the arithmetic mean data, and evidence for semantic conflict was found in the ex-Gaussian parameter σ. We believe that the baseline condition used in the present study did not allow for the detection of task conflict. Strong evidence was found for a Stroop interference effect and we demonstrated that high frequency rTMS to the left DLPFC had no consequences on this effect. rTMS did have a general effect on performance by reducing RTs but had no significant effect as to the accuracy of responses. The lack of an interaction effect between stimulation and trial type would suggest that the role of the left DLPFC in resolving competition is not dependent on the type of conflict. The findings also bring into question the reliability of attributing the underlying components of interference to particular ex-Gaussian parameters since we were unable to replicate the findings from previous studies attempting to make such inferences (Steinhauser & Hübner, 2009; White, Risko, & Besner, 2016). While this supports previous findings that the DLPFC is indeed essential in implementing top-down attentional control (Vanderhasselt, De Raedt, Baeken, Leyman, & D'haenen, 2006; Vanderhasselt, et al., 2007), it suggests that its role is not conflict specific.

EXPERIMENT 2

Method

Participants

20 participants were tested; however, 7 participants were dropped from the analysis because problems with the experiment program meant that they were unable to complete all of the trials and because the timing between each trial was inconsistent. The results of 13 participants (8 female, M_{age} = 25.69, SD = 8.72), recruited from Bournemouth University and the University of Exeter's staff and student populations, were analysed. All participants were 18-45 years old, fluent in English and had normal or corrected-to-normal vision, as well as normal colour vision. Each participant was tested individually and received course credit and/or a copy of their structural brain scan for participating.

Materials and measures

Stimuli

The stimuli used for this experiment were the same as experiment 1. Each run of the 5 conditions was repeated 10 times in a random order, meaning that each participant completed a total of 600 trials (120 trials per condition). Stimuli were presented in pure blocks of 12 stimuli and participants responded to the colours red (RGB: 255; 0; 0), blue (RGB: 0; 32; 96), green (RGB: 0; 176; 80), and yellow (RGB: 255; 255; 0) by pressing the corresponding key on a Cedrus response box. Each stimulus presentation began with a fixation dot for 300 ms and was followed by the stimulus presentation for 1 s and an inter stimulus interval of 1 s.

Image acquisition

Scanning was performed on a 1.5T Philips Gyroscan magnet with a standard RF head coil at the *Exeter MR Research Centre, University of Exeter, UK*. A T_2*-weighted echoplanar imaging (EPI) sequence was used (TR = 2300 ms, TE = 50 ms, flip angle = 90°, 30 oblique transverse slices in ascending order and matrix size = 3 × 3 × 3 mm). 880 volumes were acquired for each subject. Participants were able to view the stimuli on a screen placed at the foot of the scanner via a mirror mounted on the head coil. Between each condition there was a break for 10 seconds to allow the BOLD signal to return to baseline.

Image analysis

Data were analysed using SPM12 Software (www.fil.ion.ucl.ac.uk/spm). The fMRI images were pre-processed -realigned, sliced timed (ascending sequence, 30 slices, TR = 2300 ms), normalized and smoothed (to 8 mm). Statistical regressors were generated by convolving a canonical hemodynamic response function with a series of discrete event onset times for blocks (30 s duration) corresponding to the presentation of stimuli in the baseline shapes, neutral word, semantic-associative, non-response set and incongruent conditions. A general linear model approach was used to estimate parameter values for each regressor and a series of one-sample t tests were carried out for each of the planned comparisons. Having created a series of t-contrast images for each subject, a random effects (second level) analysis was carried out to assess which voxels showed activation to critical stimuli compared to control stimuli across the different indexes of conflict types (e.g., a neutral words vs. baseline shapes comparison

was used to index activation resulting from task conflict). These analyses were confined to regions of interest (ROIs) defined using the inbuilt neuromorphometrics masking tool in SPM. The ROIs chosen were the frontal and limbic lobes and were selected on the basis of having been implicated previously in studies investigating the neural dissociation of conflict types (van Veen & Carter, 2005). An uncorrected statistical threshold $p < .050$ and a voxel cluster threshold of 8 were used. In order to determine the site of activation, MNI (SPM) coordinates were converted to Talairach coordinates and an atlas of Talairach and Tournoux (1988) was used.

Overall procedure

Before beginning the experiment, participants were asked to read the experiment information sheet (Appendix G) and complete a screening form (Appendix H). Once participants had confirmed their eligibility and had been given the opportunity to ask questions they were asked to sign a consent form (Appendix I).

After informed consent had been obtained participants entered the MRI scanner and completed practice trials while a structural scan was performed. After the practice trials participants completed the experimental trials whilst BOLD activation was recorded. Participants were instructed to respond as quickly and as accurately as possible to each stimulus. Each participant completed 10 runs of the 5 conditions. Each condition was presented in a random order for each new run, and the stimuli were presented in a random order during each condition. Responses that occurred between 60-999 ms after the onset of each stimulus presentation were recorded using a Cedrus response box. Between each condition there was a break for 10 s. Each testing session lasted approximately 45 minutes.

After completing the experimental trials, a final structural scan was performed before participants were removed from the scanner. All participants were fully debriefed (Appendix J) and thanked for their time. This study was approved by the Bournemouth University Research Ethics Committee (Appendix K).

Results

Manipulation check

In Experiment 1 we showed that the baseline shape trials produced longer RTs than neutral word trials. Although this difference was not statistically significant we

suggested that the incongruent – baseline shapes comparison was no longer the most appropriate comparison to use to index the overall Stroop effect. Instead we used an incongruent – neutral word comparison which better captured the range of interference observed in the experiment. In the present experiment however, responses to neutral word trials were only 0.48 ms faster than responses to baseline shape trials. Since RTs to these two conditions were almost identical in the present experiment it was still appropriate to use an incongruent – baseline shape comparison to index the overall Stroop interference effect. Therefore, no changes were made to the original planned comparisons outlined in the introduction.

Analysis of errors

Errors, including incorrect responses and no-responses, accounted on average for 11.92% of the trials. An omnibus ANOVA for error rates across the five conditions was conducted. Mauchly's test indicated that the assumption of sphericity had been violated $\chi^2(9) = 29.39$, $p = .001$, therefore the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .40$). The results showed that the effect of condition on the rate of response errors was non-significant $F(1.61, 36.25) = 1.51$, $p = .244$, $\eta_p^2 = .112$. Because our ANOVA revealed no significant effect of condition on error rates, follow-up pairwise comparisons between conditions were not carried out. Average error rates for each condition are displayed in figure 7.

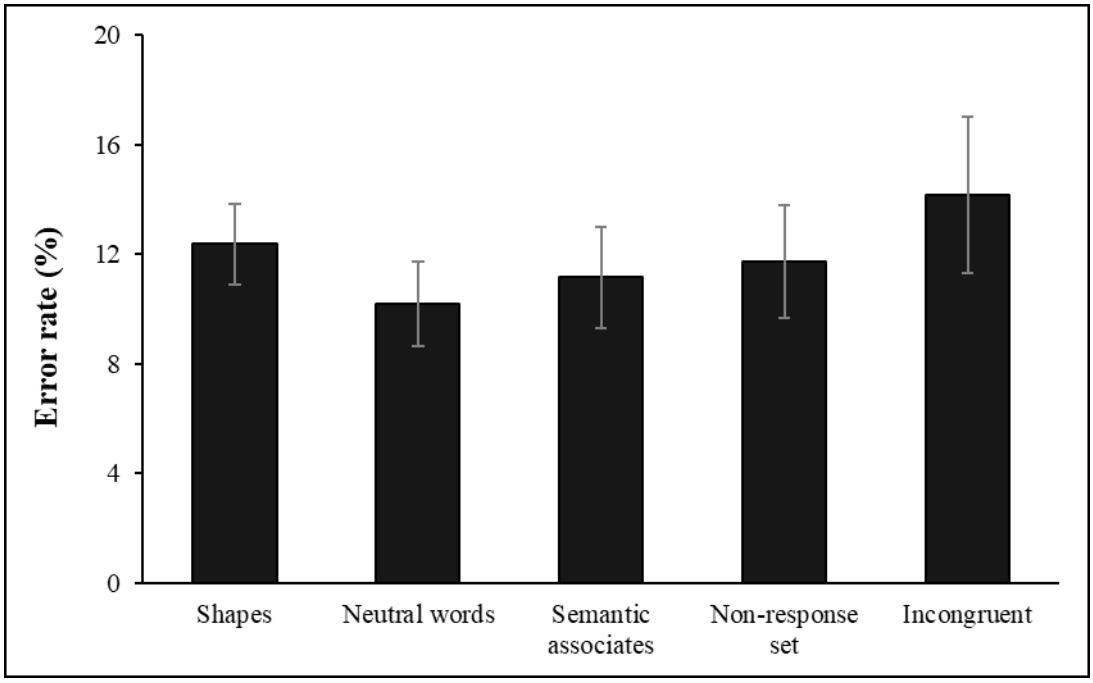

Figure 7. Error rates (%) per condition. Error bars represent SE.

Analysis of mean response times

The mean RTs of correct responses for each participant in each condition were subjected to a one-way repeated measures ANOVA. All RT outliers (RTs < 200 ms) were excluded from the analysis. The mean RTs of each experimental condition are summarized in Table 6.

Mauchly's test indicated that the assumption of sphericity had been violated $\chi^2(9) = 21.13$, $p = .013$, therefore the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .47$). The results of the one-way repeated measures ANOVA revealed that the main effect of condition was non-significant $F(1.88, 22.52) = 1.8$, $p = .189$, $\eta_p^2 = .131$. While the descriptive mean data indicates that RTs increased for trials containing semantic and response conflict, these differences were not significant at the significance level (α) of 0.05. Thus, we were unable to demonstrate evidence for the presence of task, semantic or response conflict in the arithmetic mean RT data.

Table 5. Mean response latencies (ms) per condition.

	Shapes	**NW**	**SA**	**NRS**	**Incongruent**
RTs (ms)	641.73	641.25	645.54	655.48	655.42
	(14.83)	(17.07)	(18.17)	(19.88)	(20.83)

Note. 'NW' refers to neutral words. 'SA' refers to semantic associates. 'NRS' refers to non-response set. SE is presented between parentheses.

ex-Gaussian analysis of response times

QMPE software (Heathcote, Brown, & Cousineau, 2004) was used to generate parameter estimates for μ, σ, and τ in each condition. All error trials were excluded from the analysis as were any RT outliers (RTs < 200 ms). Whilst the RTs for each individual were assumed to have an ex-Gaussian distribution, the means entered for each of the ex-Gaussian parameters were assumed to be normally distributed and were thus subjected to a one-way repeated measure ANOVA. μ, σ, and τ were entered independently.

For μ the results of the one-way repeated-measures ANOVA showed that the main effect of condition was close to being significant $F(4, 48) = 2.52$, $p = .053$, $\eta_p^2 = .174$. For σ the results showed that the main effect of condition was non-significant $F(4, 48) = 1.73$, $p = .159$, $\eta_p^2 = .126$. For τ the results showed that the main effect of

condition was also non-significant $F(4, 48) = 1.49$, $p = .219$, $\eta_p^2 = .111$. Mean ex-Gaussian parameter estimates for each condition are displayed in Figure 8.

Planned comparisons

A priori pairwise comparisons were conducted for μ, σ, and τ independently (see Table 7).

For the parameter μ none of the comparisons were found to be significant at the $p < .05$ threshold. Therefore, no evidence was found for an effect of task, semantic or response conflict in the μ parameter. However, the comparison for the overall Stroop interference effect (incongruent – baseline shapes) was close to significance $t(17) = 1.96$, $p = .074$.

