Exploring non-clinical inattention in adults: prevalence, and links to working memory and self-regulation

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Abstract

Inattention is a symptom related to several mental health disorders, most notably ADHD. Recent work has suggested that a) inattention is a symptom worth studying in it's own right regardless of co-occurring pathology, b) it persists beyond childhood and may be more relevant to adults than the other ADHD symptoms (hyperactivity and impulsivity), and c) it is dimensional so investigation of it should consider the full spectrum of symptom expression. The approach of this thesis is based on these points. A preliminary study addressed the prevalence of inattention. Findings validated the approach of the thesis and suggested that inattention is highly prevalent in a general population sample of adults (over 30% when broadly defined), more so than hyperactivity-impulsivity. Across four further studies we used behavioural and pupillometry measures to investigate the cognitive underpinnings of inattention with a view to differentiating it from hyperactivity and impulsivity. Research suggests a role for executive functions (EFs) and self-regulatory processes in ADHD, although there is conflicting theory on what aspects of these relate to which symptoms. Various EF and self-regulatory components, with consideration for "hot" and "cool" cognitive distinctions, were tested in relation to ADHD symptoms using a model based on an interpretation of the literature. Findings across studies were mixed, but make several notable contributions to literature in this area. Firstly we demonstrated a unique and robust relationship between inattention and working memory. Secondly, we show strong evidence against a relationship between inattention and norepinephrine activity as indexed by changes in pupil diameter. There were also notable distinctions between inattention and the other symptoms of ADHD across the research. We discuss how these findings relate to theory on "hot" and "cool" cognition, along with their application to both general population and clinical groups.

Thesis Structure

This thesis conforms to an "article format" whereby the experimental chapters (Chapters 2 – 6) are included as discrete articles written in a style appropriate for publication in peer-reviewed journals. The first and seventh chapters present an overview and discussion for the entire thesis, and a preface is included at the beginning of each chapter to clarify how each article contributes to the overall aims of the thesis.

The articles included in this thesis are at various stages of the publication/review process (see page v). The main text of each chapter is presented as an exact replication of that prepared for submission meaning repetition between chapters is inevitable, particularly in the introductory sections. Figures and tables are numbered within each chapter, a key to these can be seen on pages vii – x.

Status of Articles from this Thesis

Chapter 2 is currently under review with the journal "ADHD Attention Deficit and Hyperactivity Disorders"

Chapter 3 has been published as:

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Chapters 5 and 6 are in preparation for submission.

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Authors 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:

Chapter 1: Introduction

Inattention is one of the three core symptoms of attention deficit hyperactivity disorder (ADHD), a childhood-onset neurodevelopmental disorder. It is characterised by a lack of attention to detail often resulting in seemingly careless mistakes, difficulty sustaining prolonged attention to a task, daydreaming, being easily distracted by external stimuli as well as internal thought, problems with organisation and planning, and a tendency to embark on new activities before finishing previous ones. The remaining two core symptoms are hyperactivity and impulsivity, externalising symptoms sometimes grouped together which are characterised by excessive energy levels, impatience, and disruptive, often inappropriate behaviour with a lack of regard for social rules. It is possible to have inattention without the other two symptoms, and for this reason there are several sub-types of ADHD. The Diagnostic and Statistical Manual of Mental Disorders 5th edition (DSM-5) lists three; the combined type where individuals meet criteria for both inattention and hyperactivity-impulsivity (ADHD-C), the predominantly inattentive type where individuals meet criteria for inattention only (ADHD-I), and the predominantly hyperactive-impulsive type (ADHD-HI) where only hyperactive-impulsive criteria are met. To avoid confusion, diagnosis of pure inattention will herein be abbreviated to PIT (i.e. predominantly inattentive type, as per Barkley, 2001) so as not to confuse it with a disorder that includes symptoms of hyperactivity-impulsivity.

Inattention as a Symptom of other Disorders

Although the majority of research on inattention uses samples of participants with ADHD, it is not a symptom exclusive to this disorder. All symptoms of ADHD are common in children with Autism Spectrum Disorder (ASD), although the reverse (ASD symptoms being found in ADHD) is not true (Mayes, Calhoun, Mayes, & Molitoris, 2012; Sinzig, Walter, & Doepfner, 2009). Neuroimaging research has found a negative relationship

between inattentive symptoms and grey matter volume in the same brain area for both ADHD and ASD (Brieber et al. 2007). Interestingly, Sinzig et al. found that children with ASD and co-morbid ADHD could be categorised as either inattentive or hyperactive, and suggested different underlying neurochemical systems for each. Impaired attention is also typically found in schizophrenia (Egeland et al., 2003). Egeland (2010) found that on a variety of tests of attention, subjects with schizophrenia and ADHD were equally impaired. Karatekin and Asarnow (1998) found similarities in working memory (WM) impairment between subjects with schizophrenia and ADHD. This is of particular interest as inattention is thought to be related specifically to WM impairments (to be discussed in more detail later). Inattention may also contribute to the severity of some eating disorders including bulimia nervosa (Seitz et al., 2013). It has been suggested that inattention may be particularly prevalent in those eating disorders characterised by a binge-purge cycle (Yates, Lund, Johnson, Mitchell, & McKee, 2009). Sufferers of eating disorders are also typically thought to have self-regulatory deficits (Goodsitt, 1983; Marchi & Cohen, 1990), and there is reason to believe this may be related to inattention and WM (to be discussed in more detail later).

Limitations of Inattention Research

There are several limitations to much of the existing research on inattention. Firstly the majority of findings are from clinical samples of male children. ADHD is (or was) most commonly diagnosed in males, and the most common diagnosis was ADHD-C (Lahey et al, 1994). This is now thought to be a poor reflection of prevalence, as girls are less likely to have their disorder identified than males, possibly because they are more likely to have the inattentive sub-type, which has less obvious symptoms (Bradshaw, 2001; Collingwood, 2010; Froehlich et al., 2007). This has meant that overall there is considerably less research on PIT than there is on ADHD-C. This is unfortunate, as other work has suggested that PIT

may be at least as prevalent if not more so than ADHD-C (Gaub & Carlson, 1997; Wolraich, Hannah, Pinnock, Baumgaertel, & Brown, 1996). In many cases, samples of ADHD participants are referred to with no specification as to subtype at all. It is not possible to draw conclusions specifically about inattention in these cases. It is also difficult to draw conclusions about inattention in adults from research with children. For many years ADHD was thought to be a disorder exclusive to childhood, and has only recently been recognised as existing in adults.

Inattention in Adults

The latest version of the DSM, released in 2014, was the first to provide specific ADHD diagnostic criteria for adults. Longitudinal follow-up studies suggest that ADHD persists into adulthood in around 60% of cases (Elliott, 2002), and that up to 6% of adults may have ADHD (Wender, Wolf, & Wasserstein, 2001). These figures could be even higher when we consider that the diagnostic criteria developed for children and used until recently, has been deemed by many as unsuitable for application to adult populations, and may have resulted in under-diagnosis (Murphy & Barkley, 1996).

Recent research has started to explore the disorder in adults, but it remains that most of the literature on ADHD uses samples of children. It is difficult to generalise findings from this research to adults, as the disorder's manifestation appears to differ from that in children. Research suggests that symptoms of hyperactivity and impulsivity diminish with age, while inattention persists (Biederman, Mick & Faraone, 2000). It is therefore not surprising that the majority of adults diagnosed with ADHD present with prominent inattention (Millstein, Wilens, Biederman, & Spencer, 1997); the most common complaints being cognitive (e.g. difficulty concentrating, forgetfulness), and self-regulatory (e.g. problems with organisation and planning, poor discipline), and none

implying hyperactivity (Wolf & Wasserstein, 2001). This suggests there should be more of a research focus on inattention in adults.

Dissociations between PIT & ADHD

In recent years PIT has come to be thought of by many as qualitatively different from ADHD-C, and should perhaps be considered a disorder in its own right with distinct aetiology, symptoms, comorbidities, and cognitive profile (Barkley, 1997, 2001; Diamond, 2005; Milich, Balentine, & Lynam, 2001). Research has found possible differences between ADHD and PIT in several domains, which strongly supports the use of clear sub-type and/or symptom division in future work.

    Cognitive and behavioural. Children with PIT often show symptoms of a related, but separate disorder; sluggish cognitive tempo (SCT; Hartman Willcutt, Rhee, & Pennington, 2004; Wahlstedt & Bohlin, 2010), including sluggishness, drowsiness, daydreaming, and hypoactivity. These symptoms are less often seen in children with either ADHD-C or ADHD-HI (Hartman, Willcutt, Rhee, & Pennington, 2004). There are also thought to be differences in personality dimensions, with decreased self-directedness and increased harm avoidance seen in those with PIT but not in those with ADHD-C or ADHD-HI (Salgado et al., 2009). Those with ADHD-C are also more likely to be extrovert than those with PIT, although both groups score higher on neuroticism than controls (Parker, Majeski, & Collin, 2004). Both groups have been shown to have difficulties with social behaviour, but in different areas. Children with ADHD-C are more aggressive, and display emotional dysregulation, while children with PIT are more socially passive, and show deficits in social knowledge (Wheeler Maedgen & Carlson, 2000). Social problems related to ADHD mean these children are more likely to be expelled or suspended from school (Weiss Worling, & Wasdell, 2003). Children with ADHD appear to have more problems falling asleep than those with PIT (although this is also related to medication),

but those with PIT have increased daytime sleepiness (Mayes et al. 2009). Children with PIT seem to have an increased tendency towards internalizing disorders (such as depression and anxiety), or at least show an absence of externalizing disorders compared to children with ADHD (Gaub & Carlson, 1997; Weiss, Worling, & Wasdell, 2003), although this is disputed by findings from Power, Costigan, Eiraldi, & Leff (2004) who found no group differences for these variables.

Genetic. It has been suggested that PIT and ADHD symptoms may be a result of different genetic polymorphisms. Several studies have found that polymorphisms at the dopamine transporter gene DAT1 are associated with ADHD (Barr et al. 2001; Brookes et al. 2006; Cook et al. 1995; Cornish et al. 2005; Hawi et al. 2003). DAT1 is the primary protein responsible for the reuptake of dopamine. It has been linked specifically with hyperactive-impulsive symptoms but not inattention (Gizer et al. 2008; Waldman et al. 1998 cf. Franke et al. 2010). In contrast, research has found polymorphism of the DRD4 gene (which acts on D_4 dopamine receptors) is more strongly linked to PIT than ADHD (McCracken et al. 2000; Rowe et al. 1998).

Neurostructural. Diamond (2005) suggests that the striatum is the primary site for neurobiological dysfunction in ADHD. Several studies have found caudate abnormalities in participants with ADHD (Castellanos et al. 1994; Hynd et al. 1993; Mataro, Garcia-Sanchez, Junque, Estevez-Gonzalez, & Pujol, 1997), although it is noted that in one study such abnormalities were found to be more pronounced with increased inattentive symptoms (Schrimsher, Billingsley, Jackson, & Moore, 2002), and also that abnormalities are not consistent across studies. Other research has shown that children with ADHD have different patterns of fronto-striatal activity while performing an inhibitory control task compared to controls (Durston et al. 2003). It has also been suggested that perinatal damage to the striatum may increase the risk of developing ADHD (Toft, 1999). In line with a striatal role in ADHD, DAT1 is abundant in this area (Kung, Kim, Kung, Meegalla,

Piossl, & Lee, 1996; Nirenberg, Vaughan, Uhl, Kuhar, & Pickel, 1996). Research by Jucaite, Fernell, Halldin, and Farde (2005) showed a significant negative relationship between the degree of hyperactivity and DAT1 binding in the striatum, and DAT1 has been shown to preferentially influence caudate volume in participants with ADHD (Durston et al. 2005).

The primary neurostructure of dysfunction in PIT on the other hand is, according to Diamond, the prefrontal cortex (PFC). The PFC is the area of the brain thought to be responsible for executive function. The primary motivator of this is the idea of "control", including attentional control, thought to be lacking in PIT. Given the limited research on PIT, this inference comes mainly from associative findings. D_4 dopamine receptors, which as already discussed are linked to PIT, are found in the PFC, and not in the striatum (Meador-Woodruff, Damask, Wang, Haroutunian, Davis, & Watson, 1996). Furthermore, variations in the gene of this receptor (DRD4) have been shown to modulate activation of the PFC during working memory tasks (Herrmann, Walter, Screppel, Ehlis, Pauli, & Lesch et al., 2007), which is pertinent for reasons that will be discussed fully later. DRD4 has also been associated with cortical thinning in regions including the inferior PFC (Shaw, Gornick, Lerch, Addington, Seal, & Greenstein et al., 2007), as well as reduced prefrontal grey matter volume (Durston et al. 2005).

Response to drug treatment. One of the most well known treatments for ADHD is methylphenidate (also known as Ritalin). This stimulant acts by blocking DAT and norepinephrine (NE) transporters leading to increased concentrations of these neurotransmitters being active in the brain. Research by Barkley, DuPaul, and McMurray (1991) suggested that children with ADHD respond well to methylphenidate treatment and do best on a moderate to high dose. Children with PIT on the other hand were more likely to be judged as having no clinical response, or as responding most positively to a low dose of medication. Such low doses are thought to preferentially release NE (Kuczenski &

Segal, 2001; Ishimatsu, Kidani, Tsuda, & Akasu, 2002), and produce enhanced activation of this neurotransmitter in the PFC relative to subcortical regions (Berridge, Devilbliss, Andrzewski, Arnsten, Kelley, Schmeichel et al., 2006). Activation of NE is thought to modulate attention and has therefore been implicated in PIT. Accordingly in a meta-analysis, atomoxetine, a NE reuptake inhibitor, was shown to produce greater reductions in symptoms along with a reduced chance of adverse reactions in people with PIT compared to those with hyperactivity-impulsivity (Cheng, Chen, Ko, & Ng, 2007). Also, in accordance with neurostructural theories on ADHD/PIT, this drug has been shown to increase neurotransmitters in the PFC, but not the striatum, whilst methylphenidate increases DA in the latter (Bymaster, Katner, Nelson, Hemrick-Luecke, Threlkeld, Heligenstein et al. 2002).

Interestingly, other substances such as nicotine and cocaine have been shown to act on DAT in a similar way to methylphenidate, and to produce similar behavioural results (Bizaro, Patel, Murtagh, & Stolerman, 2004; Krause, Dressel, Krause, Kung, & Tatsch, 2002; Levin, Conners, Silva, Canu, & March, 2001; Rush & Baker, 2001; Volkow, Wang, Fowler, Fischman, & Foltin, 1999; Yano & Steiner, 2007). Research suggests that a history of ADHD in cocaine abusers is not uncommon, and that its use may be driven by the need to relieve hyperactivity, and not inattention (Carroll, & Rounsaville, 1993; Saules, Pomerleau, & Schubiner, 2003). Similarly, smoking is thought to be more commonly used to self-medicate symptoms of ADHD as oppose to PIT (Covey, Manubay, Jiang, Nortick, & Palumbo, 2008; Rukstalis, Jepson, Patterson, & Lerman, 2005). However, it must be noted that there is also plenty of research suggesting smoking (i.e. nicotine) is used to relieve symptoms of inattention, although perhaps differently to the way it used to relieve hyperactivity (Fuemmeler, Kollins, & McClernon, 2007; Lerman, Audrain, Tercyak, Bush, & Crystal-Manser, Rose, et al., 2001; Ohlmeier, Peters, Kordon, Seifert, Wildt & Wiese et al., 2007; Rodriguez, Tercyak, & Audrain-McGovern, 2008).

Inattention as a Continuous Trait

Recent research and subsequent debate has led many experts to a shift in approach from a categorical, to a dimensional view of ADHD (Barkley & Murphy, 2006). It is suggested that the disorder is better regarded as being at the extreme end of normal expression within the general population, as opposed to being qualitatively different with a distinct pattern of causes. Confirmatory factor analysis has shown a bi-factor model of ADHD, with a general factor and specific factors for inattention and hyperactivity-impulsivity, to be the best fit for the available data (Martel, Von Eye, & Nigg, 2010). It has thus been suggested that the commonly used ADHD category could be replaced by these three dimensions, whereby individuals would be described by their ratings on each (Coghill & Sonuga-Barke, 2012). Latent class analyses supports this idea and has found separate, continuously distributed dimensions for purely inattentive and combined subtypes (Hudziak, Heath, Madden, Reich, Bucholz, & Slutske, 1998; Lubke, Hudziak, Derks, van Bijsterveldt & Boomsma, 2009; Neuman et al., 1999). Findings from research using taxometric analysis were also consistent with a dimensional rather than taxonomic structure (Frazier, Youngstrom, & Naugle, 2007; Haslam, Williams, Prior, Haslam, Graetz, & Sawyer, 2006; Marcus & Barry, 2011), and fMRI research also supports the idea of a continuum (Schrimsher, Billingsley, Jackson, & Moore, 2002). Research looking at unaffected family members of patients with ADHD provides further evidence for a genetic component to the disorder, and for a continuum of ADHD traits (Crosbie, Arnold, Swanson, Dupuis, Shan, & Goodlae et al., 2013; Hudziak et al. 1998). A meta-analysis on genetic and environmental influences found clear differences between inattentive and hyperactive-impulsive symptoms, and concluded that looking at these as behavioural dimensions rather than diagnostic subtype categories is more useful for identifying differences between the two (Nikolas & Burt, 2010).