Analysis of the parameter σ revealed evidence for response conflict as σ estimates for the incongruent condition (M = 105.73 ms, SE = 5.94) were significantly greater than in the non-response set condition (M = 94.69 ms, SE = 5.63) $t(17) = 2.56$, $p = .025$. No evidence was found for the presence of task conflict or semantic conflict in this parameter. The comparison for the overall Stroop interference effect was almost significant $t(17) = 2.09$, $p = .058$.

All comparisons for the parameter τ were non-significant and therefore no evidence was found for the effect of task, semantic or response conflict in this parameter. However, comparisons of the means in this parameter did reveal that contrary to what was expect, τ parameter estimates were greater in the baseline shapes condition compared to the incongruent condition, although this difference was non-significant $t(12) = -1.80$, $p = .097$.

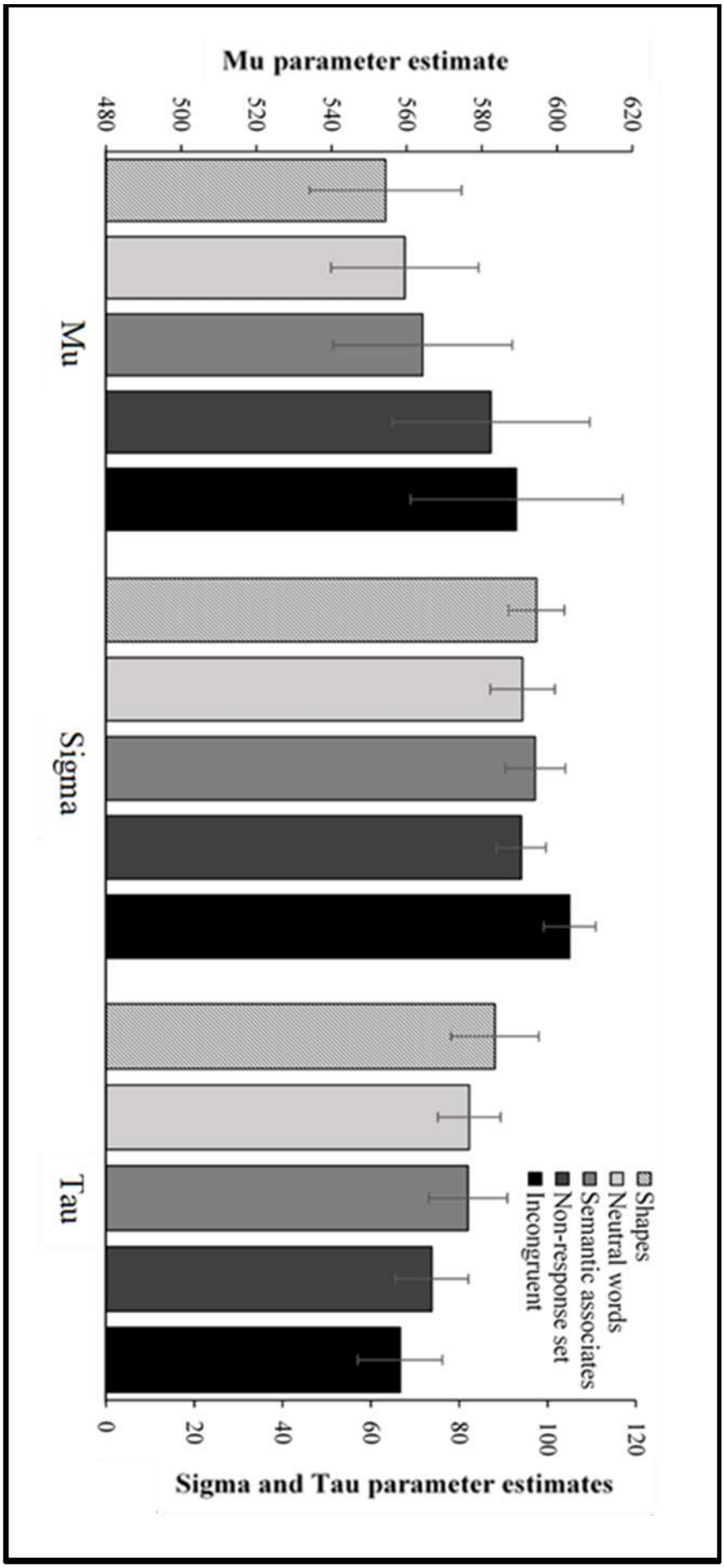

Figure 8. Mean ex-Gaussian parameter estimates in the fMRI Stroop task as a function of condition. Error bars represent SE.

Table 6. Planned pairwise comparisons between conditions in each of the ex-Gaussian parameter estimates.

Comparison	Mean difference	*t*	*p*
NW – BS			
μ	5.11 (9.83)	0.52	.613
σ	-3.15 (4.17)	-0.76	.464
τ	-5.81 (8.96)	-0.65	.528
SA – NW			
μ	4.77 (13.56)	0.35	.731
σ	2.87 (5.27)	0.54	.597
τ	-0.28 (10.22)	-0.27	.979
NRS– NW			
μ	22.9 (13.53)	1.69	.116
σ	-0.31 (6.35)	-0.05	.962
τ	-8.47 (10.03)	-0.85	.415
I – NRS			
μ	6.81 (10.4)	0.66	.525
σ	11.04 (4.31)	2.56	**.025**
τ	-7.19 (7.45)	-0.96	.354
I – BS			
μ	34.81 (17.81)	1.96	.074
σ	7.57 (3.62)	2.09	.058
τ	-21.48 (11.92)	-1.80	.097

Note. Mean standard errors are presented between parentheses. 'BS' refers to baseline shapes. 'NW' refers to neutral words. 'SA' refers to semantic associates. 'NRS' refers to non-response set. 'I' refers to incongruent.

fMRI data

Analysis of the fMRI data revealed that different brain regions were responsive to the different types of conflict (see Figure 9). Activated regions were confined to areas within the left and right DLPFC as well as the ACC. Planned contrasts were carried out to reveal the brain regions that elicited activity in response to each of the types of

conflict and the results are displayed in Table 8. Task conflict was shown to elicit activation in both the left and right DLPFC. The two indexes of semantic conflict showed inconsistent patterns of activation. Compared to neutral word trials, non-response set trials resulted in increased activity in the left and right DLPFC as well as in the ACC. Semantic associative trials on the other hand produced no significant activation in these regions when compared to neutral word trials. Response conflict was shown to elicit activation in the DLPFC but only in the right hemisphere. Finally, the incongruent – baseline shapes contrast revealed the brain regions recruited when performing the standard Stroop task. Large clusters of activation were found in both hemispheres of the DLPFC, as well as activation within the ACC.

Table 7. Activated areas in response to each of the components of Stroop interference.

Region	**No. voxels**	**Talairach coordinates (x, y, z)**	***t***	***p***
NW – BS				
L middle frontal gyrus	11	-26, 7, 28	2.42	.016
R middle frontal gyrus	12	26, 14, 31	2.33	.019
SA – NW				
No significant activation	n/a	n/a	n/a	n/a
NRS– NW				
L middle frontal gyrus	13	-20, 10, 27	2.85	.007
R middle frontal gyrus	14	35, 11, 29	2.74	.014
Anterior cingulate gyrus	8	2, 26, 32	2.48	.023
I – NRS				
R middle frontal gyrus	25	47, 24, 32	3.13	.004
I – BS				
L middle frontal gyrus	35	-38, 14, 30	3.34	.003
R middle frontal gyrus	46	23, 17, 31	3.17	.004
Anterior cingulate gyrus	8	12, 20, 33	2.63	.011

Note. 'BS' refers to baseline shapes. 'NW' refers to neutral words. 'SA' refers to semantic associates. 'NRS' refers to non-response set. 'I' refers to incongruent. The normalised voxel size was 3 × 3 × 3 mm. Only clusters of 8 voxels or greater are presented. '*t'* and '*p'* represent values from a t-test of the peak voxel (showing the greatest statistical difference within a cluster).

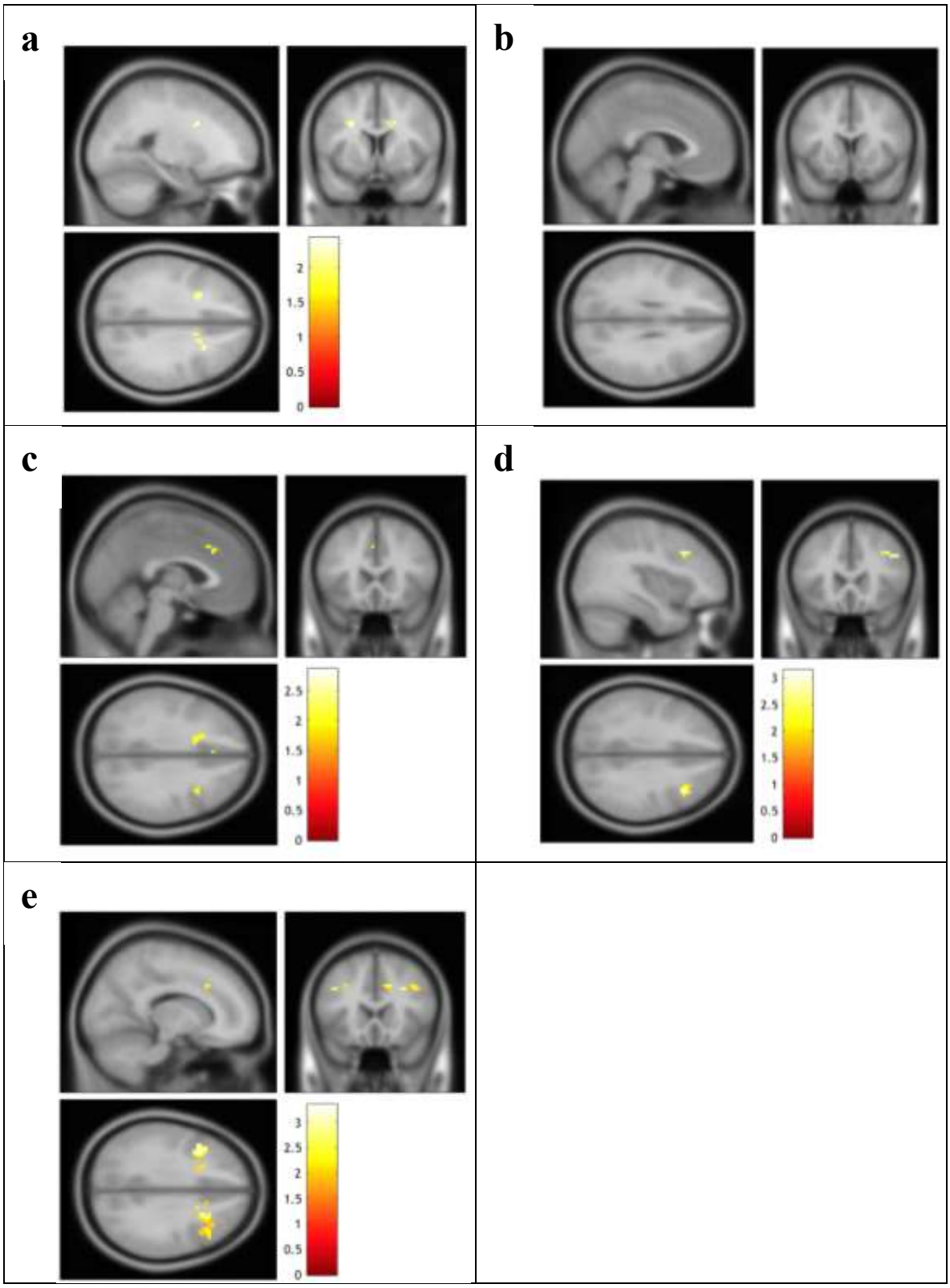

Figure 8. Functional magnetic resonance imaging activation elicited by a) task conflict indexed using a neutral words – baseline shapes contrast, b) semantic conflict indexed using a semantic associates – neutral words contrast, c) semantic conflict indexed using a non-response set – neutral words contrast, d) response conflict indexed using a incongruent – non-response set contrast, e) Stroop interference indexed using an incongruent – baseline shapes contrast. Activation colour represents *t* values.

Discussion

In Experiment 1 we demonstrated evidence for the role of the left DLPFC in implementing top down attentional control. However, functional brain imaging research is necessary before we can draw conclusions about the differential involvement of the DLPFC in the circuitry responsible for attentional control, especially in regard to the different forms of conflict being investigate here. Therefore, in the present experiment we set out to investigate the relative activation of the DLPFC at each level of conflict using fMRI. Also of interest was the involvement of the ACC, since numerous studies have previously implicated this region as playing a critical role in identifying cognitive conflicts.

We were unable to successfully demonstrate evidence for the presence of any of the various components of interference in the behavioural data. The analysis of error rates revealed no significant differences between the trial types. As expected the incongruent condition produced the highest percentage of errors however the error rate in this condition did not significantly differ from any other condition. The analysis of the mean RTs also revealed that differences between each trial type were not statistically significant.

As in Experiment 1 we also subjected the behavioural RT data to an ex-Gaussian analysis as previous research has found evidence for its utility in detecting effects that otherwise go unnoticed in chronometric analyses (Parris, Dienes, & Hodgson, 2013). The only significant effect from the ex-Gaussian analysis was the finding that σ estimates in the incongruent condition were significantly greater than in the non-response set condition, indicating the presence of response conflict. However, this finding is somewhat surprising considering that no evidence for response conflict was found in this parameter in Experiment 1. All other comparisons in each of the three ex-Gaussian parameters were non-significant. Although, the comparison for the overall Stroop interference effect was close to significance in both the μ ($p < .074$) and σ ($p < .058$) parameters.

While it can be challenging to behaviourally examine the contribution of the various types of conflict to Stroop interference, what tends to be easier is identifying the presence of an overall Stroop interference effect. Therefore, the most surprising finding from the present study is the lack of evidence for a Stroop interference effect in the behavioural data. However, the fact that the Stroop interference comparison was close

to significance in both the μ and σ parameters might indicate that the low sample size in the present study confounded the results. Therefore, the low sample size may have increased the likelihood that the behavioural results represent a type II error. A larger sample size may have yielded behavioural results closer to those demonstrated in Experiment 1.

Although the RT data revealed no significant differences in performance between any of the trial types, we were able to demonstrate an increased engagement of particular brain regions at each level of conflict. This would suggest that while behaviourally participants performed equally as well across all trial types, neurologically they were processing each trial type differently. Reaction time and accuracy are imperfect measures of cognition and as such the absence of an allied behavioural effect does not render neuroimaging data uninterpretable. Wilkinson and Halligan (2004) make this case and argue that behavioural data does not necessarily have to corroborate the imaging data as both can be treated as independent indexes of underlying cognition. Notwithstanding this point, many have criticized studies in which the data can only be fully explained with reference to other experiments, as inferences from the data should rely on the inherent logic found within an experiment (Lakatos & Musgrave, 1970). In instances where the behavioural data does not uphold the fMRI data, explanations for the neuroimaging results can only be made with reference to other studies which have demonstrated an association between the behavioural measures and cortical function. In the case of the present experiment the logic behind the comparisons is clear and the fact that numerous other studies have demonstrated significant behavioural differences between the conditions we employ suggests that the lack of a behavioural effect may be due to chance or low sample size. In which case it is still appropriate to make inferences from the imaging data without behavioural corroboration. To this end our fMRI data is interpreted independent of the lack of any behavioural effect since absence of evidence is not necessarily evidence of absence.

Task conflict, as indexed by a neutral word – baseline shapes contrast, elicited activation in both the left and right DLPFC. The significant increase in activation of these regions during neutral word trials compared to baseline shape trials is consistent with the role of the DLPFC in implementing attentional control (Miller & Cohen, 2001). Neutral words trigger an unavoidable reading process which in turn creates conflict between the two dimensions of the Stroop stimulus. Such conflict should be absent during baseline shape trials as the stimuli cannot be read. Consequently, more cognitive

resources are required during neutral word trials in order to discriminate the relevant task goal (i.e., word reading vs. colour naming). Increased activation in the DLPFC therefore reflects the greater need to bias information and represent context in response to task conflict.

Interestingly no significant increase in activation was observed within the ACC for this contrast. The finding that the ACC appeared more active during congruent compared to neutral non-word stimuli has previously been explained as reflecting the increased task conflict during congruent trials (MacLeod & MacDonald, 2000). If the ACC is responsive to task conflict, then we might expect greater ACC activation during neutral word compared to baseline shape trials. That said, the absence of any ACC activation in this contrast does not, by itself, demonstrate that the ACC was unresponsive to task conflict. Rather it suggests that any activation within this region was not significantly greater than the activation during the baseline condition. It might therefore be the case that both conditions elicit ACC activation for different reasons. In this instance and considering the lack of difference between these two conditions in the behavioural data, it is possible that the irregular shapes were not a suitable baseline for indexing task conflict.

Semantic conflict observed in the neuroimaging data mirrors the behavioural data in the sense that RTs were slower during the non-response set trials compared to semantic associative trials (although not significant), while the fMRI data also shows greater activation during non-response set compared to semantic associative trials. Previous neuroimaging studies of the Stroop task have not yet compared the activation between these two indexes of semantic conflict. However behavioural studies that have compared the two trial types often report that participants respond faster to semantic associative trials than to non-response set trials (Klein, 1964; Sharma & McKenna, 1998). This would imply that non-response set trials are more cognitively challenging, a claim which our data supports. Compared to neutral word trials, semantic associates did not elicit any significant increases in activation within the ROIs. Conversely, non-response set trials elicited activation in both the right and left DLPFC as well as in the ACC. Although both trial types were employed as an index of semantic conflict, the disparity between the two conditions in the fMRI data might indicate that they involve dissociable neural processes. In explaining why non-response set colour words produce longer RTs than semantic associates Sharma and McKenna (1998) argue that non-response set trials involve an additional level of semantic processing which they call

semantic relevance. Put simply they claim that non-response set colour words are more semantically associated with the response colours than non-colour words, even those with an association to colours. It might therefore be the case that the increased activation observed during non-response set trials reflects this increased difficulty in semantic processing. In which case it could be argued that semantic associative trials do not capture the entire semantic Stroop effect. As such it would be more appropriate for future studies concerning the semantic Stroop effect to employ non-response set trials as the critical condition for indexing semantic conflict. Nonetheless it is worth noting that non-response set trials may still be an imperfect index of semantic conflict, as they may still index response conflict to some extent, for instance when the colour word is close to a response set colour on the electromagnetic spectrum (Klopfer, 1996; Roelofs, 2003).

Evidence for semantic conflict was present in the fMRI data for the non-response set – neutral word contrast. Here we observed increased activation in the left and right DLPFC as well as in the ACC. The precise sites of these activations however are notably different from those observed in a semantic conflict contrast in the study by van Veen and Carter (2005). Although, such differences might be explained in part by the different indexes of semantic conflict employed between the two studies. While van Veen and Carter (2005) used a two-to-one response mapping paradigm to index semantic conflict we observed evidence for semantic conflict using non-response set trials. This highlights the need for more consistent methods between studies investigating Stroop conflict before we can draw more convincing conclusions about the relative involvement of different brain regions in resolving the underlying components of Stroop interference. Nevertheless, the finding that regions within both hemispheres of the DLPFC and ACC were activated in response to semantic conflict reaffirms the claim that these regions are indeed critical for the management of semantic conflict (Chen, Lei, Ding, Li, & Chen, 2013; van Veen & Carter, 2005).

Surprisingly response conflict only elicited activation in the right DLPFC. No significant increase in activation was observed in the left DLPFC or ACC in the incongruent – non-response set contrast. These findings therefore contradict previous suggestions that the ACC is only activated by response conflict (Milham, et al., 2001; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001). Instead we found that the ACC was responsive to semantic conflict, but activation did not significantly increase on trials containing response conflict. Other studies have since found evidence that the

ACC continues to play a role in regulating attentional control in the absence of response conflict (Roelofs, van Turennout, & Coles, 2006), and our findings appear to confirm such claims. Our findings therefore run counter to the conflict monitoring hypothesis (Botvinick, Braver, Barch, Carter, & Cohen, 2001) which states that the ACC monitors conflict in the processing stream and determines the extent to which attentional control needs to be exerted. Such an account implies that conflicts that require implementing a greater degree of cognitive control (e.g., response conflict) should elicit greater ACC activation. However, we found no evidence to suggest that the ACC was activated by response conflict above what could be attributed to pre-response conflict.

Other neuroimaging studies have purported that distinct subdivisions of the ACC are in fact specialised for detecting pre-response and response conflicts (Kim, Kroger, & Kim, 2011; Milham & Banich, 2005; van Veen & Carter, 2005). Such findings would favour a multi-stage selection account (e.g., Kornblum, 1992) in which pre-response and response conflict call on dissociable neural networks to exert attentional control. Kim, Kroger, and Kim (2011) argue that the rostral dorsal region of the ACC (rdACC) is activated by response conflict, whereas the caudal dorsal region (cdACC) monitors pre-response conflict (including semantic conflict). Since our data shows that the ACC was activated by semantic conflict and not response conflict, we are unable to support claims of specialised functionality within the ACC. A potential caveat however, as previously discussed, is the possibility that non-response set trials partly index response conflict, and thus recruit similar neural processes to incongruent trials. It might therefore be that the incongruent – non-response set contrast did not reveal any significant ACC activation because both trial types index response conflict to some extent. When examining the contrast for overall Stroop interference we can see that incongruent trials did elicit activation in a distinct region of the ACC, compared to the site of activation elicited by semantic conflict. While this is not evidence to suggest that response and pre-response conflict are monitored by dissociable ACC regions, it does at the least imply that distinct regions within the ACC are necessary for performing the Stroop task.

While the general consensus surrounding the role of the ACC in Stroop task performance is that it monitors conflict and alerts relevant systems when attentional control is required, some have suggested that ACC activation is not reflective of conflict monitoring at all (Grinband, et al., 2011). Although their methods have been criticized (see Yeung, Cohen, & Botvinick, 2011) Grinband et al. (2011) argued that the ACC is

actually responsive to time-on-task and not conflict. In their fMRI study the researchers claimed to demonstrate how ACC activity is not sensitive to congruency, error likelihood, or response conflict, but is monotonically related to time-on-task. In the context of the findings from the present study a case could be made in support of this claim. In our results we observed ACC activation in a non-response set – neutral word contrast and in an incongruent – baseline shapes contrast. Behavioural performance between incongruent and non-response set trials (0.06 ms difference) as well as between neutral word and baseline shape trials (0.48 ms difference) were almost identical, with the latter two being faster than the former. Therefore, the two contrasts in which ACC activation was observed were the two contrasts with the greatest difference in time-on-task. The apparent lack of ACC activation in both the task conflict and response conflict contrasts might therefore reflect the fact that both conditions in these contrasts produced identical RTs. That considered, the overwhelming majority of the literature supports a theory that emphasises the ACC as having a unique role in conflict monitoring. Thus, the previously stated role of the ACC should not be dismissed on the basis of our findings alone, especially since our data does not negate the claim that the ACC is central to the management of cognitive conflict.