Knowing whether ADHD is a discrete category or a continuous trait is important for developing causal models, and a dimensional structure is consistent with the multiple pathway models of ADHD currently thought to best represent the disorder (e.g. Nigg, Goldsmith & Sachek, 2004; Sonuga-Barke, 2005; Sonuga-Barke & Fairchild, 2012). However, it is also important from a sampling perspective. If ADHD symptoms exist on a continuum, then symptoms will occur at sub-clinical levels within the general population. Faraone and Biederman (2005) found prevalence rates for adult ADHD went up considerably when those meeting criteria for sub-threshold diagnosis were included in analysis. This suggests it is possible, and necessary, to research a wider spectrum of symptom expression. Benefits of using a non-clinical sample include a break-away from medicated, paediatric populations which allows investigation of symptoms of ADHD independent of developmental delays, general cognitive dysfunction, or history of medication use (Cocchi et al., 2012), along with the increased relevance of findings to family members of people with ADHD and to a wider population generally. Research utilizing such samples is beginning to take off and has had some fruitful results, for example looking at ADHD symptoms and big five personality characteristics (Parker, Majeski, & Collin, 2004), heritability of symptoms (Boomsma, Saviouk, Hottenga, Distel, De Moor, & Vink et al. 2010), cognitive performance (Crosbie et al. 2013; Herrmann, Saathoff, Schreppel, Ehlis, Scheuerpflug, & Pauli et al. 2009; Kuntsi, Wood, Van Der Meere, & Asherson, 2009), smoking abstinence (Ashare & Hawk, 2012), and neural systems for reward (Stark, Bauer, Merz, Zimmermanm Reuter, & Plichta et al. 2011).

Such research has often used self-report measures of ADHD symptoms based on DSM criteria i.e. the Adult ADHD Self-Report Scale (ASRS; Adler, Kessler, & Spencer, 2003), the Strengths and Weaknesses of ADHD Symptoms and Normal Behaviour Scale (SWAN; Swanson, Schuck, Mann, Carlson, Hartman, & Sergeant et al. 2001) or the Barkley Adult ADHD Rating Scale (BAARS-IV; Barkley, 2011). These measures allow

participants to be grouped into subtypes analogous to those used in diagnosis via DSM criteria. For adults this states that patients have at least 5 of the symptoms listed on either or both of the 9 symptom lists for inattention, and hyperactivity-impulsivity. Researchers can lower the threshold of diagnosis in order to include participants with sub-clinical traits. Another measure, the Connors Adult ADHD Rating Scale (CAARS; see Appendix A) is a broad-spectrum scale with subscales for inattention, hyperactivity, impulsivity, self-concept, and an ADHD index. The broad scale of this measure lends itself well to correlational research.

Cognitive Underpinnings of Inattention

There is a vast body of literature looking at the relationship between all three symptoms of ADHD and executive functions (EFs). EF is a multidimensional construct, but can generally be thought of as cognitive processes that guide goal-related behaviour (Banich, 2009). Intrinsic to this idea is the concept of control, hence these processes are thought to primarily fall within the remit of the PFC (Alvarez & Emory, 2006). There is debate in the literature as to how separable EF's are. In this thesis the view is taken that EF consists of both unity and diversity of function (Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000) such as demonstrated in Diamond's (2013) model (Figure 1). This model shows the relationship between the three core EFs examined by Miyake et al. and is shown to be clearly separable, but moderately correlated with each other. The model also highlights the potential role of self-regulation in EFs, which will be looked at more closely later. The following is a brief overview of each EF and their proposed relationships with each other, followed by a review of evidence for their relationship with inattention and ADHD. The EF of focus for this thesis is working memory (WM), and is described in detail. However, the close-knit relationship between all three EFs necessitates that all of them are covered here.

Cognitive flexibility. This component of executive functioning has produced some disagreement in the literature concerning operational definition. Miyake et al. (2000) limit it to shifting back and forth between multiple tasks, operations, or mental sets, and refer to it simply as "set shifting". By this definition it involves disengaging
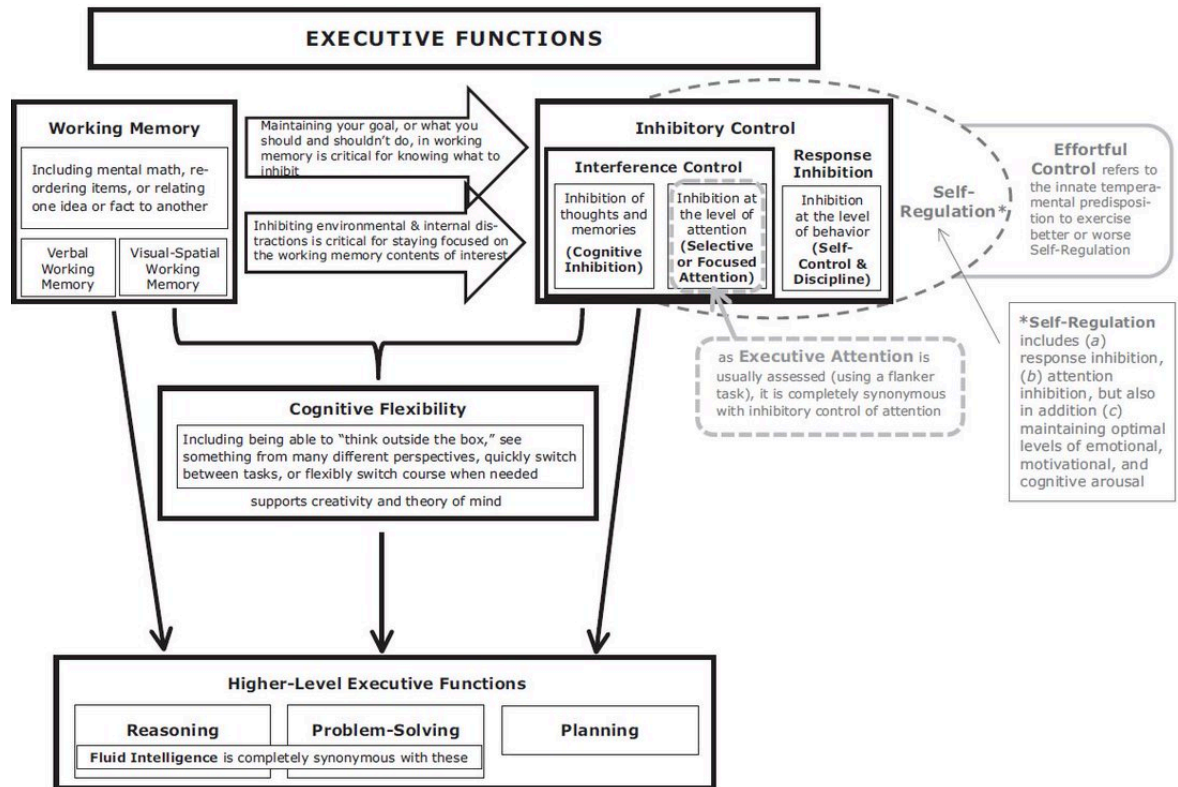
Figure 1. Executive functions and related terms as per Diamond (2013).

from an irrelevant task set in order to actively engage in a relevant one. This is a cognitive switch not to be mistaken for being synonymous with switching visual attention, or making voluntary eye movements. Ability is demonstrated in the "plus-minus task" (Jerslid, 1927), where participants are presented with lists of two-digit numbers that are to be operated on by either adding or subtracting 3. The task assesses their ability to switch between these operations. Tests such as the "Wisconsin card sorting task" and the "trail making test" have also been used to tap this domain, however they are often used as more general EF tasks thought to assess planning and problem solving ability.

Others have suggested that set shifting is just one part of a wider concept of more general mental flexibility, and that a broader definition is needed to fully explain it. Spiro (1988) suggested the core component of cognitive flexibility was the ability to selectively use available knowledge in order to adapt and fit the needs of particular situations. For this to be effective, a person would need to have both a sufficient knowledge base, as well as a flexible approach to thinking. This more abstract understanding of cognitive flexibility is harder to assess objectively. Self-report measures have been used to assess what could be thought of as a personality variable, and aim to gauge a persons' a) awareness that in any given situation there are options and alternatives available, b) willingness to be flexible and adapt to the situation, and c) self-efficacy in being flexible (Martin & Rubin, 1995; Dennis & Vander Wal, 2010). Both definitions agree on the idea of simultaneous processing of multiple alternatives, be they conceptual (ideas, thoughts etc.), or externally presented stimuli such as those in set shifting tasks.

Inhibitory control. Inhibitory control involves being able to control ones thoughts, behaviours and/or emotions in order to override a strong internal or external drive, and to instead behave or think in a way that is more appropriate or suited to the situation. For example, it allows us to refrain from acting on impulse, or through habit. It is a key part of what allows us to choose how to behave, as opposed to being ruled by our impulses. It covers a wide range of processes, and for this reason many believe it is best split into several related concepts (Dempster, 1993; Friedman & Miyake, 2004; Harnishfeger, 1995; Nigg, 2000). Friedman and Miyake describe three variations; prepotent response inhibition, resistance to distractor interference, and resistance to proactive interference (PI).

A response becomes prepotent when it is associated with immediate reinforcement and is therefore automatically elicited upon presentation of certain cues/stimuli. Prepotent response inhibition is the ability to deliberately suppress such habitual responses. The

"Stop-Signal" task (Logan, 1994) is often used to asses this type of inhibition; participants build up a prepotent response to categorise words in a certain way, and then attempt to suppress that response on hearing an auditory signal.

Resistance to distractor interference is the ability to selectively inhibit processing of distracting or irrelevant information. This is commonly associated with focused or selective attention. It is often assessed using the "Eriksen flanker task" (Eriksen & Eriksen, 1974) in which participants identify a target letter that is presented either alone or with non-target letters flanking it. Another commonly used paradigm to test this is the Stroop task (Stroop, 1935) where colour words are presented either congruently (i.e. the word "red" written in red font colour), or incongruently (i.e. the word "red" written in font colour yellow). Reaction times are significantly and reliably reduced in incongruent conditions due to the interference arising from competing information.

Proactive interference occurs when information that has previously been remembered interferes with memory for new information. Resistance to PI is the ability to resist such memory intrusions. It differs from resistance to distractor interference in that distracting information is presented prior to, rather than simultaneously with target information, and is information that was previously relevant. The "AB-AC-AD task" (Rosen & Engle, 1998) demonstrates this ability; participants learn a list of cue-target word pairs, and then a new list of targets that are paired to the same cues. Upon recall they have to suppress responses that were cued to the original targets.

Working memory. Working memory (WM) has been defined in several ways. All agree that it has a limited capacity, and requires holding information in mind in an active, easily retrievable form, but that it is distinct from short-term memory. The seminal model of Baddely & Hitch (1974; see fig 2) defined WM as holding information in mind combined with performing another operation. For example, the "backward digit span" task designed to test working memory in this way, requires participants to remember a

sequence of digits and to manipulate this information by turning the sequence around in order to produce it verbally in the opposite order. It need not be the information to be remembered that has to be processed to constitute a working memory task. For example, the "Operation Span" task requires participants to remember words while carrying out mental arithmetic. Another model of WM defines it as the ability to hold information in mind whilst blocking or inhibiting counter-productive information (Conway & Engle, 1994; Kane & Engle, 2000, 2002).

The multi-component model of Baddeley & Hitch proposes that a 'central executive' is responsible for directing attention to relevant information, and suppressing irrelevant information. Often described as a single unit, the central executive is probably better thought of as a system emergent from an alliance of executive processes (overlap between executive functions will be discussed in more detail later). It coordinates the use of two "slave systems"; the phonological loop (verbal WM), and the visuospatial sketchpad (visuospatial WM). The phonological loop stores and rehearses verbal and acoustic information by continuous articulation of its contents, thus creating a rehearsal loop. It is the most well developed component of the model, and is reflected most clearly in the "forward digit span" task where a sequence of digits must be repeated back immediately in the same order as presented. The visuospatial sketchpad can be further broken down into spatial and visual subsystems, the former dealing for example with location, and the latter with shape, colour, and texture. It can be used for constructing and manipulating visual images, and for the representation of mental maps.

In 2000, Baddeley extended the model to include a fourth component; the episodic buffer. He described this as a limited-capacity temporary-storage system that is capable of integrating information from a variety of sources. It serves as an interface between a range of systems, including long term memory (LTM). Each system has its own set of codes; the buffer is thought to use a common, multi-dimensional code (like a master key) in order to

interact with all of them. Like the slave systems it is controlled by the central executive, which is able to retrieve information from it for the purposes of reflection, manipulation and modification. The attention of the central executive is directed consciously, meaning that it can influence the content of the buffer by determining what sources of information are in focus.

Mechanisms of working memory are thought to operate primarily within the PFC (Curtis & D'Esposito, 2003; Funahashi & Kubota, 1994; Goldman-Rakic, 1995; Kane & Engle, 2002; Miller, Erickson, & Desimone, 1996). Note that this is the structure that Diamond (2005) proposed is implicated in PIT. Several key neurotransmitters are thought to underpin WM including DA (Rossetti & Carboni, 2005; Stern, 2009) and NE (Chamberlain, Muller, Blackwell, Robbins, & Sahakian, 2006; Rossetti, & Carboni, 2005). Findings from Rossetti and Carboni (2005) suggest that DA and NE have different roles in facilitating WM; DA is primarily associated with reward expectancy, and NE is key in the active maintenance of goal-relevant information.

There is a wealth of tasks measuring different aspects of WM including the backward digit span, operation span, and reading span task all of which were designed from the perspective of Baddeley and Hitch's (1974) model of WM. All these tasks involve remembering a string of stimuli (i.e. words or number) whilst undertaking some kind of secondary processing, or under conditions of interference. Several tasks developed by Duncan et al. (1996; 2008) purport to assess the episodic buffer component of WM by inducing a type of performance failure called "goal neglect". These tasks differ from the traditional span tasks in that they require representations in WM to be maintained over the course of the task rather than being refreshed in each trial.

Relationships between the three EFs. The close relationship between WM and inhibitory control is such that some researchers would not describe them as separate components. In their two-factor model of executive control, Engle and Kane (2004)

suggest that WM and inhibitory control share the same limited capacity resource. Increasing demand on one affects ability to do the other. Others suggest that inhibition is a behavioural product of WM. In other words, it is the effect of bias towards or amplification of task-relevant information in WM that reduces interference (Egner & Hirsch, 2005; Miller & Cohen, 2001; Munakata, Herd, Chatham, Depue, Banich, & O'Reilly, 2011). In Diamond's model the term WM is used in it's purest form, to mean holding information in mind and working with it. WM and inhibitory control are separate, but support one another (although conversely the arrows in her model imply a unidirectional relationship). Firstly, WM supports inhibitory control by holding our goals in mind. Without this we would not know what information was relevant or appropriate, and what information we should inhibit. By focusing on information held in mind, we increase the likelihood that this will influence our behaviour and therefore limit the likelihood of an inhibitory error. In other words WM acts like a reminder of what we should be focusing on, making us more likely to inhibit what we should not be focusing on. Secondly, inhibitory control supports WM by removing irrelevant or inappropriate distractions, both internally and in our external environment. This increases the likelihood of focus being kept on goals held in WM, and limits the likelihood of mind wandering. Since WM is a limited-capacity resource, we need to keep it from becoming cluttered with irrelevant information. This includes information that was previously relevant (i.e. through resistance to proactive interference).

In Diamond's model cognitive flexibility is described as being a product of WM and inhibitory control. However, other than evidence suggesting this EF develops later in the life-span than the other two (Davidson, Amso, Anderson, & Diamond, 2006; Garon, Bryson, & Smith, 2008), this assertion is not well supported. It does make sense intuitively that set shifting would be reliant on WM and inhibitory control (information for each set needs to be held in mind, and information from irrelevant sets need to be inhibited), but it is more difficult to marry them with the more abstract components of cognitive flexibility

such as openness of thought.

Executive Functions, Self-Regulatory Processes, and "Hot and Cool" Cognition

The executive functions described above are often regarded as "cool" cognitive processes. Tasks used to tap these EFs do not involve reward or cost; there is no requirement to assess gains and losses when making decisions. In contrast to this a second line of inquiry considers the role of "hot" cognition. This type of EF is required for tasks that entail judgments based on utility, or when the affective appraisal of stimuli is involved, and is considered to fall within the remit of the medial prefrontal cortex (particularly orbitofrontal; Diamond, 2013). Zelazo and Muller (2002) describe these top-down control processes as operating in motivationally and emotionally salient contexts; such as those unlikely to occur in a laboratory setting without specific design considerations. The notion being that motivationally salient situations demand different top-down processes to those without an affective element (Zelazo & Carlson, 2012).

A related, but somewhat overlapping, body of literature concerns self-regulatory processes. Broadly defined, self-regulation can be thought of as cognition and behaviours that serve a purpose toward one's goal representations. Carver and Scheier (2004) describe a commonly accepted view of the term as below:

> "When we use the term self-regulation, we intend to convey the sense of purposive processes, the sense that self-corrective adjustments are taking place as needed to stay on track for the purpose being served (whether this entails overriding another impulse or simply reacting to perturbations from other sources), and the sense that the corrective adjustments originate within the person. These points converge with the view that behaviour is a continual process of moving toward (and sometimes away from) goal representations." (In Vohs & Baumeister, 2011, p. 3).