In both the task and semantic conflict contrasts we observed increased activation in both hemispheres of the DLPFC. Yet the contrast for response conflict revealed a significant increase in activation in the right hemisphere only. This would suggest that the right DLPFC may play a more important role in stimulus-response control. In support of this Zmigrod, Colzato, and Hommel (2014) found that temporarily lesioning the right DLPFC using transcranial direct current stimulation (tDCS) impaired the efficacy of managing stimulus-response conflict, whereas the same stimulations to the left DLPFC had no significant impact on performance. The researchers claim that the right DLPFC is involved in suppressing incorrect stimulus-induced responses, which fits previous suggestions for a role of the right DLPFC in cognitive inhibition processes (Kelly, et al., 2004). Since the greatest amount for stimulus-response conflict in the present study occurs during incongruent trials (where both dimensions of the stimulus provide conflicting response options), it is likely that the increase activation of the right DLPFC on incongruent relative to non-response set trials reflects its role in inhibiting information from the word dimension at the response level. Future research might wish to investigate this claim more precisely, using methods such as EEG which offers high temporal resolution to determine the point in the processing stream at which right

DLPFC activation peaks. If one assumes that the left DLPFC plays a more important role in stimulus-stimulus control then it could be expected that an earlier peak in activation on the left hemisphere represents the management of pre-response competition, while a later peak on the right hemisphere would indicate the control of conflict at the response level.

Our data therefore suggests hemispheric differences in attentional control. While parallel regions in the left and right DLPFC were shown to be activated in response to task and semantic conflict, only the right hemisphere was activated by response conflict. This finding is partially consistent with earlier neuroimaging investigations of Stroop conflict that report response-related activity in the right DLPFC only (Milham, et al., 2001). On the other hand, the study also found that non-response-related activity was unique to the left hemisphere, whereas we observed activity in both hemispheres during instances of pre-response conflict. However, in such instances we did find that activation was stronger in the left hemisphere. On the whole the present findings point to a critical role of the right DLPFC in managing response conflict whereas the left DLPFC appears more engaged during instances of pre-response conflict. Nevertheless, within the literature that discusses the possible asymmetric contribution of the DLPFC to cognition, it is clear that a consensus is yet to be reached (Balconi, 2013).

The incongruent – baseline shapes contrast revealed the brain regions recruited when performing the standard Stroop task. While this contrast offers little in revealing activation that can be attributed to specific types of conflict it is useful in identifying the neural regions that are central to overcoming interference. We observed large clusters of activation in both the left and right DLPFC as well as a small cluster of activation within the ACC. Such findings support the well-established theory that the ACC monitors conflict and engages regions within the DLPFC to exert attentional control. What is more is that the activation observed in each of the conflict contrasts represent distinct neural regions with only small amounts of overlap. The results therefore support the claim that similar but dissociable neural networks are engaged by different types of cognitive conflict (van Veen & Carter, 2005). While attempting to precisely localise the areas within the DLPFC responsible for resolving each conflict type is beyond the scope of this thesis, our results suggest that such attempts may become possible after a greater number of neuroimaging studies employing more consistent methods are conducted. Nonetheless our findings must also be interpreted with consideration of the limitations of our experiment.

Firstly, the low sample size used in the present study may have reduced the replicability of our results. In early fMRI studies it was generally regarded that a sample size of about 12 subjects was required to achieve an acceptable level of power for typical activations at the single voxel level (Desmond & Glover, 2002). However more recent work has indicated that these small sample sizes are inadequate and only produce modestly replicable results (Turner, Paul, Miller, & Barbey, 2018). The present study used a sample size of 20 participants however due to some coding issues with the experiment program 7 participants were dropped from the analysis, meaning that the results of only 13 participants were analysed. Therefore, an fMRI investigation with a larger sample size may be necessary before we can draw any strong conclusions about the validity of our results.

It is also worth noting that in the present study the haemodynamic response function was analysed using a relatively liberal threshold for significance ($p < .050$ uncorrected). Most previous fMRI studies tend to use a more conservative threshold of $p < .005$ (Song & Hakoda, 2015; van Veen & Carter, 2005) or control for multiple comparisons (Kim, Kroger, & Kim, 2011) and also report having used either a larger sample or a more powerful scanner. Because we confined our analysis to ROIs that had been previously implicated in fMRI investigations of Stroop conflict, it is reasonable to suppose that the activations observed in the present study are a true reflection of the relative engagement of each region, despite the low significance threshold that was applied.

In sum, our data supports the claim that distinct but parallel attentional mechanisms are responsible for resolving different types of cognitive conflict (Milham & Banich, 2005; van Veen & Carter, 2005). We demonstrated that the right DLPFC appears to play a critical role in resolving conflict at the response level, whereas left DLPFC activation is unique to pre-response conflict. The results contradict previous claims that the ACC is only engaged in the presence of response conflict (Milham, et al., 2001). Instead we showed that the ACC only showed significant activation in response to semantic conflict. Our results suggest that non-response set trials may provide the best index of semantic conflict, since semantic associative trials did not produce any significant activation when compared to neutral trials. We acknowledge that the low sample size in the present experiment is likely to reduce the replicability of our finding. More neuroimaging studies employing conditions similar to those utilised in the present experiment are needed before we can draw strong conclusions about the

dissociable involvement of the DLPFC and ACC in resolving different forms of conflict. Nonetheless our data promises that clarifying the neural networks involved in resolving each conflict type will be achievable, as the results indicate that the trial types recruited distinct cognitive processes despite the lack of behavioural corroboration. While our study focused on the role of the DLPFC and ACC in attentional control, this does not rule out contributions from other regions (e.g., posterior parietal cortex) that may also show a differential involvement in resolving conflict types (Milham & Banich, 2005).

GENERAL DISCUSSION

The main aim of this thesis was to add to the growing body of literature attempting to clarify the role that the DLPFC and ACC play in implementing attentional control. Furthermore, we sought to understand whether the neural basis of attentional control is best explained by single-stage response level conflict resolution models (e.g. Botvinick et al. 1990; Roelofs, 2003) or whether multi-stage models (e.g., Kornblum, 1992), that suggest early and late selection mechanisms, provide a better account. We devised a Stroop task that employed five different trial types which allowed us to estimate the contribution of task, semantic and response conflict to Stroop interference. In Experiment 1 we observed changes in behavioural performance on the Stroop task after high frequency stimulation of the left DLPFC. In Experiment 2 we used fMRI to record the relative engagement of the DLPFC and ACC when completing the same Stroop task.

When comparing the two experiments it is clear that although participants were given the same task the behavioural data is inconsistent. Firstly, a greater number of errors were observed in the fMRI study compared to the TMS study. However, fMRI investigations of the Stroop task typically tend to report a higher percentage of incorrect responses compared to behavioural studies (e.g., Potenza, et al., 2003; van Veen & Carter, 2005). Thus, this disparity may be accounted for by the different environments of the two experiments. For instance, the restricted space inside the scanner along with the explicit instruction to avoid unnecessary movement creates a potentially claustrophobic environment for the subject which is naturally different from that experienced in the TMS study. The position of the subject also varied between the two experiments, from supine to sitting upright, which can have a substantial influence on

bodily and behavioural processes (Caldwell, Prazinko, & Caldwell, 2003). In addition, the loud noise caused by the magnetic gradient switching in the MR environment acts as a distractor which is hard to replicate outside the scanner room due to it being partly bone-conducted.

Such differences in the environment of the two studies may also, so some extent, explain the inconsistent detection of the various conflict types. In Experiment 1 we demonstrated an overall Stroop interference effect, and a significant effect of response conflict in the mean RT data. Evidence for semantic conflict was also found in the ex-Gaussian parameter σ. Whereas in Experiment 2 we were only able to demonstrate evidence for response conflict in σ. Despite the potential distractions involved in completing the Stroop task in an MR environment, previous studies have been able to successfully demonstrate significant behavioural differences between trial types (Milham & Banich, 2005; van Veen & Carter, 2005). Therefore, it is likely that the low number of subjects whose results were analysed in the fMRI experiment confounded the behavioural results. A larger sample size in the fMRI experiment may have produced more consistent findings between the two studies.

It is also important to point out the consistent lack of evidence for the effect of task conflict in the behavioural data. In both experiments no significant difference was found between neutral word and baseline shapes trials in regard to accuracy, mean RTs and the ex-Gaussian parameters. In Experiment 1 we actually observed that RTs for the shape stimuli were longer than those to neutral word stimuli. The use of coloured shape strings as a baseline condition is scarce within the current literature, with most studies employing non-word letter strings instead (e.g., Entel & Tzelgov, 2016; Kalanthroff, Avnit, Henik, Davelaar, & Usher, 2015; Monsell, Taylor, & Murphy, 2001). However, in the introduction we suggested that irregular shapes might provide a better baseline than non-word letter strings since they cannot be read and are difficult to name/attribute meaning to. This seemed a reasonable assumption since previous studies which used regular shapes (e.g., rectangle, triangle, circle) as a baseline for isolating task conflict were able to find evidence for a large effect ($\eta_p^2 = 0.86$) of task conflict (Levin & Tzelgov, 2016). Nevertheless, this study was conducted in Hebrew and Russian, whereas the present experiments were conducted in English. The differences in the alphabet of these languages may therefore explain the variable success of shape strings as a baseline for indexing task conflict. It is possible that, for English speakers at least,

the irregular shapes were too visually complex in comparison to letters, or that their unfamiliarity recruits additional processing resources reducing goal focus.

Further to this point, the feedback from participants after the study seems to support such claims. In both experiments some participants reported that the shape trials 'threw them off' and on reflection it is conceivable why this might be the case. Considering four of the five trial types contained words, for the most part participants are preparing to see both letters and colours. As such, the effect of task conflict is proposed to arise even before the presentation of the stimulus as the task activates competing task sets for reading vs. colour naming (Braverman, Berger, & Meiran, 2014; Monsell, Taylor, & Murphy, 2001). When trials appear containing irregular unnameable shapes, it may initially require some refocus on the task goal. Therefore, non-word letter strings may still provide the best baseline for indexing task conflict as the lack of any significant effect between irregular shape and neutral word stimuli in our behaviour data would indicate that little or no difference in task difficulty exists between these trial types. However, more research is needed before this argument can be convincingly made.

Another notable observation is the fact that participants consistently performed better on semantic associates compared to non-response set trials. Such observations have also been made in previous behavioural studies comparing these trial types and are explained as being due to the increased semantic relevance of non-response set trials (Sharma & McKenna, 1998). This finding is perhaps best understood in terms of the WEAVER ++ model proposed by Roelofs (2003). The model suggests a spreading activation of concepts in a network, whereby words with a greater association to colours will activate other colour concepts to greater extent. Since non-response set colour words are themselves colour concepts they may activate the superordinate concept of 'colours' to a greater extent than would semantic associates (e.g., the word 'purple' is more semantically related to the concept of 'colours' than the word 'sky'). In which case it can be argued that non-response set trials provide a better index of semantic conflict since they more likely to capture the effect in its entirety. This is a claim which is also supported by the neuroimaging data in Experiment 2, since we only observed a significant increase in activation that can be attributed to semantic conflict when using non-response set trials as our critical comparison condition. Although, the obvious downfall of this proposition is the realisation that non-response set trials may partially index response conflict. As demonstrated by Klopfer (1996), colour-word pairings that

are closer to each other on the electromagnetic spectrum (e.g., ‘purple’ in blue) produce more interference than distant stimulus-stimulus pairings (e.g., ‘orange’ in blue). Therefore, non-response set trials in the present study may have still indexed response conflict to some extent, for example when the non-response set colour word was closely associated to a response set colour concept (e.g., ‘purple’ in red may have activated competing response options ‘blue’ and ‘red’, resulting in response conflict). Identifying the optimal method for indexing semantic conflict provides a considerable challenge for future research to address, however our results would argue in favour of using non-response set trials over semantic associative trials. Nevertheless, since this is the first study to compare the neural activity elicited by semantic associative and non-response set trials, more research is needed in order to validate these claims.