Self-regulatory processes can be thought of as comprising several interlinking facets including cognitive effort, cognitive control, and optimal goal directed behaviour. They are neither strictly "cool" nor "hot" in regards to cognition.

Cognitive Control. This can be defined as the collection of processes that allows the human cognitive system "to configure itself for the performance of specific tasks through appropriate adjustments in perceptual selection, response biasing, and the online maintenance of contextual information" (Botvinick, Braver, Barch, Carter, & Cohen, 2001 p.1). This is strongly related to the "cool" EF concept of inhibitory control, and is assessed in psychological research using tasks from this literature such as Stop-Signal, and Stroop. It is related to processes of "self-control" (the ability to regulate emotions, thoughts and behaviour in the face of temptations and impulses that conflict with our goals), which falls within the remit of "hot" cognition.

Cognitive effort. This can be thought of as allocation of resources to a task or decision. It is heavily influenced by cognitive load along with a myriad of other factors; some "cool" such as task difficulty and knowledge availability, and some "hot" such as motivation and curiosity (Longo & Barrett, 2010). Effort can be assessed in several ways; reaction time tasks that utilise variations in load can gauge the effort required for different conditions, and self-report measures can assess "effortful control", the willingness to engage in an effortful task (Rothbart & Bates, 1998). Frederick (2005) developed a measure useful in assessing cognitive effort, which has its roots in the heuristics and biases literature of Tversky and Kahneman (1974). The Cognitive Reflection Test (CRT) requires that participants override an immediate and incorrect response elicited by the nature of the questions, in order to arrive at the correct answer.

Optimal goal directed behaviour. This refers to behaviours toward maximisation of utility in-line with goal representations. This involves the evaluation of costs and rewards in order to identify strategies that will most efficiently achieve one's goals. Whether this facet of self-regulation would be related to "hot" or "cool" cognition would depend largely on the nature of the goals in question, and whether there was affect and motivation intrinsic to them. Tasks used to assess this usually involve some kind of

strategy in order to assess the utility of decisions made such as the Iowa Gambling task (Bechara, Damasio, Damasio, & Anderson, 1994), and usually involve cost and reward evaluation making them "hot" in nature. Another task specifically designed to assess this is the *diminishing utility task* (DUT), which provides a behavioural measure of the trade-off between "exploiting" known sources of reward and "exploring" for other potentially rewarding opportunities (see below for more detail). The activity of NE is thought to be influential in this facet of self-regulation, due to its role in adjusting gain modulation in appropriate neural circuits related to utility assessment (see below for more detail).

It is difficult to see immediately how self-regulatory processes are different from EFs as previously defined (cognitive processes that guide goal related behaviour) certainly with regard to "cool" cognition, there seems to be considerable overlap. Despite this, historically the literatures on EFs and self-regulatory processes have been treated separately. The term self-regulation has been used primarily in the context of social issues (i.e. Baumeister & Heatherton, 1996), while EF has been studied in relation to cognition. However, it is argued that the two fields would benefit greatly from each other's insights and expertise (Hofmann, Schmeichel, & Baddeley, 2012). Diamond (2013) includes self-regulation in her EF model (see fig 1), and sees inhibitory control as the primary core EF related to it. However, she describes it only in relation to the self-control aspect of self-regulation, and does not justify its relevance to other self-regulatory processes. She also describes a reciprocal relationship between WM and inhibitory control (which is not represented in her model), but neglects to talk about whether/how this EF is implicated in self-regulation. A more comprehensive review is provided by Hofmann et al. (2012), who suggest that EF problems underlie issues with self-regulation, and furthermore postulate that training of EFs could potentially improve poor self-regulation. Particular attention is given to the facilitation of self-regulation through WM, which the authors attribute to three

factors; active representation, executive attention, and goal shielding. Active representation of goal-relevant information in WM refers to the need for goal information to be stored in a readily retrievable form. Such goal-relevant information would typically include a mental representation of the desired end-state, as well as the means by which to get there. Active representations of goal information are essential as a reference point for self-regulatory processes. When representations are kept fresh and accessible over time, goals are able to bias the top-down control of behaviour (Miller & Cohen, 2001). Executive attention is required to direct and re-direct attention back to goal-relevant information so that it can maintain this bias. Studies suggest that the central executive component of WM supports proactive forms of self-regulation by enabling individuals to resist having their attention drawn by distracting stimuli (Friese, Bargas-Avila, Hofmann, & Wiers, 2010; Hofmann et al. 2008). This "spotlight" control of executive attention is suggested to be the primary mechanism by which goals are "shielded" from irrelevant stimuli (Hofmann et al. 2012). Goal shielding is seen as a by-product of sustained attention to a goal or task. This view is supported by research suggesting that a "global shielding mechanism" prevents interfering information from being processed (Dreisbach & Haider, 2009). To the keen eyed this may sound very much like the inhibitory control mechanisms described earlier. Indeed Hofmann et al. (2012) also describe the role of active inhibition (as oppose to the passive inhibition achieved through executive attention) in facilitating self-regulation, i.e. through suppression of unwanted thoughts and emotional reactions. However they also note that active inhibition may be inferior to passive inhibition in achieving successful self-regulation due to its competing demand for resources (Wegner, 1994). Finally, Hofmann et al (2012) acknowledge a role for cognitive flexibility in self-regulation although there is little supporting evidence with regard to this. They suggest that task-switching ability may facilitate evaluations of utility and thus the exploit/explore trade-off discussed previously, by enabling "means shifting"; the pursual of alternative methods to achieve a goal, and

"goal shifting"; the disengagement of a current goal in favour of a new one.

        The tone of the work presented by both Diamond and Hofmann et al. leans towards the same directional relationship between EFs and self-regulatory processes (i.e. EFs underlie self-regulation). This position may have its roots in the work of Miyake et al. (2000) who note that their choice of the three core EFs, while not arbitrary, served a practical purpose in making EF classification less chaotic; they are viewed as relatively basic in comparison to "higher level concepts" (which could include self-regulation). However, there is an argument that self-regulatory processes underlie general executive function. Specifically that NE activity (associated with self-regulation as mentioned above) facilitates WM by acting on the PFC (Arnsten & Li, 2005; Oades et al. 2005; Rosseti & Carboni, 2005). Findings from studies using drugs that act on NE to look at the effects on WM are mixed, but a link between the two has been reported (Chamberlain, Muller, Blackwell, Robbins, & Sahakian, 2006).

        With consideration for the arguments presented here, this thesis primarily takes the stance presented by Diamond, and Hoffman et al. that self-regulatory processes are sub-processes of general EFs. In this view "hot" and "cool" cognition is relevant to both general EFs and self-regulatory processes. This is represented diagrammatically in figure 2 and can be summarised as follows; general executive functions are primarily "cool" processes, while "hot" cognition refers largely to self-regulatory sub-processes of these. However, self-regulatory processes are not exclusively "hot", and general executive functions are seen as facilitating both "hot" and "cool" self-regulatory processes. Self-regulatory processes overlay both "hot" and "cool" cognition in the model, but we make no prediction as to what portion of "hot" cognition relates to self-regulation; this is not well defined in the literature. We also note that there is something of a gap in the literature with regard to "hot" cognition generally, and it could be that there is more overlap between the two "temperatures" than the model gives credit for; it is based on an interpretation of the

literature reviewed above, but is not intended to be definitive. It provides a means of testing the concepts included in relation to ADHD symptoms, the rationale for which is provided by the literature reviewed below.
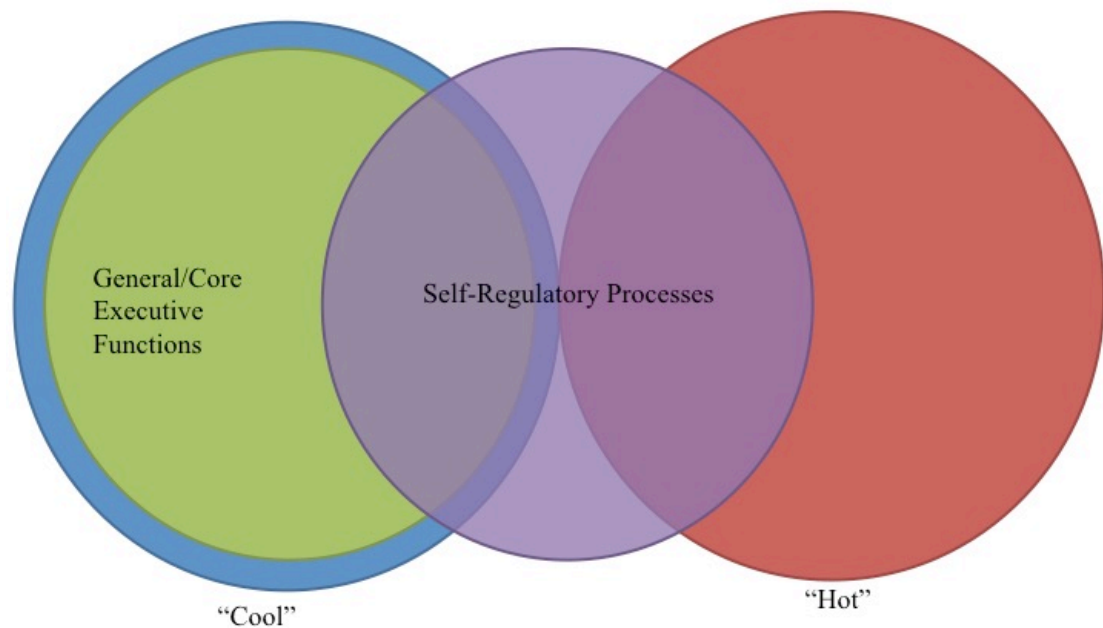
Figure 2. A schematic of the relationships between "hot" and "cool" cognition, general executive functions (working memory, inhibitory control, and cognitive flexibility), and self-regulatory processes based on the views put forward by Hofmann et al. (2012), and Miyake et al. (2000). General executive functions are primarily "cool" processes, while "hot" cognition refers largely to self-regulatory sub-processes of these. However, self-regulatory processes are not exclusively "hot", and general executive functions are seen as being related to both "hot" and "cool" self-regulatory processes, although the direction of this relationship is unclear.

ADHD Symptoms and General Executive Functions

Research on ADHD symptoms and EFs comes in several forms; studies that use general EF tasks (such as the Tower of London test) that cover more than one EF, versus studies that use tasks designed to target specific EFs; studies that consider the different ADHD symptoms versus those that refer to ADHD generally; and child/adolescent versus adult

research. The primary concern for this thesis is research using specific EF tasks that accounts for ADHD subtypes or looks at symptoms dimensionally, using samples of adults. However, it is necessary to consider literature from the other categories, as some of this work is seminal in the field for informing theory and methodology. Perhaps the most influential of these is Barkley's (1997) article "behavioural inhibition, sustained attention, and executive functions: constructing a unified theory of ADHD". Barkley suggests that the symptoms associated with ADHD result from a core deficit in behavioural inhibition. This impairment results in the improper functioning of a variety of intermediate EFs which have a direct effect on behaviour. In Barkley's model behavioural inhibition facilitates the performance of four EFs; working memory, internalization of speech, self-regulation of affect-motivation-arousal, and reconstitution. These directly influence the motor system guiding goal-directed behaviour, as does behavioural inhibition itself. Barkley's model is reasonably well supported in literature, although there are several criticisms (Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Importantly Barkley states his model applies only to the predominantly hyperactive-impulsive and combined subtypes of ADHD, not the inattentive subtype, and supports the notion of inattention as a qualitatively different disorder. Diamond (2005) has suggested that symptoms of inattention are uniquely related to impairments in WM, and that performance on both verbal and visuospatial tasks will be noticeably affected in individuals with the predominantly inattentive subtype of ADHD. A strong relationship between inattention and WM is somewhat intuitive when we consider that the central executive component of WM, and cognitive processes of attention are considered by some as isomorphic. For example, Engle (2002) describes his view of WM capacity as "the ability to control attention to maintain information in an active, quickly retrievable state" (p. 20). He suggests that WM is not just about storing a limited number of items or chunks of information, but about using attention to maintain or supress information. Literature looking at WM and inattention specifically is fairly limited, but

what there is tends to support Diamond's view. In a clinical sample of children, Martinussen & Tannock (2006) found performance on measures of both verbal and visuospatial WM were related to symptoms of inattention, and not to symptoms of hyperactivity-impulsivity. Further supporting evidence comes from the finding that computer training that improved WM performance also produced a reduction in parent-rated symptoms of inattention (Klingberg et al. 2005). In a non-clinical sample Gathercole et al. (2008) found that children with low WM scored highly for inattentive symptoms and were highly distractible. Research with adult participants has had similar findings (Gansler et al. 1998; Kim, 2004), although there are limitations to these studies (see Chapter 4).

ADHD Symptoms and "Hot" vs. "Cool" Cognition

ADHD has traditionally been considered a disorder of "cool" EFs, but it has been proposed that there is a dissociation between the core symptoms; inattention is associated with deficits in "cool" cognition, while symptoms of hyperactivity-impulsivity are associated with "hot" cognition (Castellanos, Sonuga-Barke, Milham, & Tannock, 2006).

Two of the most prominent theories relating to "hot" cognition in ADHD are the *Delay Aversion* model, and the *Cognitive-Energetic* model. The delay aversion model (Sonuga-Barke, 2002) works on the hypothesis that atypical expressions of behaviour in ADHD are driven not by dysfunctional cognition, but by an atypical yet functional underlying motivational style. Quite simply behaviour is driven to avoid or escape delay, often at the cost of acceptable social etiquette. Symptoms of ADHD are seen as the functional expression of this. There is a wealth of evidence showing that children with ADHD prefer small immediate rewards over large delayed ones in a variety of circumstances (Pauli-Pott & Becker, 2011). In line with the hot/cool hyperactivity-impulsivity-inattention distinction, the focus of this model is on explaining hyperactivity-impulsivity. However, findings from Paloyelis, Asherson, and Kuntsi (2009), using a

dimensional approach, suggested that inattention was unique in predicting a preference for small immediate rewards. We are unaware of any research looking at delay aversion in adults with ADHD symptoms. This is probably in part due to the need for any paradigm designed to test it to be highly sensitive, as adults would be likely to override external expression of delay aversion in an experimental situation. The *cognitive-energetic* model (CEM, Sergeant, 2000) was also developed with hyperactivity-impulsivity in mind, and works on the premise that while there may be certain aspects of inhibitory control that are deficient in ADHD, this is also dependent on the energetic state of the subject. The state level of Sergeant's model encompasses three energetic pools. These are "effort" which refers to the necessary energy required to meet task demands and is highly affected by cognitive load, "arousal" which is defined as phasic responding time-locked to stimulus processing and is influenced by salience and novelty, and "activation" which refers to tonic changes in physiological activity associated with readiness to respond.

The latter two pools of the CEM map directly onto the proposed action of the locus-coeruleus norepinephrine (LC-NE) system. The LC synthesises and distributes NE through numerous projections throughout the brain, and, as previously mentioned, NE, and the neural circuitry it acts on, has been linked preferentially to symptoms of inattention. The most comprehensive explanation of LC-NE function is provided by Aston-Jones and Cohen (2005), who describe how it moderates attention through adaptive gain to optimize reward-seeking behaviours. The *adaptive gain theory* (AGT) refines traditional theories of LC-NE function, to describe the specific mechanisms by which the system produces changes in arousal. This view of LC-NE function highlights it's role in optimizing task performance through two overlapping modes of activity; tonic and phasic. LC phasic mode is associated with bursts of activity in relation to task-related decision processes and indicates high levels of engagement. LC tonic mode baseline activity is elevated and phasic bursts are absent indicating distractibility. Optimal performance is thought to occur

with moderate baseline activity (neither too high nor too low), coupled with phasic bursts. Aston-Jones and Cohen propose that the LC-NE system is responsible for online evaluations of utility (i.e. the costs and benefits associated with task-related decisions) provided by input from frontal structures. When utility is low, changes in LC tonic mode facilitate disengagement from the current task in order to explore alternative sources of rewards. This is known as the *exploit/explore trade-off* mentioned above in relation to the "optimal goal directed behaviour" facet of self-regulation. At a neural level this is achieved by the modulating NE release at cortical targets, regulating the gain (responsivity) of processing in cortical circuits responsible for task performance. This adjustment between modes in accordance with utility serves to optimize rewards associated with task performance. Several researchers have predicted dysfunctional LC-NE activity in ADHD (Aston-Jones, Rajkowski, & Cohen, 2000; Howells, Stein, & Russell, 2012; Ressler & Nemeroff, 2001); specifically, that ADHD would be associated with an overly tonic mode of activity coupled with infrequent phasic bursts. This is supported by the finding that the cognition enhancing effects of low doses of methylphenidate probably involve modest alterations in LC discharge (Devilbiss & Berridge, 2006). I am unaware of any work that has investigated LC-NE function in participants with ADHD symptoms. This may be due to the fact that measuring LC-NE activity would involve expensive, complicated, and invasive procedures (i.e. intra-cellular recording). However, evidence supporting the use of pupillometry as a proxy for LC-NE activity has been mounting since a relationship between the two was first identified by Koss (1986). This has been shown using direct neuronal recordings from monkeys while they performed a target detection task (Joshi, Li, Kalwani, & Gold, 2016; Rajkowski, Kubiak, & Aston-Jones, 1993). Larger baseline pupil diameters reflected LC tonic mode and task disengagement, while smaller baseline pupil diameters reflected LC phasic mode and engagement with the task. Task evoked pupillary dilations are thought to be indicative of an LC phasic response to salient stimulus

(Einhauser, Stout, Koch, & Carter, 2008). It is suggested that the LC has projections within the neural circuitry that also controls the muscles of the iris, meaning that activity in the LC-NE system is reflected via an externally observable pupil response (Laeng, Sirois, and Gredeback, 2012). This makes pupillometry an ideal tool for investigating LC-NE activity in ADHD non-invasively.

Summary and Aims

The literature reviewed identifies inattention as potentially being the primary symptom of ADHD relevant to adults. Taking into account research suggesting ADHD symptoms should be treated as dimensional, investigation of this symptom will be relevant to both clinical and community populations. These inferences are addressed in Chapter 2 of the thesis, which is a study conducted to assess prevalence of ADHD symptoms in a community sample. The sample was specifically chosen to represent a population similar to that planned for recruitment in subsequent research. The research in Chapters 3-6 was driven by the five theoretical approaches described in detail above; 1) that the core EF principally and uniquely related to inattention is WM, 2) the proposed relationship between EFs and self-regulatory processes, 3) the potential for a relationship between ADHD symptoms and self-regulatory processes, 4) distinctions between "hot" and "cool" cognition, and 5) theory relating to a hot/cool – hyperactivity-impulsivity/inattention distinction. In Chapter 7 we discuss how the findings collectively support/refute the EF relationships proposed in the Venn diagram above (Figure 2). The main aim of this thesis was to look at the relationships between components of the model with ADHD symptoms, but also, as a secondary aim, to attempt to clarify the relationships between the facets of cognition themselves.

Sample sizes for the research in each of the Chapters reflect the approach and method of analysis used. The prevalence research in Chapter 2 naturally required a large

sample size (555) in order for findings to be generalizable. Sample sizes of similar research in the field vary dramatically but are generally above 400. Chapters 3-5 use regression analysis with the three ADHD symptoms (CAARS t-scores) and IQ as predictors. Using the recommended figures for probability and power (as per Cohen, 1992; .05 and .8 respectively) this requires a minimum sample size of 84, which we adhered to across the three Chapters. The complexity of the research in Chapter 6 determined that a smaller sample size be used. Participants (55) were selected for experimental groups based on DSM ADHD criteria.

Note that while the focus of the thesis is inattention, the approach to it is based on DSM criteria and measurement. It was therefore practical to include and investigate all three symptoms of ADHD in the research, with the aim of demonstrating distinctions between them.

Chapter 2: Prevalence of DSM-5 Inattentive Symptoms in a Community Sample

As previously noted (see Chapter 1), there is a good argument for researching a wider range of ADHD symptom expression than that refined to categorisation through DSM thresholds. The research in this chapter is influenced mainly by the work of Faraone and Biederman (2005) who found prevalence rates for adult ADHD went up significantly when those meeting criteria for sub-threshold diagnosis were included in analysis. However, the research looked at ADHD as a whole, and did not tell us about the prevalence of inattention as a distinct dimension. A further problem with the study was that its diagnostic criteria created the potential for inaccurate diagnosis. The work presented here addresses two main research questions. Firstly, regardless of co-existence with other ADHD symptoms, how prevalent is non-clinical inattention in the general population of adults who have not had a previous diagnosis of ADHD? Secondly, is inattention the most prevalent of the ADHD symptoms in this population?

Abstract

Research suggests that of the three core attention deficit hyperactivity disorder (ADHD) symptoms, inattention may be the most relevant to adults. The present study reports on the prevalence of DSM-5 ADHD symptoms, as well as symptoms meeting a lowered threshold in a community sample of 555 university students (aged 18-35). Participants completed a self-report rating scale of DSM-5 ADHD items, which was used to assess symptoms both categorically and dimensionally. Overall ADHD prevalence was 15.32% for DSM-5 defined symptoms. Although we found no difference in prevalence between the purely inattentive and combined subtypes, results showed that inattention was the most prevalent symptom in the sample. Symptoms were more prevalent in males than females when DSM-5 criteria were applied, but no gender differences were observed when symptoms were scored using a scale. Findings highlight the pervasiveness of inattention in adults and support the idea that this symptom is highly relevant to the general population.

Prevalence of DSM-5 Inattentive Symptoms in a Community Sample

It is estimated that attention deficit hyperactivity disorder (ADHD) extends into adulthood in around 60-70% of cases (Biederman, Mick, & Faraone, 2000; Elliot, 2002; Kessler et al. 2005). In these cases, it is reported that symptoms of hyperactivity and impulsivity decline at a higher rate and at an earlier age, whilst symptoms of inattention are more persistent (Biderman et al., 2000; Helligenstein, Conyers, Berns, & Smith, 1998). It is not surprising then that in clinically referred adults with ADHD, inattentive symptoms were the most prominent (Millstein, Wilens, Biederman, & Spencer (1997), and that adults seeking evaluation for ADHD frequently complain of cognitive and self-regulatory problems (such as difficulty concentrating, poor organization, and forgetfulness), but not those implying hyperactivity (Wolf & Wasserstein, 2001). These findings suggest that inattention dominates the experience of ADHD in adulthood.

DSM-5 criteria state that adults must rate positively for at least 5 items from either or both of the inattention, and hyperactivity-impulsivity (HI) symptom lists (previous editions i.e. DSM-IV, DSM-III, required 6). This allows categorisation into one of three ADHD sub-types; predominantly inattentive (ADHD-I, where criteria for inattention is met and criteria for HI is not met), predominantly hyperactive-impulsive (ADHD-HI, where the opposite is true), and combined type (ADHD-C, where criteria for both are met). Although diagnosis of ADHD is still based on these categorical criteria, it is generally accepted that symptoms are dimensional, and exist along a continuum with clinical cases being at the extreme end of normal expression, meaning that less severe symptoms are present within the general population. Prevalence rates for ADHD in adults go up significantly when participants meeting criteria for a broader definition of the disorder are included in analysis (Faraone & Biederman, 2005; Helligenstein et al., 1998).

Research often uses DSM categorisation for estimating prevalence, with which there are two issues. Firstly, ADHD sub-types are not symptoms, they are diagnoses based on symptoms, so categorisation only tells us about the presence of a disorder, not a symptom. This of course is fine if we just want to know about the prevalence of the disorder, but if we want to look at the prevalence of a symptom i.e. inattention, it needs to be as a distinct dimension, not in relation to it's co-existence with HI.

Secondly, the current criteria can result in misleading diagnosis. For example, according to DSM-5 criteria someone who rates positively for 5 inattention items, and 4 HI items, would be categorised as ADHD-I even though they are only just below the threshold for ADHD-C. If they had been assessed prior to the release of DSM-5 (2013) they would have been considered sub-threshold for diagnosis even for ADHD-I. This may be less of an issue in clinical diagnosis that involves thorough assessment and consideration before diagnosis, but in prevalence studies where brief interviews or questionnaires are used to rate symptoms, it presents a problem. Milich, Balentine, and Lynam (2001) suggest that inconsistencies in the literature may be partly explained by heterogeneity between ADHD subtypes caused by sub-threshold diagnosis. This can be circumvented by categorising "sub-threshold" participants; these participants are then not included in estimates of sub-type prevalence.

There are in fact four ways to score/categorise self-report ratings of DSM ADHD items. *Item counts* score the number of items rated positively (i.e. rated as often or very often) for the inattention and HI lists separately, along with the combined total for both. These scores are used to derive *diagnostic categories* (as detailed above), as well as to determine *symptom presence*, where participants are deemed to show evidence of inattention, HI, or both based on DSM item cut-offs (i.e. it is possible for participants to fall into all three groups). *Summary scores* are calculated as the total of the ratings for each item (items are rated from 0-3) for inattention and HI lists separately, along with the

combined total of both, giving a maximum of 27 for the 9 items in each symptom list (see
Method section for more detail on scoring procedures). A cut-off (of SD +1.5) can be
applied to the item counts and summary scores as an indication of potential diagnostic
threshold. The item counts, symptom presence, and summary scores methods can all be
used to look at dimensional symptom prevalence. To get a comprehensive picture of
prevalence, it is useful to use all four methods as they can produce marked differences in
the observed prevalence and character of a disorder (Helligenstein et al., 1998).

Unfortunately, consistent methodology is lacking in the literature, and as such
estimates of prevalence vary quite substantially across studies. Overall prevalence of
ADHD in adults is thought to be between 1.0 and 7.3% (de Zwaan et al. 2012). Contrary to
what we might expect, several studies have found the ADHD subtype with the highest
prevalence in community samples to be ADHD-HI (Murphy & Barkley, 1996; DuPaul et
al., 2001). However, notably these studies only report data trends, and do not test the
significance of differences between proportions (i.e. using McNemar's test). We are not
aware of any findings pertaining to the prevalence of inattention or HI as independent
symptoms. Although there are studies that have looked at summary scores and item counts
to explore group differences such as age and gender (Helligenstein et al., 1998; Murphy &
Barkley, 1996), their analysis does not extend to answer the general questions of how
prevalent the symptoms are, and which, if either, is more prevalent.

In children ADHD is often thought to be more common in boys, but this may be a
poor reflection of the truth. Some research has suggested there may be differences in the
way ADHD manifests according to gender. It is thought that boys are more prone to the
externalizing symptoms hyperactivity and impulsivity and girls are more likely to have
internalizing symptoms (Gershon & Gershon, 2002), which are less likely to be picked up
resulting in underestimations of prevalence. Findings from research with adults do not
present a strong case for gender differences. Faraone & Biederman (2005) found overall

prevalence of ADHD was greater in males than females, but only when broad definition of symptoms was used. Using the summary scores method Murphy and Barkley (1996) found that males had higher scores for HI (although the authors note the difference was slight), but no differences in inattention or combined scores for self-reports of current ADHD symptoms. They also found no gender differences when looking at item counts. Helligenstein et al. (1998) found no gender differences in either summary scores or item counts, and DuPaul et al. (2001) found no gender differences in ADHD subtype using diagnostic categories, or in item counts.

The aim of the present research was to provide information on the prevalence of ADHD symptoms in adults using revised DSM-5 criteria. We used both broad and narrow definitions of ADHD to estimate prevalence, as well as comprehensive scoring methods that allowed us to look at the symptoms uniquely as well as in traditional diagnostic format.

Method

Participants

555 men (N = 202) and women (N = 353) aged 18-35 (M = 21.19, SD = 4.12) were screened for self-reported symptoms of ADHD. All participants were students at Bournemouth University, and were recruited in several ways; through the Bournemouth University Psychology undergraduate experiment participation scheme, through advertisements at Bournemouth University and on social media sites, and through opportunity sampling by the researcher. Participants came from a variety of courses within the school of Science and Technology including Psychology, Archeology, Forensic Science, Environmental Sciences, Geography, and Industrial Design.

Procedures

Screening for ADHD symptoms was completed using a questionnaire based on the Adult ADHD Rating Scale-IV (Barkley, 2011), but adapted to reflect DSM-5 criteria (see Appendix B). The scale contains the 18 items (9 for inattention, 9 for hyperactivity-impulsivity) from the DSM-5 criteria for ADHD with each item answered on a 4-point scale (from 0-3; *not at all*, *sometimes*, *often* and *very often*). As per DSM criteria, items were taken to be indicative of a symptom if they were rated often or very often (2 or 3); this is referred to as a positive rating.

Participants were asked to read each question carefully and consider to what extent they had experienced each item description over the last 6 months. They completed the questionnaire either in paper or electronic format.

In order to be comprehensive, and to comment on the validity of the methods and the measure as a whole, analysis was carried out using all four scoring methods:

1) Item counts. This refers to the number of items rated positively, and produces three scores. One for each of the subscales (out of 9), and one for the overall questionnaire (out of 18).

2) Diagnostic criteria. Diagnostic groups are derived from the item counts. Participants were categorised as one of the three ADHD subtypes (ADHD-C, ADHD-I, or ADHD-HI), or as either sub-threshold, or control. As previously mentioned, the DSM-5 threshold for symptom presence in adults is a score of 5 items or more rated positively from either or both of the inattention and hyperactivity-impulsivity subscales (referred to as narrow definition.) For this study we also looked at scores of 4 items or more for a broader representation of ADHD symptoms (referred to as broad definition; Helligenstein et al. suggest that cutoff scores of 4 are sufficient to identify symptoms in college students). A score of 2 items or less was taken to indicate no presence. Scores of 3 were treated as sub-threshold for broad-definition. Scores of 3 or 4 were treated as sub-threshold

for narrow definition. For example, by these criteria for narrow definition participants were grouped as ADHD-C if they had at least 5 positively rated items on both sub-scales, as ADHD-I if they had at least 5 positively rated items on the inattention sub-scale and no more than 2 on the hyperactivity-impulsivity sub-scale, and the reverse for ADHD-HI. Participants with positive ratings for no more than 2 items on both scales were categorised as control. Participants were categorised as sub-threshold for one of the ADHD diagnoses if they had 3 (broad) or 3-4 (narrow) positively rated items on either or both of the sub-scales. This method of categorisation means that diagnosis is made in relation to the presence or absence or co-occurring symptoms.

3) Symptom presence. In contrast to the above, this method of categorisation identifies symptom presence regardless of co-occurring symptoms. Participants rate as positive for inattention if they have at least 4 (broad) or 5 (narrow) positively rated items on the inattention sub-scale. This is regardless of whether they also rate positively on the hyperactivity-impulsivity sub-scale.

4) Summary scores. These are summations of the item scores calculated separately for each subscale (out of 27), and for the overall questionnaire (out of 54).

Results

Cronbach's alpha coefficient assessed the internal consistency of item ratings. For the 18 DSM-5 combined ADHD items Cronbach's alpha was .889. When computed after deleting one item at a time results showed no one item strongly influenced the reliability of the total score. The alphas were .856 for the 9 inattention items, and .816 for the 9 hyperactivity items.

Pearson chi-square test was used to compare gender groups on nominal variables, and the McNemar test was used for within-subjects comparisons of nominal variables. Bonferroni adjustments were applied in the case of multiple comparisons.

Distribution of ADHD-like Traits

Histograms representing distributions of summary scores for inattention and hyperactivity-impulsivity sub-scales, and overall ADHD are shown in figure 1. Along with skewness values they suggest a skewed distribution for all three, with more people scoring at the lower end of the scale.

Sample Characteristics

   Diagnostic criteria. Figure 2 shows how each member of the sample was categorised according to ADHD groups for both broad (i.e. 4 or more positively rated items) and narrow (i.e. 5 or more positively rated items) definitions. Close to half of the participants (44.9%) showed no signs of ADHD symptoms (i.e. rated no more than two items as "often" or "very often" on each 9-item DSM subscale). The broad definition categorised a quarter (25%) of participants as "sub-threshold" (i.e. 3 positively rated items) meaning their scores were not strong enough to indicate symptom presence, but not weak enough for them to be categorised as being without symptoms. This increased to 39.8% with narrow definition (i.e. 3-4 positively rated items).