What is also apparent from the analysis of the behavioural data in both experiments is the lack of expected outcomes from the ex-Gaussian analysis of RTs. Recent work has argued in favour of applying the ex-Gaussian function to RT data, since it has been shown to reveal the presence of effects that are concealed by analysis of the means (Parris, Dienes, & Hodgson, 2013). While an ex-Gaussian analysis undoubtably gives a more descriptive overview of the RT data, what is less clear is whether the individual parameters can be reliably attributed with revealing different cognitive processes. Some studies applying the ex-Gaussian function to the Stroop task have postulated that the underlying components of interference are represented by consistent changes in the three parameter estimates. For example, White, Risko and Besner (2016) reported that semantic conflict is unique to μ. Yet in both of the present experiments we observed no significant effect of semantic conflict in this parameter. Contrary to White, Risko and Besner’s (2016) claim in Experiment 1 we actually observed a semantic Stroop effect in the parameter σ.

Most surprising was the absence of any significant effect in the τ parameter in both experiments. Previous studies have found significant differences in the skew of the RT distribution between trial types reflected by changes in τ, yet it remains unclear exactly what this represents. Steinhauser and Hübner (2009) have suggested that task conflict can be identified by an increase in the τ parameter on congruent relative to neutral trials but found no evidence for semantic or response conflict in this parameter. While other studies have demonstrated that τ estimates tend to be greatest for incongruent trials when compared to congruent and neutral trials, reflecting the greater amount of response competition (Spieler, Balota, & Faust, 2000). The obvious

difference between these two studies however is that Steinhauser and Hübner (2009) employed the two-to-one response mapping manipulation which, as noted in the introduction, does not clearly dissociate response and semantic conflict (Hasshim & Parris, 2014; Hasshim & Parris, 2015). Nonetheless, the findings from the present experiments do little to elucidate such discrepancies. In line with these previous works, it could be argued that we might expect an increase in τ on neutral word compared to baseline shapes trials (representing task conflict), and for τ estimates to be greatest for incongruent trials (representing an increase in response competition). Yet in both experiments we found no significant difference between any of the trial types in this parameter. In fact, in Experiment 2 the observed trend occurred in the opposite direction, with τ estimates highest in the baseline shapes condition and lowest in the incongruent condition. However, issues with the analysis of the data in the present studies may potentially be responsible for the non-significant results. For instance, although the QMPE software we used to run an ex-Gaussian analysis requires as little as 40 RT observations per trial type (Heathcote, Brown, & Cousineau, 2004), a minimum of 100 was recommended by Heathcote et al. (1991). In Experiment 1 participants only completed 60 trials per condition, and although they completed 120 trials per condition in Experiment 2 for some participants the number of correct responses in a condition were as low as 69. It is therefore possible that both of the present experiments did not have an adequate number of RT observations per condition in order for our results to be reliable. Although, previous studies claiming to have demonstrated differences between trial types in the τ parameter have used as few as 32 trials in a condition (Spieler, Balota, & Faust, 1996).

Nonetheless, it is clear that the results of the ex-Guassian analysis in both of the present experiments bring into question its reliability in detecting the presence of specific forms of cognitive conflict. Although repeated attempts have been made to attribute cognitive processes to ex-Gaussian parameters (e.g., Hohle, 1965; Steinhauser & Hübner, 2009; Roelofs, 2012), other researchers have warned about the perils of such an exercise (Heathcote, Popiel, & Mewhort, 1991; Matzke & Wagenmakers, 2009). Matzke and Wagenmakers (2009) argue that psychologists should resist the temptation to attribute ex-Gaussian parameters to specific components of cognitive processing but suggests that its application is still valid as a descriptive tool to summarise RT data. Although studies investigating the Stroop effect are numerous, rarely do researchers consider applying the ex-Gaussian function in their analyses. Therefore, it is clear that

more research is needed before we can be sure as to whether changes in the ex-Gaussian parameters represent distinct cognitive processes, or whether the parameter values the analysis generates should be taken only as a descriptive overview of that particular data set.

While the trial types employed in Experiment 1 did not have the expected behavioural outcome, we were still able to demonstrate a significant effect of TMS stimulation on performance. In one of the few studies to employ TMS while investigating the classic Stroop effect Vanderhasselt et al. (2006) demonstrated that high frequency stimulation of the left DLPFC reduced RTs to both congruent and incongruent trials, whilst having no significant impact on the overall Stroop interference effect. Using the same stimulation parameters and a similar experimental method, Experiment 1 set out to further investigate this finding by observing whether left DLFPC stimulation would differentially effect task, sematic and response conflict resolution. Supporting Vanderhasselt et al.'s (2006) results, our findings showed that left DLPFC stimulation reduced RTs but had no consequences on the overall Stroop interference effect nor on any of the underlying components of interference. Unlike Vanderhasselt et al. (2006) we observed this significant main effect of stimulation between two testing sessions (sham vs. TMS), whereas their study was only able to demonstrate a significant effect of TMS between pre- and post-test performance (and not between sham and TMS post-test performance). However, their study used only two response colours (red and green) and it is not reported how many trials were completed per condition. Differences in methodology might therefore account for these different effects.

Since the findings from Experiment 1 supported those of Vanderhasselt et al. (2006), we concluded that the role of the left DLPFC was to implement top-down attentional control whilst also suggesting that its role in conflict resolution appears nonspecific. However, we noted the need for functional brain imaging research before we could draw any compelling conclusions about the relative engagement of this region in the presence of each of the underlying components of interference. Therefore, in Experiment 2 we employed the same Stroop paradigm whilst the BOLD response of participants was recorded in an MRI scanner. To our knowledge no neuroimaging study has set out to compare the brain regions engaged by task, semantic and response conflict. Furthermore, the methods used to isolate semantic conflict from response conflict in most previous fMRI studies has recently been criticized (Hasshim & Parris,

2014; Hasshim & Parris, 2015). We found evidence that areas within the left DLPFC were activated by task and semantic conflict, however contrary to previous research we found that response conflict did not elicit any significant activation in this region. Consistent with Milham, et al. (2001) our results suggested hemispheric differences in attentional control, with the left DLPFC playing a more important role in resolving pre-response conflict whereas the right DLPFC appears critical for response conflict resolution.

Squaring this finding with the results obtained in Experiment 1, it is still possible to explain why TMS to the left DLPFC did not differentially affect the measures of conflict types. Assuming that the left DLPFC is unique to the resolution of pre-response conflict, it is likely that stimulation of this region would improve performance on all trial types since every condition contained at least some task conflict. Adopting the view that a role of the left DLPFC involves the implementation of a task set (i.e., resolve task conflict) would inevitable suggest that stimulation of this region results in reduced interference on incongruent trials and increased facilitation on congruent trials. This in turn provides a fitting explanation for the results obtained by Vanderhasselt, et al. (2006). If, however, we assume that the right DLPFC is more engaged by response conflict we should expect that the same stimulation to this region would disproportionately improve performance on incongruent trials compared to the other conditions. To our knowledge only one study has measured the effect of right DLPFC stimulation on Stroop task performance (Vanderhasselt, et al., 2007). Using a similar method to that used in their previous study (Vanderhasselt, De Raedt, Baeken, Leyman, & D'haenen, 2006), Vanderhasselt, et al. (2007) manipulated task control by presenting cues at the onset of each trial instructing participants to either read the word (automatic process) or name the colour (strategic process). In addition, trials were presented in two mixed blocks; ‘high expectancy’ (containing incongruent and congruent trials at a ratio of 80:20) and ‘no expectancy’ (containing incongruent and congruent trials at a ratio of 50:50). We would therefore expect response competition to be greatest for colour naming trials in the ‘high expectancy’ condition (containing more incongruent trials). Interestingly this was the only manipulation in which a significant effect of right DLPFC stimulation was observed (reducing RTs). Although surprisingly the study showed that this manipulation reduced RTs to congruent trials as well as incongruent trials. Since no response competition exists within congruent trials the researchers concluded that the right DLPFC must also be involved in attentional control

at the stimulus level, contradicting Milham, et al. (2001) who linked the right DLPFC solely to attentional processes at response level. In line with this, while our neuroimaging results suggest that the right DLPFC may play a more important role in resolving response conflict, we also demonstrated evidence for its engagement in processes at the pre-response level.

Also of interest to us was the role of the ACC, since it has long been understood to be the region that detects the presence of conflict and alerts other systems to exert control (MacDonald & Angus, 2000). Although the ACC is often treated as a unitary structure, some researchers have suggested that it exhibits anatomical and functional specificity (Kim, Kroger, & Kim, 2011). Despite this, in Experiment 2 we were only able to demonstrate evidence that the ACC was activated by semantic conflict. We were therefore unable to support claims of functional dissociation in detecting the various forms of conflict. Our data also seems to question popular models of attentional control, which suggest that while the ACC may monitor pre-response conflict, it is only at the response level which it engages other regions to exert control (Botvinick, Braver, Barch, Carter, & Cohen, 2001). In line with this we would expect the greatest amount of ACC activation to be observed in the contrast for response conflict (van Veen & Carter, 2005), whereas we found no evidence to suggest this was the case. Furthermore, studies which have administered the Stroop task to patients with ACC lesions report that the cognitive control adjustments the model predict are not consistently impaired (Boschin, Brkic, Simons, & Buckley, 2017; Swick & Jovanovic, 2002). We also noted the possibility the ACC activation we observed may represent something other than conflict detection, for example time-on-task (Grinband, et al., 2011).

Despite finding no evidence to support a dissociable role of the ACC in conflict detection, we did find evidence to suggest distinct regions of the DLPFC were activated by the different types of conflict. However, the precise location of these sites of activation did not clearly correspond with those observed in previous studies which suggest separate but analogous mechanisms deal with different kinds of cognitive conflict (Milham & Banich, 2005; van Veen & Carter, 2005). Nonetheless, differences in the trial types used to isolate these forms of conflict reduce the ability to reliably compare the findings between studies. We suggest that more research employing the same trial types used in the present experiments is needed in order to clarify this point. Future studies using larger sample sizes and higher strength magnets (Experiment 2

employed a 1.5-Tesla magnet) may also be able to show more precise sub-differentiation than our results were able to indicate.

Conclusion

This thesis supports the longstanding theory that the circuitry for attentional control involves the ACC and DLPFC (MacDonald & Angus, 2000). We provide evidence that the DLPFC is critical in implementing top-down attentional control. Although homologous regions of the prefrontal cortex (right and left middle frontal gyrus) were activated by the Stroop task, their involvement differed according to the type of conflict encountered. The right hemisphere appears more involved in response-control, whereas the involvement of the left hemisphere appears unique to stimulus-control. While the ACC was recruited by the Stroop task the precise role it plays in conflict detection remains unclear. Our findings favour a multi-stage selection account of attentional control in which the various forms of cognitive conflict are processed and resolved separately (Kornblum, 1992). Additional neuroimaging studies employing more consistent methods are needed before we can establish a more complete picture regarding the different neural substrates involved in the circuitry of attentional control.