As would be expected, the broad definition produced a higher prevalence of ADHD (any sub-type) than the equivalent narrow definition (30.9% vs. 15.32%, $X^2 = 80.012$, $p < .0001$; see fig. 3). Within this, ADHD-C and ADHD-I were equally common for both broad (14.05% vs. 12.43% $X^2 = .435$, $p < .509$), and narrow (5.59% vs. 8.65%, $X^2 = 3.241$, $p < .072$) definitions. They were also more common than ADHD-HI for both broad (14.05% vs. 3.36% $X^2 = 33.153$, $p < .0001$; 12.43% vs. 3.36% $X^2 = 25.888$, $p < .0001$), and narrow (5.59% vs. 1.08% $X^2 = 15.568$, $p < .0001$; 8.65% vs. 1.08% $X^2 = 31.130$, $p < .0001$) definitions
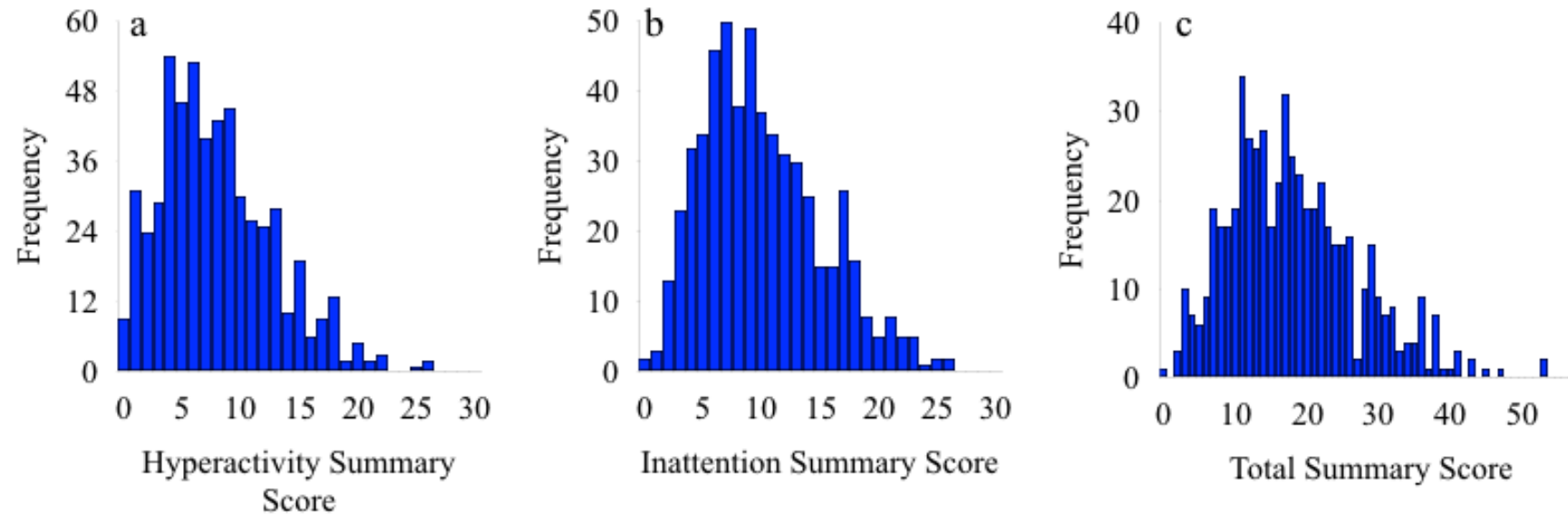
Figure 1. Histograms representing distributions for (a) total summary scores, (b) summary scores for the inattention subscale, and (c) summary scores for the hyperactivity-impulsivity subscale
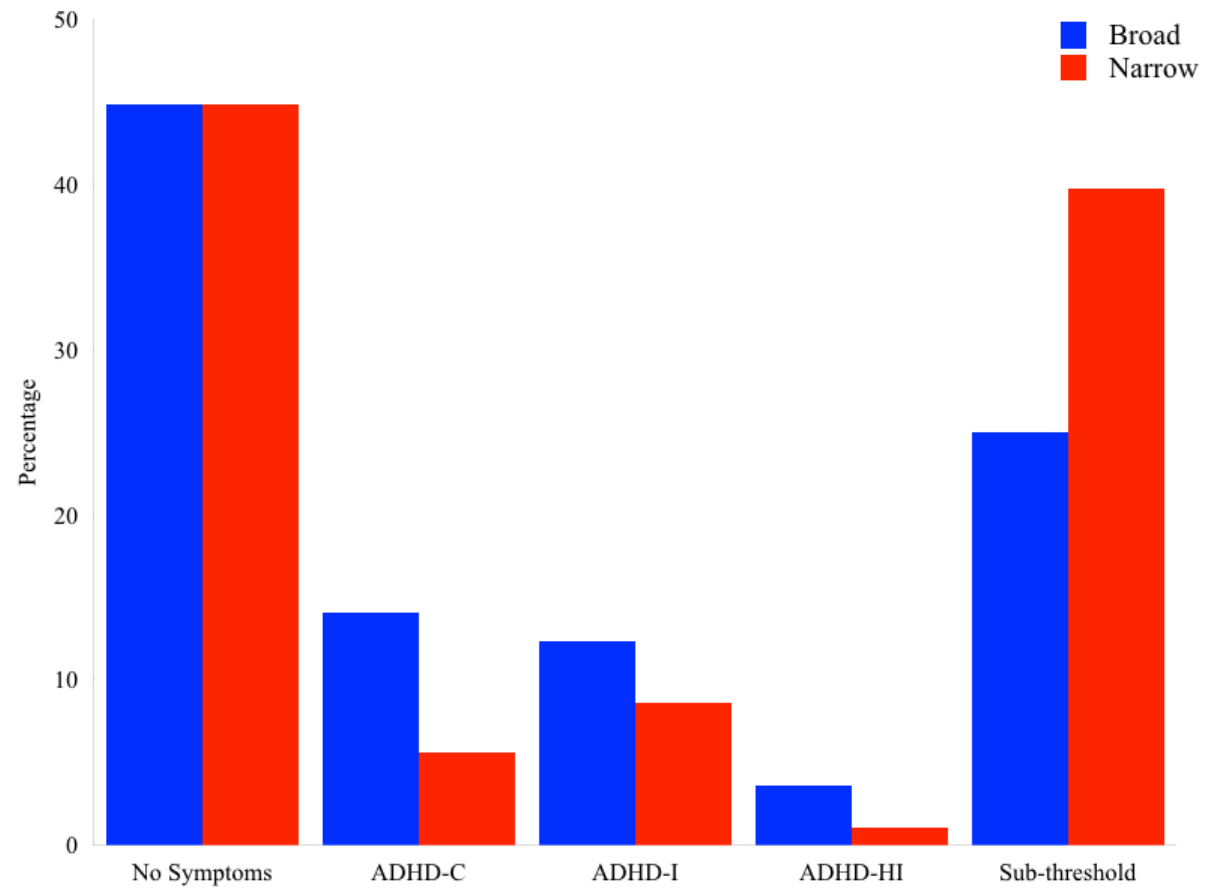
Figure 2. Whole sample category characteristics: percentage of sample in each category for both broad and narrow definition
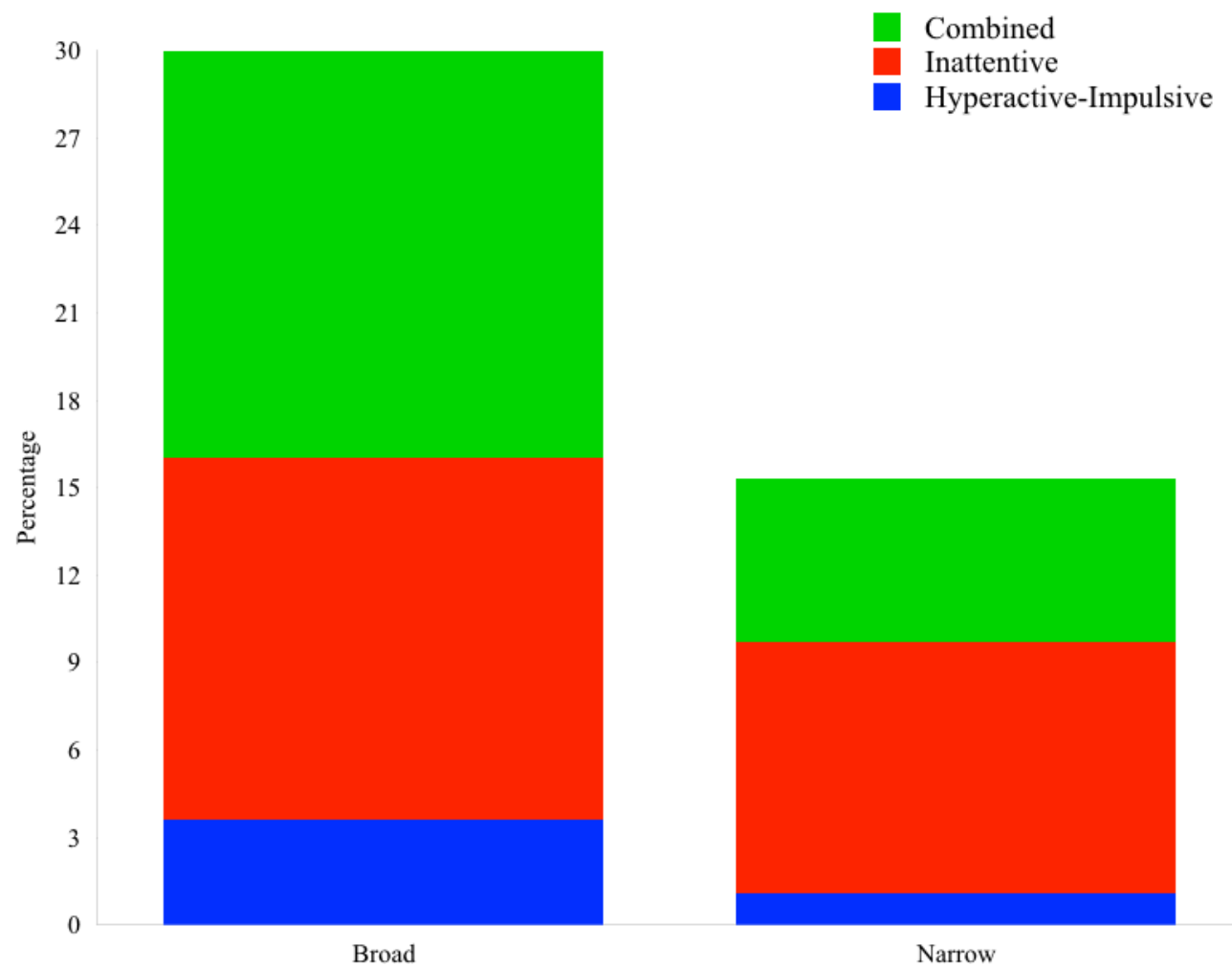
Figure 3. Percentage of sample falling into ADHD diagnostic categories for both broad and narrow definitions

Item counts. Table 1 shows the percentage of people that rated items positively for each symptom. For example, 10.19% of the sample rated 4 out of 9 inattention items positively, and 30.86% of the sample rated 4 or more inattention items positively. Average item counts for inattention were higher than for HI ($t = 6.507$, $p < .0001$).

Table 1

Number of items scored above threshold for the sample

No. of items	Inattention	Cumulative	Hyperactivity-Impulsivity	Cumulative
0	20.06%	100.00%	25.01%	100.00%
1	18.83%	79.94%	25.31%	75.99%
2	16.36%	61.11%	12.96%	49.69%
3	13.89%	44.75%	14.81%	36.73%
4	10.19%	30.86%	9.57%	21.91%
5	8.95%	20.67%	3.70%	12.35%
6	5.23%	11.72%	4.63%	8.64%
7	3.40%	6.49%	1.85%	4.01%
8	2.47%	3.09%	0.62%	2.16%
9	0.62%	0.62%	1.54%	1.54

Symptom presence. For overall symptom presence, the broad definition produced a higher prevalence of symptoms than the narrow definition (39.64% vs. 27.93% $X^2 = 80.012$, $p < .0001$). Within this, inattention was more prevalent than HI for both broadly (32.07% vs. 21.62% $X^2 = 22.88$, $p < .0001$), and narrowly (21.62% vs. 11.89% $X^2 = 22.653$, $p < .0001$) defined symptoms.

Summary scores. Table 2 shows the average summary scores for each scale, along with the +1.5 *SD* cut-off, and the percentage of people scoring equal to or above this. Summary scores for inattention were higher than those for HI ($t_{(554)} = 10.822$, $p < .0001$). More people scored at or above the +1.5 *SD* cut-off on inattention than HI ($X^2 = 66.540$, $p < .0001$). There was a greater proportion of people scoring higher than the cut-off on both inattention and HI than for the overall scale ($X^2 = 225.435$, $p < .0001$; $X^2 = 240.744$, $p < .0001$, respectively).

Table 2.

Means, standard deviations, deviance thresholds (+1.5 SD), and percentage of sample over threshold for summary scores

Scale	Mean	SD	+1.5 SD	% +1.5 SD
Total	18.08	9	32.3	39
Inattention	10.07	5.16	17.81	52
Hyperactivity-Impulsivity	8	4.9	15.35	43

Gender Differences

Diagnostic criteria. Overall prevalence of broadly defined ADHD (any sub-type) was higher for males than for females ($X^2 = 15.125$, *p* < .0001; see fig 4). This was also true for narrow definition ($X^2 = 8.733$, *p* < .0001). Within this, prevalence of broadly defined ADHD-I and ADHD-C was higher in males ($X^2 = 5.646$, *p* = .017; $X^2 = 10.248$, *p* = .001 respectively). The same was true for narrowly defined ADHD-I ($X^2 = 7.168$, *p* = .007), however there were no gender differences in prevalence of ADHD-C when narrowly defined ($X^2 = 3.284$, *p* = .07). There was no gender differences in prevalence for ADHD-HI for either the broad or narrow definitions ($X^2 = .367$, *p* = .545; $X^2 = 1.020$, *p* = .313 respectively).]

Item counts. *T*-tests showed there were no significant gender differences in item counts for either inattention [$t_{(553)} = -1.300$, *p* = .194], hyperactivity-impulsivity [$t_{(553)} = -1.295$, *p* = .196], or the combined scale [$t_{(553)} = -1.487$, *p* = .138; see table 3]. There were also no gender differences observed in the proportions scoring over the +1.5 SD cut-off for inattention ($X^2 = .106$, *p* = .745), hyperactivity-impulsivity ($X^2 = 2.472$, *p* = .116), or the combined scale ($X^2 = 1.102$, *p* = .294.
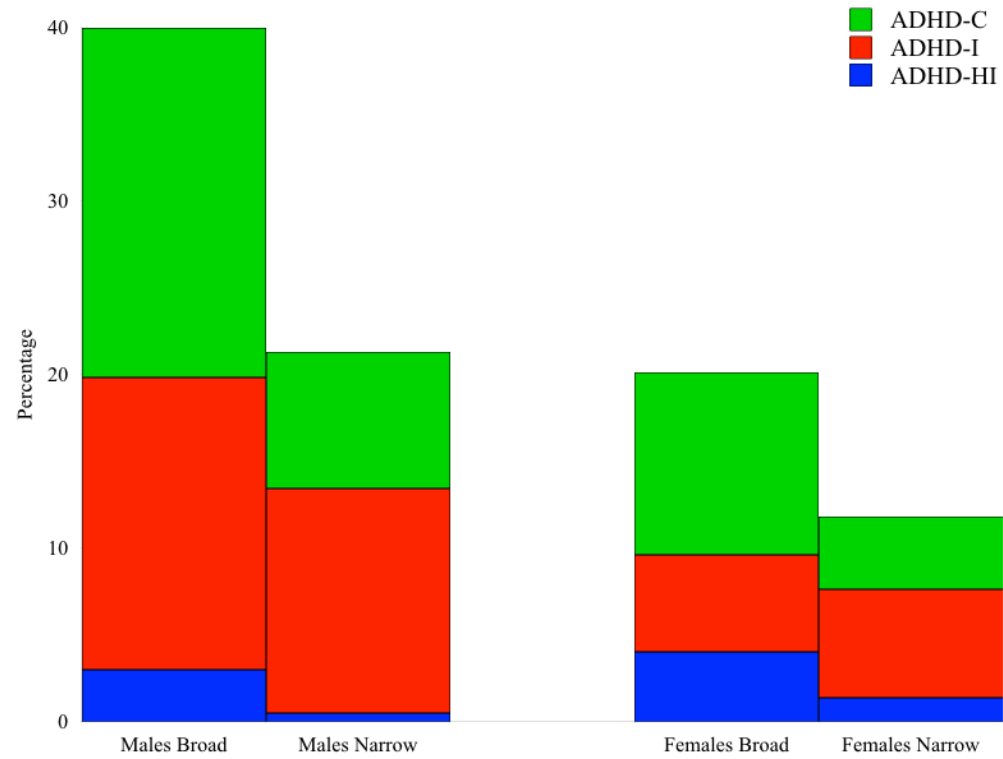
Figure 4. Percentage of sample falling into ADHD diagnostic categories for both broad and narrow definitions across gend

Table 3.

Means and standard deviations for item counts across genders

Scale	Males			Females		
	Mean	SD	% +1.5 SD	Mean	SD	% +1.5 SD
Inattention	2.83	2.49	9.9	2.55	2.44	9.1
Hyperactivity-Impulsivity	2.18	2.05	9.9	1.95	2	6.2
Combined	5.02	3.92	10.9	4.5	3.91	8.2

Symptom presence. Prevalence of both inattentive and hyperactive-impulsive symptoms were higher in males than females when broadly defined (42.1% vs. 26.3%, X^2 = 14.599, p < .0001; 26.7% vs. 18.7%, X^2 = 4.896, p = .027 respectively). This was also true for narrowly defined inattentive symptoms (28.7% vs. 17.6%, X^2 = 9.424, p = .002), but not for narrowly defined hyperactive-impulsive symptoms where there was no gender difference (14.4% vs. 10.5%, X^2 = 1.841, p = .175).

Summary scores. T-tests showed there were no significant gender differences in summary scores for either inattention [$t_{(553)}$ = -.189, p = .850], hyperactivity-impulsivity [$t_{(553)}$ = -1.085, p = .278], or the combined scale [$t_{(553)}$ = -.669, p = .485; see table 4]. There were also no gender differences observed in the proportions scoring over the +1.5 SD cut-off for inattention (X^2 = 1.521, p = .42), hyperactivity-impulsivity (X^2 = 3.116, p = .168), or the combined scale (X^2 = 4.015, p = .105).

Table 4.

Means and standard deviations for summary scores across genders

Scale	Males			Females		
	Mean	SD	% +1.5 SD	Mean	SD	% +1.5 SD
Inattention	10.12	5.46	11.4	10.04	4.99	8.2
Hyperactivity-Impulsivity	8.3	5.29	10.4	7.83	4.67	6.2
Combined	18.43	9.6	9.9	17.88	8.64	5.4

Table 5.