Plan for future research

The findings from this thesis have highlighted a few conceptual issues with our experimental design that could be improved in future work to better investigate our research question. One major drawback of the present thesis was the inability to observe the effect of task conflict, which has been widely observed within the literature (Goldfarb & Henik, 2007; Kalanthroff, Goldfarb, Usher, & Henik, 2013; Monsell, Taylor, & Murphy, 2001; Parris, 2014; Steinhauser and Hübner, 2009). As previously stated, it is likely that the use of unfamiliar shapes as a baseline condition did not allow for the detection of task conflict. Instead we argue that their unfamiliarity recruits additional processing resources in order to maintain task focus, which in turn increases RTs. Therefore, in future research we plan to employ single letter string trials as our baseline control (e.g., xxxx), which are frequently used within the literature and have been shown to produce significantly faster RTs than neutral word trials (Monsell, Taylor, & Murphy, 2001). Although this may not be optimal (since individual letters in the string may still activate lexical processing), we now consider single letter string trials to be the most appropriate baseline to compare against neutral word trials in order

to index task conflict. Detection of task conflict in the behavioural data would have allowed us to make more reliable inferences from the neuroimaging data in Experiment 2, and importantly would have allowed us to assess the contribution of the left DLPFC in resolving task conflict in Experiment 1. If we are to establish whether a role of the left DLPFC is to implement a task set (as is proposed by Vanderhasselt, De Raedt, Leyman, & Baeken, 2010) in future research, it is crucial that we first employ a reliable index of task conflict.

The work in this thesis has also led to more theoretical questions regarding hemispheric differences in attentional control which we plan to address in future research. In Experiment 2 we provided some limited evidence suggesting that the left DLPFC is more involved in resolving pre-response conflict, whereas the right DLPFC appears more involved in the management of response conflict. Although our behavioural data did not corroborate the neuroimaging data in this thesis, taken together with previous studies (e.g., Milham, et al., 2001; Vanderhasselt, De Raedt, Baeken, Leyman, & D'haenen, 2006; Vanderhasselt, et al., 2007), we maintain that the two hemispheres of the prefrontal cortex may be differentially involved in response to each of the underlying components of Stroop interference. To investigate this further we plan to run a TMS study that replicates the procedure of Experiment 1 but instead examines the behavioural responses to each of the trial types after left compared to right DLPFC stimulation. If our proposition holds true then we would expect to find that stimulation of the right DLPFC reduces response conflict compared to a control, whereas stimulation of the left DLPFC would most likely reduce task conflict compared to a control. Such a study would be the first to isolate the contributions of the left and right prefrontal cortex in resolving task, semantic and response conflicts using TMS. Therefore, the results are likely to make a large contribution to the literature and could lead to more research questions regarding the neural underpinnings of attentional control.

However, in this future TMS study we will also consider how our experimental design could be improved to maximise the control over extraneous variables. One such consideration is the use of sham-TMS as a control condition. Although sham stimulation (where the coil is positioned away from the scalp at a 90° angle) has been used in similar studies investigating Stroop interference (e.g., Li, et al., 2017; Vanderhasselt, De Raedt, Baeken, Leyman, & D'haenen, 2006), other researchers have deemed it insufficient as a full-fledged control paradigm since it does not replicate the

sensory effects experienced during active stimulation (Duecker & Sack, 2015). It is therefore possible that the reduced RTs after active compared to sham stimulation reflect effects that are not related to cortical activation. To address this, our future study will stimulate the vertex (an area thought to be unrelated to Stroop task performance) as a control site to minimize the difference in somato-sensory effects between the experimental and control conditions. In doing so we will be able to examine the influence of stimulation to the left and right DLPFC on behavioural performance more reliably.

In addition, we also noted the need to control for factors such as the day of testing. In Experiment 1 the time of day and delay between sessions was not consistent for each participant. Therefore, even though the order of the testing sessions was counterbalanced it is still possible that the results were confounded by the day or time at which participants completed a session. To account for this in our future study participants will complete each session at the same time of the day and after a consistent delay of one week between each session. Participants will also complete the Stroop task before receiving TMS as well as immediately after receiving stimulation and differences in performance between the pre- and post-tests will be compared for each condition (i.e., for vertex, left DLPFC, and right DLPFC stimulation conditions). The addition of these measures will result in a highly controlled experiment in which we can rule out the possibility that the day of testing may have confounded the results.

A final adjustment to the experimental design used in Experiment 1 will be the mode of response employed. In Experiment 1 manual responses were recorded using a Cedrus response box, whereby participants pressed a key that corresponded with the print colour of a stimulus. However, on reflection it is likely that this was not the optimal response mode to allow for the detection of each of the various conflict types. For instance, Sharma and McKenna (1998) who employed the same trial types comparing vocal and manual responses, have shown that the only component that produced a significant interference during manual responses was the response set membership (i.e., incongruent – non-response set trials). However, during vocal responses evidence was found for task, semantic and response conflict using the same comparisons we employ. This might explain why we were only able to demonstrate evidence for response conflict in the arithmetic mean RT data in Experiment 1. The different effects between response modes might be explained by the use of static button labels in the manual response task, in which participants can match the print colour of a

stimulus to the response key by direct comparison, thus reducing interference (Sharma & McKenna, 1998). Therefore, in our future study we will record vocal responses to stimuli using a microphone to measure RTs. Response accuracy will also be coded by the experimenter for each trial. In doing so we should maximise the detection of each of the underlying interference components, which will allow us to better investigate the effect of DLPFC stimulation on Stroop task performance.

While such a study will be useful in determining the causal contribution of the DLPFC to conflict resolution, we have also noted the need for more functional imaging studies in order to establish more precise sub-differentiation within regions of the DLPFC, and other structures thought to be involved in the management of cognitive conflict. To this end, we plan to replicate Experiment 2 using a 3-Tesla magnet and 32 channel head coil to provide greater spatial resolution, along with a larger sample size of 30 participants to increase the power of our study in detecting an effect. Together, these future studies will provide greater insight into the neural systems that underpin Stroop task performance, which may consequently have important theoretical implications for models of cognitive control.

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APPENDICES

Appendix A: Experiment 1 information sheet

Bournemouth University

Participant Information Sheet

TMS investigation of executive control in the human brain

You are being invited to take part in a research project. Before you decide to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Researchers

This research is conducted by Michael Wadsley (mwadsley@bournemouth.ac.uk) under the supervision of Dr Ben Parris (associated professor in Psychology at Bournemouth University).

What is the purpose of the project?

The purpose of the study is to investigate the link between the certain brain regions and executive functions. Specifically, we aim to examine whether transcranial magnetic stimulation (TMS) to the frontal lobe influences behavioural performance on the Stroop task.

Why have I been chosen?

We are inviting volunteers from the Bournemouth University student cohort (including students within and outside the Psychology department) to participate in our study. You are chosen because you are eligible for this study: between 18 and 45 years old, fluent in English, and with normal or corrected-to-normal vision.

Do I have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part, you will be asked to give consent. If you do decide to take part, you will be given this information sheet, together with a TMS Information Sheet and be asked to sign a participant agreement form. You can still withdraw up to the point where the data are processed and become anonymous, so your identity cannot be determined without it affecting any benefits that you are entitled to in any way. You do not have to give a reason if you choose to withdraw.

What would taking part involve?

In this study you will be asked to complete 5 variations of the Stroop task on a computer. In this task you will see a series of coloured words or shapes. Your task will be to respond as quickly and as accurately as possible to the print colour of each stimulus whilst ignoring the meaning of the word. Before beginning the experiment, there will be a number of practice trials in order for you to practice responding. This task will take approximately 15 minutes. Before beginning this task TMS stimulation may be applied to the frontal lobe for a duration of 20 minutes (see TMS information sheet for more details on what this involves). Data collection will take place in the Psychology Research Booths (1st floor of Bournemouth University) over 2 sessions and each session will take approximately 45 minutes to complete.

What are the advantages and possible disadvantages or risks of taking part?
The study does not involve any risk of harm and participants will receive £10 for their time after completing both sessions.

The use of TMS. TMS means transcranial magnetic stimulation. There is empirical evidence that stimulation may affect our behavioural performance by either enhancing or reducing the functioning of certain brain regions momentarily. Please refer to the additional information sheet that has been provided independent of this information sheet to give you a more detailed understanding of the process.
Safety Questionnaires. For safety measures, you will go through some screening questionnaires. It is important that you read through these questions carefully, as in some instances it may be unsafe for you to participate (e.g. if you are pregnant or taking certain drugs). We will also gather information about your age, gender, and ethnical origin.

How will my information be kept?
All the information we collect about you during the course of the research will be kept strictly in accordance with the current Data Protection Regulations. You will not be able to be identified in any reports or publications without your specific consent. All personal data relating to this study will be held for 5 years from the date of publication of the research. BU will hold the information we collect about you in hard copy in a secure location and on a BU password protected secure network where held electronically. Except where it has been anonymised, we will restrict access to your personal data to those individuals who have a legitimate reason to access it for the purpose or purposes for which it is held by us. The information collected about you may be used in an anonymous form to support other research projects in the future and access to it in this form will not be restricted. It will not be possible for you to be identified from this data.

For further information, please contact
Michael Wadsley
Postgraduate research student
mwadsley@bournemouth.ac.uk

Dr Ben Parris
Project supervisor
Fern Barrow, Poole, Dorset.
BH12 5BB

Complaints
In case of complaint please contact Deputy Dean for Research and Professional Practice Professor Tiantian Zhang on researchgovernance@bournemouth.ac.uk

If you decide to take part, you will be given a copy of the information sheet to keep.

Please ask the experimenter for further clarification if there is anything that you do not understand.

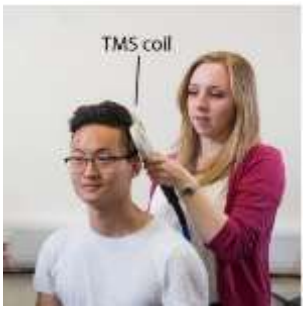
Appendix B: TMS information sheet

Information about Transcranial Magnetic Stimulation (TMS)

Procedures
If you volunteer, we will ask you some safety questions. The stimulation will be performed well within published safety limits (Rossi et al., 2009). We will not proceed with the experiment if you match certain exclusion criteria. These criteria are listed on the separate safety questionnaire.

You will also be asked to perform a simple task after TMS has been applied. This task will require you to make responses to the print colour of various words/shapes. This task is expected to last approximately 15 minutes and the researcher will explain to you what to do before the task begins. You will be given a chance to practice the task to make sure you understand what to do.

What happens?
TMS is used to stimulate your brain. TMS is a technique that allows us to stimulate the brain by rapid switching of a magnetic field in a coil placed over the head. During TMS, a coil is positioned over the scalp and single pulses are used to stimulate the brain.



What is the intensity?
1) We will use a predetermined intensity across all our participants based on published safety limits.
2) In some cases the intensity of stimulation is varied until the EMG recording consistently shows activity in the muscle in response to the stimulation. Once we have determined the minimum intensity at which this activity is observed, we proceed with the experiment.

What kind of stimulation methods are used?
We will use one of the following methods to stimulate your brain, to see how this may affect the cognitive task in questions. In most studies we may not tell you which one we will use, as the methods are normally randomised to prevent any bias. Once you complete the study, during the de-brief we may be able to tell you which condition you were part of, if you are interested.

1) Single- dual- or triple-pulse stimulation (known as 'multi-pulse TMS')
Single pulses or pairs or triplets of pulses (separated by less than a second) will be applied over the scalp. At the same time, the activity may be measured in your muscles using EMG or you may be asked to complete a task on the computer. You

will be told to either contract or relax your muscles.

2) Low-frequency repetitive stimulation (rTMS at or < 1Hz)

The TMS will be applied over the scalp at a maximum rate of one pulse per second (0.6 - 1 Hz) for up to 20 minutes.

3) High-frequency repetitive stimulation (rTMS > 1Hz)

4) Patterned rTMS: e.g. theta-burst stimulation will involve bursts of high-frequency (50 Hz) triplets applied every 200ms for up to 40 sec total stimulation time; max 600 pulses.

Risks

All forms of brain stimulation carry risks. We will be operating strictly within published safety limits from the literature (Rossi et al., 2009). Researchers who decide on these parameters are trained by labs who are expert users of stimulation methods and have published a number of studies using similar parameters. We will also ask you a number of safety questions before we begin to make sure you do not have any possible risk factors for this technique, such as having had a brain surgery or a history of epilepsy or regular episodes of fainting. Participants may experience some discomfort (slight tingling or some irritation – similar to what you may experience with a pin-prick experience) during TMS.

Headache: A small minority (1%) of people experience a headache as a result of the stimulation. In most cases this is because the head is fixed in a place for the duration of the experiment. If you experience a dull headache it is safe to treat this with any over-the-counter remedy that you may use for headache, or in the usual way you deal with it. If you feel any unusual symptoms such as headache, dizziness or nausea in the 24 hours following the experiment we ask you to contact the experimenter (by email) and to go to the local A&E if necessary.

TMS carries a risk of causing seizures (fits) in susceptible individuals (in less than 0.1%). In most cases the seizure was associated with a family history of epilepsy, existing neurological disease (e.g. multiple sclerosis) or medication (anti-depressant or dopamine medication). The risk of a provoked seizure occurring in healthy individuals due to TMS is extremely small. As a precaution, it may not be possible to give TMS to someone with a personal or close family (first-degree relative e.g. parent, sibling, child) history of epilepsy, another significant neurological or psychiatric disorder, or extreme mood fluctuations. If you suffer with migraine headaches, you should not take part in this study. Therefore, you will be requested to complete a screening form before you take part in the study.

To minimise the possibility of cumulative effects of brain stimulation for healthy participants not enrolled in treatment studies, we recommend that you should participate in no more than four sessions in a month. While no guideline has been provided for a "cooling-off" period between stimulation sessions, some have suggested it to be 48 hours after stimulation. Therefore, to protect participants from repeatedly being called upon to participate in non-invasive brain stimulation studies (this includes TMS and transcranial current stimulation or TCS), we recommend that the period of abstinence between different brain stimulation experiments would be at least 48 hours.

What if something goes wrong?

Before being asked to give your consent, you will be asked if you have any history of epilepsy, migraine or severe headaches or any other brain disorder. You will also be asked if there is anyone in your family with a history of epilepsy, as it could raise your risk of side effects. You will not be asked to participate if you have any condition or risk factors that could make it unsafe for you to receive TMS. Before giving your consent, you will be asked to complete the safety checklist for stimulation studies. In the unlikely event of adverse reaction to TMS, first aid and medical assistance will be provided promptly.

Understanding the TMS Machine

What does the TMS Machine look like?

See picture to the right for an example of how the machine looks like.

What does the coil that provides the stimulation look like?

or

References

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Appendix C: Experiment 1 Screening questionnaire

Bournemouth University

Safety Screening Questionnaire for Transcranial Magnetic Stimulation (TMS)

(Version 1, 13th March 2017)

Researcher: _____ Date: _____

Participant ID: _____ Age: _____ Gender: _____

Please read through each question carefully and tick the box to indicate that you can answer NO to each question.

Have you ever had an adverse reaction to TMS?	☐ NO
Do you have epilepsy or have you ever had a seizure/convulsion?	☐ NO
Have you ever had a fainting spell or syncope?	☐ NO
Have you ever had a stroke?	☐ NO
Have you ever had a serious head injury (with loss of consciousness)?	☐ NO
Have you ever had neurosurgery of any type (including brain or spinal cord)?	☐ NO
Do you have hearing problems or ringing in your ears?	☐ NO
Do you have any metal in your body such as shrapnel, surgical clips, or fragments from welding or metalwork?	☐ NO
Do you have any implanted devices such as cardiac pacemakers, aneurysm clips, cochlear implants, medical pumps, deep brain stimulators, or intracardiac lines?	☐ NO
Do you have a medication infusion device?	☐ NO
Do you suffer from frequent or severe headaches?	☐ NO
Have you ever had any illness that caused brain injury?	☐ NO
Are you taking any psychiatric or neuroactive medications? For instance, antidepressants, anti-anxiety, anti-psychotics, anti-convulsants, or anything else with nervous system effects?	☐ NO
Are you taking any other psychotropic drugs or have you drunk more than 3 units of alcohol in the last 24 hours?	☐ NO
Are you pregnant or do you have any reason to believe that you may be?	☐ NO
Do you, or does any family member, have epilepsy/history of seizures?	☐ NO

Do you hold a heavy goods vehicle driving licence or bus licence?	☐ NO
Was your sleep less than adequate last night?	☐ NO
Have you participated in a TMS study within the past 24 hours?	☐ NO

Participant's signature:

Instructions for use:

Fainting: A one of spell of fainting due to a clear cause that would cause anyone to faint is permissible. A history of regular fainting episodes should be taken as contraindication.

Ringing in ears: Transient, one-off experiences of this are fine but persistent tinnitus or problems with this can indicate a neurological problem and should preclude participation

Drugs/substances: check against list at bottom of screening form. Generally, we will avoid participants taking any of the drugs/substances on this list. If the participant is on any unknown drugs/substances or you have reason to believe that they are not sober or under the influence of a substance, this should be taken as a contraindication.

Potential Contraindication Drugs

Strong Potential Hazard:

imipramine, amitriptyline, doxepine, nortriptyline, maprotiline, chlorpromazine, clozapine, foscarnet, ganciclovir, ritonavir, amphetamines, cocaine, MDMA, ecstasy, phencyclidine (PCP, angel's dust), ketamine, gammahydroxybutyrate (GHB), alcohol, theophylline

Relative Potential Hazard:

mianserin, fluoxetine, fluvoxamine, paroxetine, sertraline, citalopram, reboxetine, venlafaxine, duloxetine, bupropion, mirtazapine, fluphenazine, pimozide, haloperidol, olanzapine, quetiapine, aripiprazole, ziprasidone, risperidone, chloroquine, mefloquine, imipenem, penicillin, ampicillin, cephalosporins, metronidazole, isoniazid, levofloxacin, cyclosporin, chlorambucil, vincristine, methotrexate, cytosine arabinoside, BCNU, lithium, anticholinergics, antihistamines, sympathomimetics. Withdrawal Hazard:

alcohol, barbiturates, benzodiazepines, meprobamate, chloral hydrate.

Ensure participants are honest when completing the questionnaire.

Appendix D: Experiment 1 consent form

Consent Form

Full title of project

TMS Investigation of Executive Control in the Human Brain

Researchers

Michael Wadsley (mwadsley@bournemouth.ac.uk) Postgraduate Student

Project Supervisor: Dr Ben Parris (bparris@bournemouth.ac.uk)**,** Associated Professor in Psychology

	Please Initial Or Tick Here
I have read and understood the participant information sheet for the above research project.	
I confirm that I have had the opportunity to ask questions.	
I understand that my participation is voluntary.	
I understand that I am free to withdraw up to the point where the data are processed and become anonymous, so my identity cannot be determined.	
During the task or experiment, I am free to withdraw without giving reason and without there being any negative consequences.	
I confirm that I do not use a pacemaker, an implanted medication pump, a metal plate in the skull, or metal objects inside the eye or skull (for example after brain surgery or a shrapnel wound.	
I confirm that I am not pregnant. I also confirm that I did not consume alcohol in the last 24 hours or psychoactive drugs in the last month, nor did I have a bad night's sleep prior to the experiment.	
I confirm that I have informed the researcher(s) about cases of epilepsy in my family (if applicable).	
I give permission for members of the research team to have access to my anonymised responses. I understand that my name will not be linked with the research materials, and I will not be identified or identifiable in the outputs that result from the research.	
I agree to take part in the above research project.	

_____ _____ _____

Name of Participant Date Signature

_____ _____ _____

Name of Researcher Date Signature

This form should be signed and dated by all parties after the participant receives a copy of the participant information sheet and any other written information provided to the participants. A copy of the signed and dated participant agreement form should be kept with the project's main documents which must be kept in a secure location.

Appendix E: Experiment 1 debrief sheet

TMS Investigation of Executive Control in the Human Brain: Debrief

Thank you for taking part and completing our study, we appreciate your participation and we hope that you enjoyed the experience!

This study used TMS to investigate the role of the left dorsolateral prefrontal cortex (DLPFC) in resolving three different types of conflict experienced in the Stroop task (response, semantic and task conflict). In the experiment we asked you to respond as quickly and as accurately as possible to the print colour of the stimulus, whilst ignoring the meaning of the word. We expected this to be harder during some conditions compared to others!

Previous studies have shown that people are slower at responding to the print colour when the irrelevant word is semantically related to another colour (e.g., SKY – blue) compared to when the word is neutral (e.g., TABLE), but slower still when the word spells out a possible response option (e.g., RED in blue). It is believed that this is because when we read a word that activates a colour different to that of the print colour, choosing the correct response becomes harder as there is more competition between possible response options.

Some research has suggested that using TMS to stimulate the DLPFC improves performance on the Stroop task. In order to test this, participants in our study received stimulation of the DLPFC during one session and sham-TMS (no stimulation) in another. In line with previous findings we expect to find that participants perform better on the Stroop task after receiving real stimulation compared to when they receive no stimulation.

It is important that we understand the neural mechanisms which underpin the Stroop task since it is one of the most commonly used measures of selective attention in cognitive and clinical research. The findings of this study will therefore help to improve our understanding of how we process conflict, which in turn may help to inform future treatment of patients with focal lesions, dementia, anxiety and other clinical disorders.

Confidentiality

All the data that you provided is de-identified, meaning that any information collected is not associated with your name, and is entirely confidential within Bournemouth University. De-identified data may be used for future research and published in scholarly articles.

Should you have any questions about the study, please contact:

Michael Wadsley

Email: mwadsley@bournemouth.ac.uk

THANK YOU AGAIN FOR PARTICIPATING

Appendix F: Experiment 1 ethics approval

Bournemouth University

Research Ethics Checklist

Reference Id	20156
Status	Approved
Date Approved	22/05/2018

Researcher Details

Name	Michael Wadsley
Faculty	Faculty of Science & Technology
Status	Postgraduate Research (MRes, MPhil, PhD, DProf, DEng)
Course	Postgraduate Research - FST
Have you received external funding to support this research project?	No
Please list any persons or institutions that you will be conducting joint research with, both internal to BU as well as external collaborators.	Dr Ben Parris, Bournemouth University

Project Details

Title	TMS Investigation of Executive Control in the Human Brain
Proposed Start Date of Data Collection	25/04/2018
Proposed End Date of Project	01/12/2019
Original Supervisor	Ben Parris
Approver	Research Ethics Panel

Appendix G: Experiment 2 information sheet

Bournemouth University

Participant Information Sheet

Functional Magnetic Resonance Imaging of Executive Control in the Human Brain

You are being invited to take part in a research project. Before you decide to take part it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

What is the purpose of the project?

The aim of this project is to investigate the functions of the front part of the brain. We are particularly interested in investigating its role in the control of human behaviour.

Why have I been chosen?

We aim to recruit 20-30 participants. We are recruiting from Bournemouth and Exeter Universities' and partner colleges' student and staff populations. You are chosen because you are eligible for this study: between 18 and 45 years old, fluent in English, and with normal or corrected-to-normal vision.