Percentage of positive ratings for each item

Item	Inattention	Hyperactivity-Impulsivity
1	26.5%	54.1%
2	36.9%	4.3%
3	18.6%	18.9%
4	20.7%	25.2%
5	25.4%	28.3%
6	42.9%	22.5%
7	15.1%	15.7%
8	55.3%	22%
9	23.8%	12.6%

Item endorsement

We also examined the rate of endorsement for each of the 18 DSM-5 ADHD items (see Table 5). The item most commonly rated positively on the inattention sub-scale was number 8; "have you been distracted by activity or noise around you?". The item least endorsed on this sub-scale was number 7; " have you lost things necessary for tasks or activities?". The item most commonly rated positively on the hyperactivity-impulsivity sub-scale was number 1; "have you fidgeted with hands or feet, or squirmed in your seat?". The item least endorsed on this sub-scale was number 2; "have you left your seat in situations where you were expected to remain seated?".

Discussion

Overall Prevalence

Prevalence of ADHD when narrowly defined was 15.32%. This may seem high compared to previous estimates, but makes sense in light of the lowered threshold for DSM-5. It is more realistic to compare this figure to the broad estimate of prevalence made by Faraone and Biederman (2005), where criteria were broadened from DSM-IV giving a figure of 16.4%. Even taking into account that this figure is probably at the higher end of what

might be expected from clinician diagnosis, it still suggests that ADHD is quite common in adulthood. Our broad definition of ADHD nearly doubles prevalence to 30.9%, suggesting that lower level forms of the sub-types of ADHD could be present in up to a third of the general population.

We found no difference in prevalence between the subtypes ADHD-I and ADHD-C for either broad or narrow definitions. However, both these subtypes were significantly more prevalent than ADHD-HI for both broad and narrow definitions. This is in contrast to previous findings that suggested ADHD-HI was the most prevalent subtype (DuPaul et al. 2001; Murphy & Barkley, 1996). However, we note that only data trends were reported in these studies. For broad diagnosis (most comparable to our narrow diagnosis), Faraone and Biederman's results are in line with our own. This is also consistent with findings from clinical samples; a meta-analysis of the prevalence of DSM-IV ADHD found ADHD-I to be most the common sub-type in adults, and that prevalence of ADHD-HI diminishes with age past pre-school (Willcutt, 2012).

For overall symptom presence, regardless of co-occurrence, inattention was more prevalent than hyperactivity-impulsivity when both broadly and narrowly defined. Scores for both our dimensional measures (item counts and summary scores), were higher for inattention than HI. There were also significantly more people scoring above the + 1.5 *SD* cutoff thought to represent a clinical threshold, for inattention than HI on summary scores. However, there were no differences between inattention and HI in the proportions scoring above the threshold on item counts. We have no frame of reference to compare these findings; although Murphy and Barkley (1996) look at summary scores and item counts, they do not report equivalent analysis of their data.

Gender Effects

Findings for gender effects were mixed. For both broad and narrow definitions, overall prevalence of ADHD was higher in males than in females. Once again our findings are line with the broadly defined prevalence of ADHD found by Faraone and Biederman (2005). They found no gender differences in narrowly defined ADHD prevalence. This supports the idea that previous DSM thresholds were too high for adult populations, as suggested by Murphy and Barkley (1996). For subtypes, both broadly and narrowly defined ADHD-I was more prevalent in males than in females. Broadly defined ADHD-C was also more prevalent in males, and although not significant the trend was in this direction for narrowly defined ADHD-C also. There were no gender differences in ADHD-HI for either broad or narrow definitions, however we note that a very small number of people fell into the sample for this analysis (3.6% for broad, 1.1% for narrow). When categorised by symptom presence both inattention and HI were more prevalent in males than females when broadly defined, but this was only true of inattention when narrowly defined. However, when symptoms were assessed on a scale, using both item counts and summary scores, no gender differences were evident. This suggests that only when ADHD symptoms are categorised using DSM criteria are gender differences apparent; implying that males would be more likely to be given a diagnosis. This fits with the findings from clinical populations that show ADHD diagnosis is more prevalent in males (Willcutt, 2012).

Item Endorsement

Like Murphy and Barkley (1996), we looked at the rate of endorsement (as "Often" or "Very Often") for each DSM ADHD item. They suggest that a guideline to determine whether an item is developmentally inappropriate is that it should be endorsed by no more than 10% of the population, and note that their data showed many items (12 out of 18) to be over this. In the current work only one item from the list ("have you left your seat in

meetings or other situations where your are expected to remain seated?") was endorsed by less than 10% of the sample. Whether this reflects an over-estimation of self-reported symptoms, or the sheer pervasiveness of ADHD symptoms is unclear. In addition, our data suggests an overall much higher rate of item endorsement than that reported by Murphy and Barkley (1996). We can only speculate that this may be due to differences in sample characteristics such as age range (Murphy & Barkley included older adults), or occupation (our sample was exclusively students).

Limitations

As with other work on ADHD prevalence, our findings are limited in their relevance to the population represented by our sample. Given the research suggesting a relationship between ADHD and academic attainment (Kuriyan et al. 2013), it may be reasonable to suspect that university students would be less likely to have ADHD symptoms simply by the nature of them having made it as far as university. However, although they differ on a number of features including educational attainment, previous work suggests that prevalence of ADHD in university students is generally comparable to other adult samples. Estimates of prevalence of DSM-IV ADHD in university students are between 2-4% (DuPaul et al. 2001; Helligenstein et al. 1998; Weyandt, Linterman, & Rice, 1995). For the inattentive subtype Helligenstein et al. (1998) found a prevalence rate of 2.2%. In a sample of adults renewing their drivers licences Murphy and Barkley (1996) reported a figure of 2.3% for the same subtype. We also note Murphy and Barkley found that scores varied as a function of location (urban vs. sub-urban), and that our sample was collected from an affluent, primarily middle-class area. That said, overall, our findings corroborate those of the two studies with methodologies most similar to our own (Murphy & Barkley, 1996; Faraone & Biederman, 2005), whilst having different sample characteristics.

We also stress, as others have, that results should be considered in light of the self-report nature of data collection, and that this is no substitute for clinical assessment. However we note that Richards, Rosen, and Ramirez (1999) conclude that students with a clinical diagnosis of ADHD have very similar psychological functioning to students with self-reported ADHD. Regardless, it was not our primary aim to estimate prevalence of clinical cases, but to estimate the prevalence of the symptoms of ADHD regardless of diagnosis or co-morbidity.

Conclusion

Our findings highlight the prevalence of ADHD symptoms in the general population, but in particular they highlight the pervasiveness of inattention, and support the idea that inattention is the defining symptom of ADHD in adults. Our data suggest clear gender differences in categorisation of symptoms, in that males are more likely to meet both DSM-5 (narrow) and broadly defined thresholds.

Chapter 3: The Relationship Between Core Symptoms of ADHD and Reasoning in a Non-Clinical sample

The experiment in this chapter makes use of a quick, easy to administer, and readily available task, the Cognitive Reflection Test (CRT, Frederick, 2005). The task is used to assess higher level EFs, such as complex reasoning and problem solving, as well as to tap into the *cognitive effort* component of self-regulation. This simple study was intended as a starting point for looking the relationship between ADHD symptoms and self-regulatory processes.
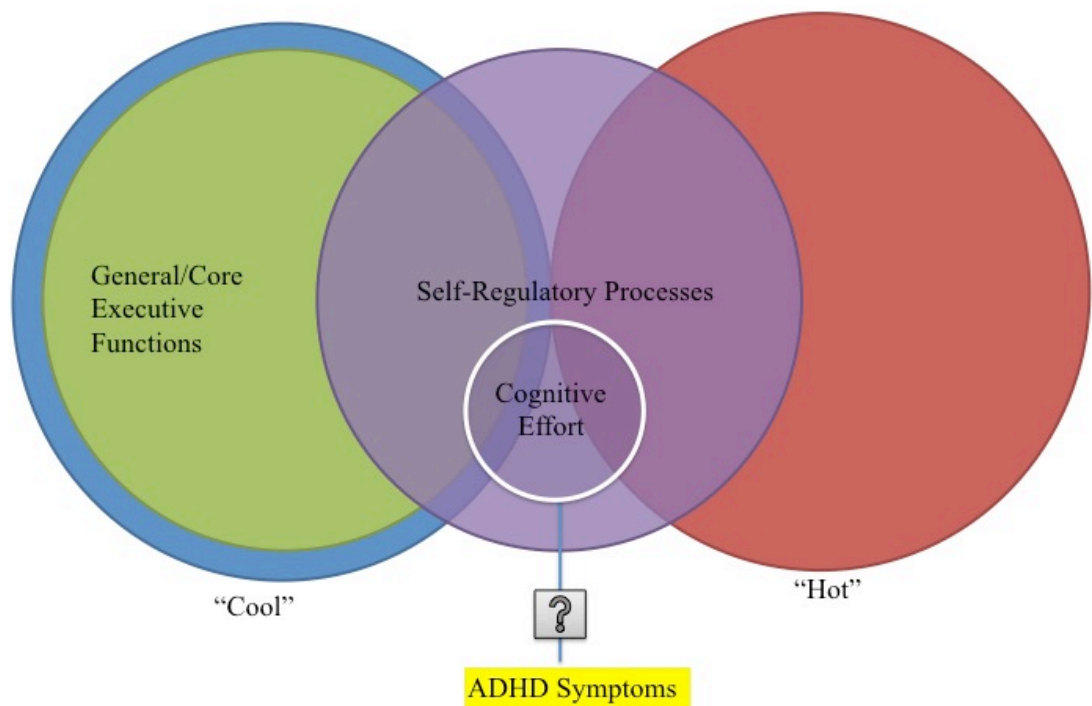
Abstract

Attention Deficit and Hyperactivity Disorder (ADHD) symptoms are frequently linked to executive function deficits. There is reason to believe that these deficits may give rise to problems with complex reasoning and problem solving. 86 men (N = 45) and women (N = 41) completed a self-report measure to assess ADHD symptoms, along with a complex reasoning task; the Cognitive Reflection Test (CRT). IQ was also tested due to its covariance with reasoning ability. Analysis suggested that all three symptoms of ADHD (inattention, hyperactivity, and impulsivity) are negatively related to performance on the CRT, however only inattention significantly contributed to a model that predicted CRT performance. Of the three core symptoms of ADHD, inattention is most important for reasoning ability. Results are discussed in reference to an executive function model of ADHD, with particular emphasis on the role of working memory in inattention.

The Relationship Between Core Symptoms of ADHD and Reasoning

in a Non-Clinical Sample

Attention Deficit Hyperactivity Disorder (ADHD) is a childhood-onset neurodevelopmental disorder with core symptoms of inattention, hyperactivity, and impulsivity. These primary symptoms vary in degree between sufferers of the disorder, which has led to division of ADHD into three subgroups: the combined type (ADHD-C), the predominantly inattentive type (PIT), and the predominantly hyperactive-impulsive type (ADHD-HI).

It is estimated that symptoms of ADHD persist into adulthood in around 60% of cases (Kessler et al., 2006), and that up to 6% of adults may have ADHD (Murphy & Barkley, 1996; Wender, Wolf, & Wasserstein, 2001). The most prominent symptom of adult ADHD appears to be inattention, with the majority of adults having either the predominantly inattentive or combined subtype (Millstein, Wilens, Biederman, & Spencer, 1997). Interest in adult ADHD and its correlates has been growing over the last decade. However little is known about it relative to its childhood manifestation.

Recently, research has supported a shift in approach, from a categorical to a dimensional view of ADHD. Symptoms can therefore be described as existing along a continuum, where, for example, people with clinically diagnosed inattentive subtype (PIT) are at the extreme end (Levy, Hay, McStephen, Wood, & Waldman, 1997; Lubke, Hudziak, Derks, van Bijsterveldt, & Boomsma, 2009). This means the use of a non-clinical sample will be beneficial for analysis of the full range of symptom severity, and for understanding the nature of symptoms within the general population. Furthermore, the benefits of using a non-clinical sample include a break-away from medicated, paediatric populations which allows investigation of symptoms of ADHD independent of developmental delays, general cognitive dysfunction, or history of medication use (Cocchi et al., 2012).

ADHD has been linked to all three core executive functions (EFs); Working Memory (WM), Inhibitory Control, and Cognitive Flexibility (Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Barkley's (1997) theory of ADHD cited inhibitory control as the core deficit for the disorder; however this was stated to be specific only to the ADHD-C and predominantly hyperactive-impulsive (ADHD-HI) subtypes. Recent arguments have put forward working memory as the core deficit in PIT (Diamond, 2005). Evidence suggests that both ADHD-C and PIT have problems with inhibitory control (although there are differences in types of errors) but only PIT has specific problems with WM (Carr, Henderson, & Nigg, 2010; Huang-Pollock, Mikami, Pfiffner, & McBurnett, 2007; Johnstone & Clarke, 2009; Martinussen & Tannock, 2006).

Diamond (2013) lists the three core EFs, along with self-regulatory processes, as part of a system that facilitates complex reasoning and problem solving. Based on Diamond's model, impairments in all or just one of the core EFs would lead to poorer performance on reasoning tasks. ADHD is regularly cited as being linked to difficulties with complex reasoning and problem solving, however, we are aware of very few studies that have investigated these higher-level abilities in ADHD directly (Harrier & DeOrnellas, 2005; Tamm & Juranek, 2012). Indeed, Tamm & Juranek reported poorer performance on a reasoning task in the ADHD group. A question remains, however, as to *which* core symptom of ADHD is more likely to lead to poorer reasoning. Harrier and DeOrnellas found that only PIT and ADHD-C groups had difficulty on a planning and reasoning task, while ADHD-HI children showed no difficulty compared to controls suggesting that inattention may drive the relationship between ADHD and reasoning.

The aim of the present study was to identify which of the symptoms of ADHD is related to performance on a recently established reasoning task; the Cognitive Reflection Test (CRT; originally discussed by Kahneman and Frederick, 2002, and later developed by Frederick, 2005). The test has its heritage in tasks from the heuristics and biases literature

of Tversky and Kahneman (1974) who identified a number of heuristics (roughly described as general rules of thumb), reliance upon which causes predictable biases or systematic errors in reasoning and judgment. Although consisting only of three-items, the CRT was found to strongly predict performance on these earlier tasks (Hoppe & Kusterer, 2011; Toplak, West, & Stanovich, 2011), and other assessments of reasoning ability (Hoppe & Kusterer, 2011; Oechssler, Roider, & Schmitz, 2009) making it a reliable and easy to administer test. In the CRT, participants must coordinate the demands of both comprehension and the manipulation of information, meaning they are constrained by the limited resources of working memory. However, the task is also designed to elicit an immediate and incorrect first response that must be inhibited in order to be successful. Whilst originally thought to be a measure of cognitive effort (Frederick, 2005), recent work suggests that working memory capacity is the strongest predictor of performance on the CRT (Stupple , Gale, & Richmond, 2013). Importantly, the CRT is purported to measure a dimension that is separable from that which is assessed in general IQ tests. Of the limited literature that has looked into ADHD and reasoning abilities, the majority of tasks used are subsets from IQ tests.

It is possible that all three symptoms of ADHD will be related to CRT performance. Impulsivity would seem the most likely candidate, firstly because of the impulsive heuristic response the CRT elicits. Secondly, the inhibition hypothesis of ADHD has already been linked to effort in the context of the cognitive-energetic model (Sergeant, 2000). However a link between working memory capacity and CRT performance has already been established (Stupple et al., 2013). Given this, along with the suggestion that WM is the key EF deficient in PIT, we predict that inattention is likely to be a major factor influencing performance on the CRT.

The current study investigated the relationship between core ADHD symptoms in a non-clinical population and performance on the CRT. We expected that one or more

symptoms of ADHD would be related to, and predict poor performance on, the CRT.

However, based on the relationship that both inattention and CRT performance have to

working memory, it was predicted that the core symptom of inattention would have the

greatest predictive power. Such a finding would suggest that inattention is the most

important factor in potential reasoning deficits in ADHD and that inattention might play a

role in reasoning deficits, beyond IQ, in the general population.

Method

Participants

Ninety participants were recruited for this research. Four participants who disclosed a

diagnosis of ADHD were excluded as the sample was intended to represent the general

population. This left a sample of 86 men (N = 45) and women (N = 41) aged 18-74 years

(M = 23.97, SD = 10.22), who were recruited largely through opportunity sampling. All

participants gave written informed consent to participate in the research, which was

approved by Bournemouth University Ethics Committee.

Materials

Cognitive Reflection Test (CRT). From Frederick (2005). The test is composed of

three items as follows:

(a) A bat and ball cost £1.10 in total. The bat costs £1.00 more than the ball. How much

does the ball cost?

(b) If it takes 5 machines 5 minutes to make 5 widgets, how long would it take 100

machines to make 100 widgets?

(c) In a lake, there is a patch of lily pads. Every day, the patch doubles in size. If it takes

48 days for the patch to cover the entire lake, how long would it take for the patch to cover

half the lake?

In order to answer correctly it is necessary to suppress and/or evaluate the quick intuitive answer that immediately comes to mind (Frederick, 2005). The solution to the bat and ball problem is 5 pence, to the widget problem is 5 minutes, and to the lily pad problem is 47 days.

Weschler's Test of Adult Reading (WTAR). To assess cognitive ability, an intelligence quotient was obtained from the WTAR, which shares normative data sets with the Weschler Adult Intelligence Scale (WAIS) and the Weschler Memory Scale (WMS).

Connors Adult ADHD Rating Scale–Self-Report: Short Version (CAARS-S:S). The CAARS-S:S (Connors et al., 1999) is a 26 item self-report measure designed to assess current ADHD symptoms in adults. Items are rated on a 4-point Likert-type scale, where 0 = *not at all* and 3 = *very much.* The measure contains 5 factor-derived subscales; A: inattention/memory problems, B: hyperactivity/restlessness, C: impulsivity/emotional lability, D: problems with self-concept and E: an ADHD index comprised of items from the other subscales. Scores of 56 or above are described as "elevated", and indicates that further investigation (i.e. full clinical assessment) may be warranted.

Procedure

Each participant was individually administered each test item (test administration order was counterbalanced to control for order effects).

Results

On the CAARS questionnaire 27.91% of participants had elevated symptoms (i.e. a t-score of 56 or above) on the composite subscale for ADHD. For individual symptoms; 45.35% of participants had elevated scores for inattention, 20.93% had elevated scores for hyperactivity, and 15.12% had elevated scores for impulsivity.

Correlations showed WTAR IQ did not have a significant relationship with CRT scores (see Table 1). Of the CAARS questionnaire, only one subset showed a significant

relationship with WTAR IQ, this was Impulsivity (see Table 1.) Reflecting the difficulty of

the CRT, over half of participants (58.1%) failed to get a single correct answer, and only

12.8% got all three questions correct. CAARS subsets for inattention, hyperactivity, and

impulsivity were significantly and negatively correlated with CRT scores (see Table 1).

Table 1.

Correlations between WTAR IQ, CAARS subsets, and Cognitive Reflection Test

	Mean	SD	1	2	3	4	5	6	7
			Pearson Correlations						
1.IQ	110.77	12.83	-						
2.Inattention	56.74	11.43	-0.017	-					
3.Hyperactivity	50.61	9.91	-0.153	.548**	-				
4. Impulsivity	49.36	10.09	-0.214	.461**	.612**	-			
5. Self-Concept	53.75	11.05	0.107	.514**	.353**	.414**	-		
6. Composite	53.61	11.01	-0.90	.731**	.731**	.747**	.688**	-	
7. CRT	0.84	1.12	0.148	-.368**	-.279**	-.246**	-0.146	-.337**	-

*p < .05, **p < .001

To assess the relative input of each ADHD symptom on CRT score, hierarchical

regression was carried out with WTAR IQ included as a covariate[1]. Incidentally, IQ did

not explain a significant amount of variance [($F(1,84) = 2.313$, $p = .174$]. Inattention was

the only of the three symptoms to make a significant contribution to the model (see Table

2.) Neither hyperactivity nor impulsivity explained a significant amount of variance once

inattention had been accounted for, therefore the best model did not include them [$F(2,83)$

$= 8.217$, $p = .001$]. No further investigation was carried out on CAARS subset E, as this

composite measure was accounted for by the other subsets.

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[1]Post-publication regression was repeated using the format followed in Chapter 4 (with
inattention added as the final variable), and did not alter the findings. See appendix C.

Table 2.
Summary of regression for IQ, hyperactivity, impulsivity and inattention on CRT scores.

Variable	b	SEb	β	t	R^2	F for change in R^2
Step 1					0.023	2.066
WTAR IQ	0.013	0.009	0.151	1.437		
Step 2					0.164	14.680**
WTAR IQ	0.012	0.009	0.141	1.436		
Inattention	-0.035	0.009	-0.376	-3.831**		
Step 3					0.169	0.478
WTAR IQ	0.011	0.009	0.13	1.303		
Inattention	-0.03	0.011	-0.327	-2.712**		
Hyperactivity	-0.009	0.013	-0.084	-0.691		
Step 4					0.17	0.159
WTAR IQ	0.011	0.009	0.122	1.203		
Inattention	-0.029	0.012	-0.316	-2.541**		
Hyperactivity	-0.007	0.015	-0.061	-0.444		
Impulsivity	-0.006	0.014	-0.052	-0.399		

**$p < .01$

Discussion

The aim of this study was to relate the core ADHD symptoms to performance on a measure of reasoning ability. The results suggest that all three symptoms were related to performance on the cognitive reflection test. However, only inattention made a significant contribution to a model that predicted CRT performance. Participants with higher scores on the subset for inattention were less likely to be successful on the task. This suggests that even non-clinical symptoms of inattention can affect the tendency to engage in effortful cognition.

There are several explanations for the relationship between inattention and CRT performance. Stupple et al. (2013) found working memory to be a strong predictor of CRT performance and describe it as being essential to success on the task. This executive function has also recently been put forward as the core deficit in PIT (Diamond, 2005). The limited literature on the relationship between inattention and WM in children tends to

support Diamond's view (Klingberg et al. 2005; Lui & Tannock, 2007; Martinussen & Tannock, 2006; Wåhlstedt & Bohlin, 2010), and a study looking at groups with pure hyperacivity-impulsivity and pure inattention in adults, found only those with inattention had a deficit in WM compared to controls (Gansler et al. 1998). We suggest it is likely that working memory deficits associated with even non-clinical inattention, affect the ability to solve the complex reasoning problems of the CRT, however this is an area for further work.

Secondly, the CRT was originally created for the assessment of cognitive effort, and to identify those with a 'miserly' approach to cognition. While it would be inappropriate to describe people with inattentive symptoms as 'miserly', they may be less able to apply the necessary effort for the task, due to self-regulatory and motivational problems. Deficient self-regulation is associated with ADHD and is thought to be a result of EF problems (Barkley, 2001; 2004). Working memory in particular is thought to be essential for successful self-regulation (Hofmann, Friese, Schmeichel, & Baddeley, 2011), and it is suggested self-regulation is strongly linked with attentional control (Fonagy & Target, 2002; Rueda, Posner, & Rothbart, 2005). In light of this it is understandable that those with inattentive symptoms would be most likely to have difficulty with the CRT.

The successful use of a non-clinical sample in this research supports the dimensional view of ADHD symptoms, in that members of the general population report having symptoms (often low levels) of ADHD. Over a third of participants scored above average on the composite measure for ADHD (a T-score of above 56 on the CAARS), not necessarily indicating a need for clinical intervention, but suggesting reasonable prevalence of symptoms in the general population. Interestingly the most prominent symptom in the general population appears to be inattention, with over half of participants scoring above average (but not necessarily at a clinical level) T-scores on the CAARS for this subset.

Symptoms of inattention appear to predict success on the Cognitive Reflection Test, which suggests people with these symptoms may have difficulty with reasoning and problem solving. This is likely explained by the close relationship between attentional control, working memory, and self-regulation. However, further research is required to better understand the nature of this relationship in adults.

Chapter 4: Inattention, Working Memory and Goal Neglect in a Community Sample

Given the theorised relationship between working memory and self-regulation (Hoffman et al., 2012), and between working memory and inattention (Diamond, 2005), this chapter investigated the relationship between various measures of working memory and inattention. Across two experiments both traditional and novel tests of WM are used, and the predictive value of each of the core ADHD symptoms to performance on these is assessed using regression.
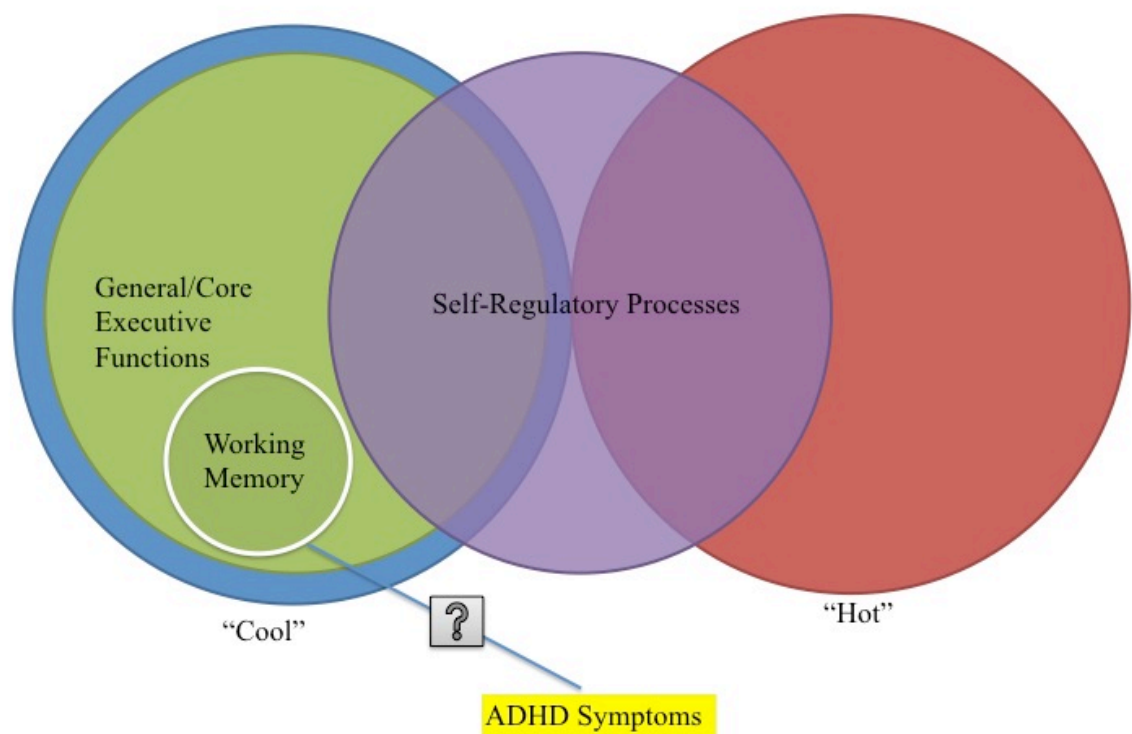
Abstract

Executive function deficits have been linked to attention deficit hyperactivity disorder (ADHD), but it has been theorised that the symptom inattention is specifically related to problems with complex verbal working memory. Using the Conners Adult ADHD rating scale, adults aged 18-35 were assessed for ADHD symptoms, and completed tasks designed to tap verbal and spatial aspects of WM (Experiment 1). Results showed that high inattention predicted poor performance on both simple and complex verbal working memory measures. Results relating to spatial working memory were inconclusive. In a follow up experiment based on the theory that those with inattention have problems receiving verbal instructions, a measure of goal neglect assessing integration of information into a task model in working memory was employed (Experiment 2). Results showed that high inattention uniquely predicted performance on this task, representing the first reported association between inattention and the phenomenon of goal neglect. The results from both experiments lend support to the WM theory of inattention.

Inattention, Working Memory and Goal Neglect in a Community Sample

Inattention is one of three core symptoms characterising attention deficit hyperactivity disorder (ADHD); a childhood onset, neurodevelopmental disorder. It is characterised by an inability to focus, high levels of distractibility, forgetfulness, and poor organisation and planning. The two other symptoms associated with ADHD, hyperactivity and impulsivity, are characterised by excessive energy levels, impatience, and disruptive, often inappropriate behaviour, with a lack of regard for social rules. The Diagnostic and Statistical Manual of Mental Disorders 5th edition (American Psychiatric Society, 2013) lists three presentations of ADHD; the combined type where individuals meet criteria for both inattention and hyperactivity-impulsivity (ADHD-C), the predominantly inattentive type where individuals only meet criteria for inattention (ADHD-I), and the predominantly hyperactive-impulsive type (ADHD-HI) where only hyperactive-impulsive criteria are met.

Most of the existing work on this disorder focuses on participants with combined symptoms, and some of the work makes no reference to subtype at all. It is not possible to draw conclusions specifically about inattention in these cases. This is important, as several authors have argued that ADHD-I is likely qualitatively different from ADHD-C, and should perhaps be considered a disorder in its own right with distinct aetiology, symptoms, comorbidities, and cognitive profile (Barkley, 1997, 2001; Diamond, 2005; Milich, Balentine, & Lynam, 2001). Furthermore, describing pure inattention as ADHD-I is something of a misnomer because of the implied hyperactivity. Therefore in this work diagnosis of the predominantly inattentive type (PIT) will be referred to as such in order to avoid confusion (as in Barkley, 2001). Furthermore, although most commonly associated with ADHD, inattention is not specific to it, and is also a symptom of other disorders such as Autism Spectrum Disorder (Mayes, Calhoun, Mayes, & Molitoris, 2012) schizophrenia (Egeland et al. 2003), and some eating disorders (Seitz et al. 2013), warranting further investigation of this symptom/disorder as an independent entity.

Inattention in Adulthood

For many years ADHD was thought to be a disorder exclusive to childhood, and has only recently been recognised as existing in adults. The latest version of the DSM, released in 2014, was the first to provide specific diagnostic criteria for adults. Longitudinal follow-up studies suggest that ADHD persists into adulthood in around 60% of cases (Elliott, 2002), and that up to 6% of adults may have ADHD (Wender, Wolf, & Wasserstein, 2001). These figures could be even higher when we consider that the diagnostic criteria developed for children has been deemed by many as unsuitable for application to adult populations, and may have resulted in under-diagnosis (Murphy & Barkley, 1996). It is difficult to generalise findings from child research to adults, as the disorder's manifestation appears to differ. Research suggests that symptoms of hyperactivity and impulsivity diminish with age, while inattention persists (Biederman, Mick & Faraone, 2000). It is therefore not surprising that the majority of adults diagnosed with ADHD present with PIT (Millstein, Wilens, Biederman, & Spencer, 1997); the most common complaints being cognitive (e.g. difficulty concentrating, forgetfulness), and self-regulatory (e.g. problems with organisation and planning, poor discipline), none implying hyperactivity (Wolf & Wasserstein, 2001).

Inattention in the General population

Recent research and subsequent debate has led many experts to a shift in approach, from a categorical, to a dimensional view of ADHD symptoms (Barkley & Murphy, 2006). It is suggested that they are better regarded as being at the extreme end of normal expression within the general population. This is supported by the prevalence of symptoms in community samples (Alloway, Elliott, & Holmes, 2010; Faraone & Biederman, 2005). With this in mind, the aim of this research is to explore inattention as a symptom in its own right, as it appears within the general population, rather than one as part of a disorder. As

the majority of work on inattention falls within the ADHD literature, this is necessarily the main frame of reference. However, inattention is the primary focus of this work.

Inattention and Working Memory

Much of the research on ADHD has focused on neuropsychological deficits. This literature has established a reliable link between ADHD and executive functions (EFs) in children (Doyle, 2005; Willcutt, Doyle, Nigg, Faraone & Pennington, 2005), and in adults both clinically, and in community samples, and EF's (Alderson, Kasper, Hudec, & Patros, 2013; Boonstra, Oosterlaan, Sergeant, & Buitelaar, 2005; Hervey, Epstein, & Curry, 2004; Woods, Lovejoy, & Ball, 2002 cf. Johnson et al. 2001; Schoechlin & Engle, 2005). However, this research is largely relevant only to those with hyperactivity-impulsivity (HI). Indeed, Barkley's (1997) influential EF model of ADHD is intended to describe only those with ADHD-C, not PIT. There is however, reason to believe that there may be differences in neuropsychological profile between subtypes (Chhabildas, Pennington, & Willcutt, 2001; Nigg, Blaskey, Huang-Pollock, & Rappley, 2002; Schmitz et al. 2002). Diamond (2005) posits that the defining EF impairment in PIT is in working memory (WM), and that deficits in this particular EF are associated with inattention alone; not hyperactivity or impulsivity. She suggests that *complex-span tasks* i.e. those that require working with information under high interference conditions, will be most sensitive to the WM problems experienced with inattention.

Working memory (WM) has been defined in several ways. All agree that it has a limited capacity, and requires holding information in mind in an active, easily retrievable form, and that it is distinct from short-term memory. Baddely and Hitch (1974) defined WM as holding information in mind combined with some kind of ongoing mental activity. This can mean manipulating the information being held, or performing an entirely separate but simultaneous operation. Another model of WM defines it as the ability to hold

information in mind whilst blocking or inhibiting counter-productive information (Conway & Engle, 1994; Kane & Engle, 2000, 2002). The WM model of Baddeley and Hitch has three components; the central executive, the visuospatial sketchpad and the phonological loop. The central executive is responsible for coordinating attention, and has the use of two "slave systems" for the storage of verbal (phonological loop) and visual/spatial (visuospatial sketchpad) information. Moreover, Baddeley (2000) proposed a further slave system called the *Episodic Buffer* whose role was to integrate phonological, visual and spatial information and has recently been associated with the phenomenon of goal neglect (Duncan, Emslie, Williams, Johnson, & Freer, 1996). In many ways the central executive of WM, and attention, are overlapping constructs; indeed it is sometimes referred to as executive attention. Deficits in WM associated with inattention are therefore thought to be related to this component of the model.

The literature on WM and inattention in children in both clinical and community samples tends to support Diamond's view (Klingberg et al. 2005; Lui & Tannock, 2007; Martinussen & Tannock, 2006). A study that looked at differences in WM performance between the subtypes ADHD-C and PIT in adults, found only weak evidence that PIT may be related to greater impairment (Schweitzer, Hanford, & Medoff, 2006). However without an ADHD-HI group to compare to, it is difficult to ascertain the role of inattention in any impairment, as both groups performed significantly poorer than normal controls. A study comparing ADHD-HI and PIT groups of adults found only the participants with PIT had a deficit in WM compared to controls, however group sizes were notably small (Gansler et al. 1998). In a non-clinical sample of adults, Kim (2004) found inattention was predicted by verbal WM performance. Other research on non-clinical inattention in adults has found inattention to be the only symptom of ADHD to predict performance on a reasoning task strongly correlated with WM (the Cognitive Reflection Test; Elisa & Parris, 2015, see Chapter 3; Stupple, Gale, & Richmond, 2013).