Do I have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep (and be asked to sign a participant agreement form) and you can still withdraw at any time up to the point the data are anonymised without it affecting any benefits that you are entitled to in any way. You do not have to give a reason.

What do I have to do?/ What will happen to me if I take part?

In the present study you will complete an MRI safety form to ensure you are able to enter a room with a large magnet. We will need to ensure that you have no ferrous metal on or in your body. Once we have established you are metal-free you will be asked to practice the task we will want you to do in the scanner. This task is straightforward: You will be asked to respond to the colour of the font in which a word is presented on the screen, whilst ignoring the meaning of the word, and to do so as quickly and as accurately as possible. Once you are happy you understand the task, you will enter the magnet room and be asked to lie on a mattress near to the bore of the magnet. You will have your head strapped in place so as to avoid unnecessary movement; this is important because we are aiming to register brain activity in regions less than 1mm apart and so any movement will prevent the accurate measurement of the location from which images originate. A head coil will then be slid over your head to enable the images to be registered. You will also be given a response box and a safety button should you want to stop the experiment at any time. When you are ready the scanner operator will make the final checks and then send you into the bore of the machine (which is a meter wide, three meter long tunnel). Your feet will be near the entrance of the bore. Before you start the experiment proper you will be able to practice the task once again whilst a structural scan of your brain is completed. This will take about 5 minutes. You will be able to talk with the scanner operator between scans. Immediately after the structural scan

the experiment will begin. The experiment will take 36 minutes to complete. The safety button will ensure you can end the experiment at any time but for most people it is a relaxing experience. The scanner makes a noise when it is operating but you will be given ear defenders to muffle the sound.
This research is being undertaken by Dr. Ben Parris, and Michael Wadsley and their research collaborator Dr. Abdelmalek Bennattayallah, the Magnetic Resonance Physicist at Exeter University.

What are the possible disadvantages and risks of taking part?

We are asking that you give up one hour of your time to help us with our research so the main and direct disadvantage is the loss of your time. You should not take part in this experiment if you are claustrophobic because the bore of the scanner is only a meter wide and three meters long and it might be an uncomfortable experience for you.

What are the possible benefits of taking part?

Whilst there are no immediate benefits for those people participating in the project, this research is exploring the function of an area of the brain implicated in clinical disorders such as ADHD and Schizophrenia and so will ultimately have clinical and medical significance.

How will my information be kept?

All the information we collect about you during the course of the research will be kept strictly in accordance with the current Data Protection Regulations. You will not be able to be identified in any reports or publications without your specific consent. All personal data relating to this study will be held for 5 years from the date of publication of the research. BU will hold the information we collect about you in hard copy in a secure location and on a BU password protected secure network where held electronically. Except where it has been anonymised, we will restrict access to your personal data to those individuals who have a legitimate reason to access it for the purpose or purposes for which it is held by us. The information collected about you may be used in an anonymous form to support other research projects in the future and access to it in this form will not be restricted. It will not be possible for you to be identified from this data.

What type of information will be sought from me and why is the collection of this information relevant for achieving the research project's objectives?

We will be collecting three types of information from you: 1) Your reaction times to the colours that you see on the screen; 2) Errors that you make when classifying the colours; 3) Your brain activity that is related to colour classification.

Who is organising/funding the research?

This research is organised by Dr. Ben Parris in the Psychology Department in the Faculty of Science and Technology. The research will be carried out by Dr. Ben Parris, Michael Wadsley and Dr. Abdelmalek Bennattayallah. Dr Parris will be responsible for experiment design, analysing the brain scans and writing the report and Dr Bennattayallah is the MR Physicist at Exeter University who will be responsible for scanning and data collection for this experiment. Michael Wadsley will be responsible for participant recruitment and management.

Contact for further information

For further information please contact Michael Wadsley on mwadsley@bournemouth.ac.uk or Dr Ben Parris on bparris@bournemouth.ac.uk or 01202 965485. You could also visit Dr Parris' office on the third floor of Poole House in room P331 between 3.30pm and 5pm on Mondays and Tuesday.

In case of complaint please contact Deputy Dean for Research and Professional Practice Professor Tiantian Zhang on tzhang@bournemouth.ac.uk

Thank you

Thank you for taking the time to read through the information sheet. Please take this information sheet with you when you leave. If you have any further questions please do not hesitate to contact us. We would be happy to talk with you about the experiment and its purpose in greater detail.

Appendix H: Experiment 2 screening questionnaire

Participant Safety Checklist

Name: **…….** Date of Birth: **……..**
Weight**: ……..** Study Name/Volunteer Number: **……**

Please check the following list carefully, answering all appropriate questions.
Please do not hesitate to ask staff, if you have any queries regarding these questions.

1.Do you have a pacemaker, artificial heart valve or coronary stent? Yes☐ No☐

2.Have you ever had major surgery? Yes☐ No☐
If yes, please give brief details:

3.Do you have any aneurysm clips (clips put around blood vessels during surgery)? Yes☐ No☐

4.Do you have any implants in your body?

Yes☐ No☐ Joint replacements, pins or wires
Yes☐ No☐ Implanted cardioverter defibrillator (ICD)
Yes☐ No☐ Electronic implant or device
Yes☐ No☐ Magnetically-activated implant or device
Yes☐ No☐ Neurostimulation system
Yes☐ No☐ Spinal cord stimulator
Yes☐ No☐ Insulin or infusion pump
Yes☐ No☐ Implanted drug infusion pump
Yes☐ No☐ Internal electrodes or wires
Yes☐ No☐ Bone growth/bone fusion stimulator
Yes☐ No☐ Any type of prosthesis
Yes☐ No☐ Heart valve prosthesis
Yes☐ No☐ Eyelid spring or wire
Yes☐ No☐ Metallic stent, filter or coil
Yes☐ No☐ Shunt (spinal or intraventricular)
Yes☐ No☐ Vascular access port and/or catheter
Yes☐ No☐ Wire mesh implant
Yes☐ No☐ Bone/joint pin, screw, nail, wire, plate etc.
Yes☐ No☐ Other Implant ……..

5.Do you have an artificial limb, calliper or surgical corset? Yes☐ No☐

6.Do you have any shrapnel or metal fragments, for example from working in a machine tool shop? Yes☐ No☐

7.Do you have a cochlear implant? Yes☐ No☐

1.Do you wear dentures, plate or a hearing aid? Yes☐ No☐

2.Are you wearing a skin patch (e.g. anti-smoking medication), have any tattoos, body piercing, permanent makeup or coloured contact lenses? Yes☐ No☐

3.Are you aware of any metal objects present within or about your body, other than those described above? Yes☐ No☐

4.Are you susceptible to claustrophobia? Yes☐ No☐

5.Do you suffer from blackout, diabetes, epilepsy or fits? Yes☐ No☐

For women:

6.Are you pregnant or experiencing a late menstrual period? Yes☐ No☐

7.Do you have an intra-uterine contraceptive device fitted? Yes☐ No☐

8.Are you taking any type of fertility medication or having fertility treatment? Yes☐ No☐

Important Instructions

Remove all metallic objects before entering the scanner room including hearing aids, mobile phones, keys, glasses, hair pins, jewellery, watches, safety pins, paperclips, credit cards, magnetic strip cards, coins, pens, pocket knives, nail clippers, steel-toed boots/shoes and all tools. Loose metallic objects are especially prohibited within the MR environment.

I have understood the above questions and have marked the answers correctly.

Signature ..... Date ……
(Participant/Parent/Guardian)

MR Centre Staff Signature .....

Appendix I: Experiment 2 consent form

Participant Agreement Form

Full title of project: Functional Magnetic Resonance Imaging of Executive Control in the Human Brain

Name, position and contact details of researcher: Michael Wadsley, Postgraduate Researcher, mwadsley@bournemouth.ac.uk

Name, position and contact details of supervisor: Dr. Ben Parris, Associate Professor in Psychology, bparris@bournemouth.ac.uk 01202 96548

In case of complaint please contact Deputy Dean for Research and Professional Practice: Professor Tiantian Zhang on tzhang@bournemouth.ac.uk

Please tick the appropriate boxes	***Yes***	***No***
Taking Part:		
I have read and understood the Project Participant Information Sheet.	☐	☐
I confirm that I have had the opportunity to ask questions.	☐	☐
I understand that my participation is voluntary.	☐	☐
I understand that I am free to withdraw up to the point where the data are processed and become anonymous, so my identity cannot be determined.	☐	☐
Should I not wish to answer any particular questions I am free to decline.	☐	☐
I agree to take part in the project.	☐	☐
Use of the information I provide for this project only:		
I understand my personal details will not be revealed to people outside this project.	☐	☐
Use of the information I provide beyond this project:		
I agree for the anonymised data I provide to be archived at BU's Online Research Data Repository.	☐	☐
I understand that the anonymised data I provide may be used by the research team to support other research projects in the future, including future publications, reports or presentations	☐	☐

_____ _____ _____

Name of Participant Date Signature

_____ _____ _____

Name of Researcher Date Signature

This form should be signed and dated by all parties after the participant receives a copy of the participant information sheet and any other written information provided to the participants. A copy of the signed and dated participant agreement form should be kept with the project's main documents which must be kept in a secure location.

Appendix J: Experiment 2 debrief sheet

fMRI Investigation of Executive Control in the Human Brain: Debrief

Thank you for taking part and completing our study, we appreciate your participation and we hope that you enjoyed the experience!

This study used fMRI to investigate the brain regions involved in resolving three different types of conflict experienced in the Stroop task (response, semantic and task conflict). In the experiment we asked you to response as quickly and as accurately as possible to the print colour of the stimulus, whilst ignoring the meaning of the word. We expected this to be harder during some conditions compared to others!

Previous studies have shown that people are slower at responding to the print colour when the irrelevant word is semantically related to another colour (e.g., SKY – blue) compared to when the word is neutral (e.g., TABLE), but slower still when the word spells out a possible response option (e.g., RED in blue). It is believed that this is because when we read a word that activates a colour different to that of the print colour, choosing the correct response becomes harder as there is more competition between possible response options.

Despite this robust finding research is yet to uncover the brain regions responsible for resolving this competition at each level. Therefore, our research was concerned with investigating whether different brain regions are responsible for resolving each type of conflict.

It is important that we understand the neural mechanisms which underpin the Stroop task since it is one of the most commonly used measures of selective attention in cognitive and clinical research. The findings of this study will therefore help to improve our understanding of how we process conflict, which in turn may help to inform future treatment of patients with focal lesions, dementia, anxiety and other clinical disorders.

Confidentiality

All the data that you provided is de-identified, meaning that any information collected is not associated with your name, and is entirely confidential within Bournemouth University. De-identified data may be used for future research and published in scholarly articles.

Should you have any questions about the study, please contact:

Michael Wadsley

Email: mwadsley@bournemouth.ac.uk

THANK YOU AGAIN FOR PARTICIPATING

Appendix K: Experiment 2 ethics approval

Bournemouth University

Research Ethics Checklist

Reference Id	19946
Status	Approved
Date Approved	17/04/2018

Researcher Details

Name	Michael Wadsley
Faculty	Faculty of Science & Technology
Status	Postgraduate Research (MRes, MPhil, PhD, DProf, DEng)
Course	Postgraduate Research - FST
Have you received external funding to support this research project?	No
Please list any persons or institutions that you will be conducting joint research with, both internal to BU as well as external collaborators.	Dr Ben Parris, Bournemouth University and Dr Abdelmalek Benattayallah, University of Exeter

Project Details

Title	Functional Magnetic Resonance Imaging of Executive Control in the Human Brain
Proposed Start Date of Data Collection	21/02/2018
Proposed End Date of Project	01/12/2019
Original Supervisor	Ben Parris
Approver	Research Ethics Panel