There is also the question of whether the impairment is with a specific type of WM. Diamond writes that verbal presentation of material places a particularly high demand on WM, and that children with PIT often have superior spatial skills. This would suggest that the key problem may be with verbal WM. However, research testing combined-type or ADHD samples of children and adults without mention of subtypes has produced mixed findings. Several studies have found an impairment in spatial WM (Dowson, et al. 2004; Westerberg, Hirvikoski, Forssberg, & Klingberg, 2004). Others have found specific impairments in verbal WM (Marchetta, Hurks, Krabbendam, & Jolles, 2008; Seidman, Biederman, Weber, Hatch, & Faraone, 1998). Two meta-analyses found impairments across both types of working memory (Kasper, Alderson, & Hudec, 2012; Martinussen, Hayden, Hogg-Johnson and Tannock, 2005; see also McInnes, Humphries, Hogg-Johnson, & Tannock, 2003). In a non-clinical sample of children, Lui and Tannock (2007) found composite WM including verbal and spatial measures predicted parent-rated inattention (but not hyperactivity-impulsivity). The mixed findings and lack of consideration for ADHD subtypes in some of these studies makes them difficult to interpret for present purposes.

The present research was designed to test Diamond's hypothesis that inattention, but not hyperactivity or impulsivity, would be associated with impairments in performance on a complex, but not a simple, verbal WM task. Given the putative dimensional nature of inattention and other ADHD symptoms, we tested a community sample of adults. We are not aware of any prior research that has looked at complex vs. simple WM tasks in relation to either clinical or non-clinical ADHD symptoms. Furthermore, we employed a variety of tests of WM capacity. Experiment 1 employed traditionally used measures of WM capacity, specifically the Backward Digit Span task and the Operation Span (OSPAN) task (Turner & Engle, 1989) to represent both simple and complex-span varieties, respectively.

We predicted that inattention but not hyperactivity or impulsivity would explain unique variance on the OSPAN task, but that a relationship may not be evident between inattention and performance on the backward digit span task. Although the literature does not lead to a strong prediction, in line with Diamond's point on the importance of verbally presented material, we expected that inattention may not explain variance in a spatial WM task. The Corsi blocks task (Corsi, 1973) was used to assess spatial WM span.

Experiment 1

Method

Participants

Ninety-five males (N = 30) and females (N = 65) aged 18-35 years ($M = 21.46$, $SD = 4.19$) were recruited for this research, largely through opportunity sampling. The majority of participants were psychology students from Bournemouth University, who collected course credits for their time. None of the participants had an existing ADHD diagnosis. All participants gave written informed consent to participate in the research, which was approved by Bournemouth University Ethics Committee.

Materials

ADHD symptoms. *Conners Adult ADHD Rating Scale–Self-Report: Short Version (CAARS-S:S; Conners et al., 1999).* This is a 26 item self-report measure designed to assess current ADHD symptoms in adults. Items are rated on a 4-point Likert-type scale, where 0 = *not at all* and 3 = *very much.* The measure contains 4 factor-derived subscales; A: inattention/memory problems, B: hyperactivity/restlessness, C: impulsivity/emotional lability, D: problems with self-concept, as well as E: an ADHD index comprised of items from the other subscales. For each subscale, a *T*-Score is derived. Guidelines suggest that a *T*-score of 45-55 is average for adults (using data from a normative sample). Scores range

from 29-90. A *T*-score of above 65 is considered to be indicative of clinically elevated symptoms.

Working memory span tasks. *Backward Digit Span (BDS).* This is a test of verbal working memory, and requires participants to maintain information online while mentally manipulating that same information. Participants were presented with series of digits spoken verbally by the experimenter. After presentation of each series, participants were instructed to verbally repeat the numbers back to the experimenter in the opposite order to presentation. Series consisted of 2 to 8 digits with two trials for each length. Testing stopped after both items of a trial were failed or all trials were completed. One point was awarded for each correct trial, giving a maximum possible score of 14.

Operation Span (OSPAN; Turner & Engle, 1989). This task also tests verbal working memory, and requires participants to hold information online while intermittently processing unrelated information. Participants were shown a series of operation-word strings (ranging from two to six in length) presented on a computer. . These consisted of simultaneously presented mathematical equations, and unrelated words to be recalled, for example:

$(9/3) + 2 = 5$? Beach

Participants were instructed to read the equation and indicate by key press whether the answer presented was correct or not. Operation-word strings were presented for 5000ms each regardless of key press. After answering, they were told to then read the word aloud. This continued until the end of the set at which point participants were asked to recall and type in all the words from that set. Three sets of each length were presented, and appeared in an unpredictable order so that the number of words to recall was unknown until recall.

A partial-credit unit scoring (where each item is scored as a proportion of correctly recalled elements per item, regardless of item size) method was used for this test as

recommended by Conway, Kane, Bunting, Hambrick, Wilhelm and Engle, (2005), and Redick and Lindsey (2013). This gave scores that ranged from 0-100.

Backwards Corsi Blocks (Corsi, 1973). This version of the traditional measure of visuospatial working memory was taken from the Psychology Experiment Building Language (PEBL) battery of tests. Participants viewed a series of blocks lighting up on screen and were required to reproduce the order they were lit in by mouse click on the correct blocks. Each trial began with a "READY" screen presented for 500ms. This was followed by the block presentation; each block in the trial lit up for 500ms. The next screen showed all the blocks and required participants to click the order from the previous screen and then click done. A screen showing "correct" or "incorrect" was then presented for 500ms. Series were 2 to 8 blocks in length with two trials for each length. Testing stopped after both items of a trial were failed or all trials were completed. One point was awarded for each correct trial, giving a maximum possible score of 14.

Intelligence quotient (IQ). A shortened version of the Wechsler Abbreviated Scale of Intelligence (WASI-II) was administered. This consisted of vocabulary and matrix reasoning subsets so that a score for both crystallized (Gc) and fluid intelligence (Gf) was obtained. From this measure a t-score for each relevant subscale (Gf & Gc) is calculated, and an approximate overall IQ score is obtained from an age-matched set of scores.

Procedure

Each participant was individually administered each test item alone, in a quiet testing room. Test administration order was counterbalanced.

Data Analysis

Relationships between variables were firstly analysed using correlation. To assess the unique predictive value of inattention on the two verbal WM tasks as per Diamond's

hypothesis, hierarchical regressions were carried out. For both, working memory scores served as the criterion, and ADHD symptoms (along with IQ for control purposes) were added as the predictors. This was to enable us to look at the variance accounted for by inattention when hyperactivity and impulsivity were already in the model rather than to imply any direction in the relationship.

Bayes Factors (B) were used to assess the strength of evidence in support of hypotheses where the p value indicated no significant result. These were calculated using the procedures outlined in Dienes (2014). Proposed cut-offs for acceptance of a hypothesis (Jeffreys, 1998), states a B above 3 as providing substantial support for the alternative hypothesis, whilst below 1/3 provides substantial support for the null hypothesis. A B that falls between 1/3 and 3 deems the data insensitive as to whether the alternative or null hypothesis should be accepted. We modelled the predictions of the theory of an absence of evidence for a relationship with a half-normal whose mean and standard deviation values were for the variable inattention in the backward digit span analysis. $B_{H(0, X)}$ refers to the Bayes Factors testing each hypothesis, where 'H' indicates a half-normal distribution, and 'X' the predicted standard deviation of this half-normal, against a null hypothesis of no difference.

Results

On the CAARS questionnaire 24.21% of participants had elevated symptoms (i.e. a t-score of 60 or above) on the composite subscale for ADHD. For individual symptoms; 32.63% of participants had elevated scores for inattention, 15.79% had elevated scores for hyperactivity, and 12.63% had elevated scores for impulsivity. Means, standard deviations, and ranges for each subscale are presented in Table 1.Means, standard deviations, and ranges for each WM test are presented in Table 2.

Correlations (see Table 3) showed fluid intelligence (Gf) score was related to performance on backward digit span score (p = .007), and Corsi blocks score (p < .001), but not OSPAN score (p = .193). Neither aspect of IQ was related to any of the ADHD subscales (ps > .05). The accuracy scores on the OSPAN task were positively correlated with the average scores for memory on the same task (r = .316, p = .002), which is typical for this task. Scores on the two verbal working memory tasks were positively correlated with each other (p < .001), but neither was correlated with performance on the Corsi blocks task (ps > .05).

Table 1

Mean scores, standard deviation, and range for each CAARS:S:S subscale

	Mean	SD	Range
Inattention	54.07	10.68	35-77
Hyperactivity	49.67	10.61	29-78
Impulsivity	47.85	8.65	34-74
ADHD Index	51.44	10.53	31-80

Table 2

Mean scores, standard deviation, and range for each WM test

	Mean	SD	Range
Backward Digit Span	8.83	2.23	5-14
Operation Span	83.59	10.64	52.13-98.97
Corsi Blocks	9.02	1.9	4-14

A significant negative relationship was found between scores for inattention and performance on the two tasks assessing verbal WM; backward digit span (p = .001), and OSPAN (p = .017), but not for the spatial span task. Contrary to predictions, significant negative relationships were also found between scores for impulsivity, and performance on the backward digit span (p = .024), and Corsi blocks (p = .024) tasks. No relationships were found between hyperactivity and any of the WM tasks (ps > .05).

As expected, IQ was a significant contributor to variance in backward digit span score (p = .028, see table 4). Bayes values suggested that hyperactivity made no contribution to

the model ($p = .225$, $B_{H(0, .25)} = 0.28$), while data for impulsivity were insensitive ($p = .104$, $B_{H(0, .25)} = 1.03$). Only inattention explained a significant amount of variance in backward digit span scores when all other variables were accounted for ($p < .001$).

Analysis for the OSPAN task was conducted in the same way (see table 5). In contrast to the findings for backward digit span, analysis suggested that data for IQ were insensitive [$F(1,93) = .069$, $p = .793$, $R^2 = .001$, $B_{H(0, .25)} = 0.47$], as was the case for the ADHD symptoms hyperactivity and impulsivity ($p = .401$, $B_{H(0, .25)} = 0.86$; $p = .427$, $B_{H(0, .25)} = 1.28$ respectively). The inclusion of inattention did improve the model, although p is just shy of significance. However, the B suggests that there is evidence for the alternative hypothesis ($p = .064$, $B_{H(0, .25)} = 4.66$), and so it is interpreted as significant. Although correlations suggested inattention might not be a good predictor of Corsi blocks performance (and that perhaps impulsivity might be), regression was carried out in the same manner for this working memory task (see table 6). This enabled us to make direct comparisons regarding the variables across all three WM tasks. IQ was a good predictor ($p < .001$), as was impulsivity ($p = .045$). Analysis suggested that hyperactivity made no contribution to variance on this task ($p = .337$, $B_{H(0, .25)} = 0.17$). The data for inattention were insensitive ($p = .337$, $B_{H(0, .25)} = 0.39$).

Table 3

Correlations between IQ, CAARS subsets, and working memory scores

	Mean	SD	Pearson Correlations							
			1	2	3	4	5	6	7	8
1. IQ Gc	51.79	7.69	-							
2. IQ Gf	47.77	8.83	0.131	-						
3. Inattention	53.85	11.26	0.142	0.139	-					
4. Hyperactivity	49.38	11.31	0.031	0.092	.653**	-				
5. Impulsivity	47.55	9.38	0.057	-0.07	.646**	.737**	-			
6. Digit Span	8.83	2.23	0.081	.251*	-.329**	-0.101	-.204*	-		
7. Ospan	83.59	10.64	0.05	-0.09	-.217**	-0.09	-0.12	.379**	-	
8. Corsi Blocks	9.02	1.9	-0.006	.491**	-0.087	-0.059	-.204*	0.121	0.044	-

*p < .05, **p < .01

Table 4

Summary of regression for IQ, hyperactivity, impulsivity, and inattention on Backward Digit Span scores.

	Variable	b	SEb	β	t	R^2	R^2 change	Semi-partial correlation
Step 1						0.051	.051*	
	IQ	0.044	0.02	0.225	2.226*			
Step 2						0.066	0.015	
	IQ	0.047	0.02	0.237	2.337*			0.235
	Hyperactivity	-0.024	0.02	-0.124	-1.222			-0.123
Step 3						0.093	0.027	
	IQ	0.043	0.02	0.216	2.139*			0.214
	Hyperactivity	0.012	0.03	0.058	0.391			0.039
	Impulsivity	-0.058	0.035	-0.244	-1.641			-0.164
Step 4						0.218	.125**	
	IQ	0.058	0.019	0.293	3.036*			0.283
	Hyperactivity	0.047	0.029	0.237	1.606			0.15
	Impulsivity	-0.012	0.035	-0.049	-0.328			-0.031
	Inattention	-0.1	0.026	-0.505	-3.793*			-0.354

*p < .05, **p < .001

Table 5

Summary of regression for IQ, hyperactivity, impulsivity, and inattention on OSPAN

Variable	b	SEb	β	t	R^2	R^2 change	Semi-partial correlation
Step 1					.001	.001	
IQ	-.026	.098	-.027	-.263			
Step 2					.008	.008	
IQ	-.018	.098	-.019	-.844			-.019
Hyperactivity	-.083	.098	-.088	-1.222			-.088
Step 3					.015	.007	
IQ	-.028	.099	-.029	-.279			-.029
Hyperactivity	.004	.147	.004	.028			.003
Impulsivity	-.141	.176	-.124	-.799			-.083
Step 4					.052	.037	
IQ	.012	.100	.012	.117			.012
Hyperactivity	.095	.153	.101	.624			.064
Impulsivity	-.020	.185	-.017	-.106			-.011
Inattention	-.259	.138	-.275	-1.875*			-.192

*B = substantial support for hypothesis

Table 6

Summary of regression for IQ, hyperactivity, impulsivity, and inattention on Corsi Blocks

	Variable	b	SEb	β	t	R^2	R^2 change	Semi-partial correlation
Step 1						0.129	.129**	
	IQ	0.06	0.016	0.359	3.708**			
Step 2						0.138	0.009	
	IQ	0.062	0.016	0.368	3.781**			0.366
	Hyperactivity	-0.016	0.016	-0.094	-0.966			-0.094
Step 3						0.175	.038*	
	IQ	0.058	0.016	0.344	3.566**			0.34
	Hyperactivity	0.02	0.024	0.121	0.851			0.081
	Impulsivity	-0.058	0.029	-0.289	-2.035*			-0.194
Step 4						0.179	0.004	
	IQ	0.06	0.107	0.357	3.605**			0.344
	Hyperactivity	0.025	0.025	0.151	1.001			0.096
	Impulsivity	-0.052	0.031	-0.256	-1.685			-0.161
	Inattention	-0.014	0.023	-0.085	-0.62			-0.059

*p < .05, **p < .001

Discussion

The aim of this experiment was to test the hypothesis that symptoms of inattention, but not hyperactivity-impulsivity, are associated with lower performance on verbal working memory measures, particularly a complex-span task, and that this relationship is evident in a community (non-clinical) sample. Findings provide partial support for this hypothesis; inattention predicted unique variance in performance on two measures of verbal WM; the backward digit span task, and the OSPAN task. However, only the latter is a complex span task indicating that the secondary processing element is not likely to be a factor determining this relationship. Findings regarding hyperactivity and verbal WM were mixed. For the BDS task, there is evidence to suggest hyperactivity makes no contribution to performance, however we cannot be confident of the same for the OSPAN task as the Bayes value suggests the data were insensitive. We are also unable to draw conclusions regarding impulsivity and verbal WM as Bayes values fell within the insensitive range for both tasks. Conversely, impulsivity significantly predicted performance on the Corsi blocks task, but we are unable to draw conclusions regarding inattention for this task as the Bayes value fell within the insensitive range. However, analysis suggests we can have confidence that hyperactivity does not contribute to performance on Corsi blocks. Since relationships were identified between the WM tasks and at least one ADHD symptom we can be sure there is sufficient power to detect such relationships. Overall, our data permit us to conclude that: 1) inattention is related to verbal working memory; 2) impulsivity is related to spatial working memory; 3) hyperactivity is not as likely to be related to the WM tasks employed in the present study.

The findings converge with previous work that has demonstrated a relationship between inattention, and performance on the backward digit span task in child (Lui & Tannock, 2007), and adult (Kim, 2004) general population samples. However, our findings do not support the idea that *complex-span* tasks are any better at elucidating the cognitive

problems experienced in PIT than simple-span tasks, as performance on both the OSPAN and BDS tasks was predicted by inattention. This finding contributes to the debate as to whether the secondary element must present new stimuli to be processed (as in OSPAN), or whether mental transformation of the target memory items (as in BDS) is enough to constitute a WM task.

There is no doubt that the backward digit span task is more difficult than the forward version which requires only serial repetition of the numbers presented, but equally it is reasonable to consider the OSPAN task to be more difficult than the BDS task, not only because of its dual-processing element, but because of the mathematical demands the secondary part of the task poses. Research by Engle, Tuholski, Laughlin, and Conway (1999) suggests that an interference component is a necessary element to a WM task. Using factor analysis they found the backward span task grouped with short-term memory, rather than complex-span WM tasks, suggesting that mental transformation of target information is not enough. However, Oberauer, Süß, Schulze, Wilhelm and Wittmann (2000) found no distinction between tasks involving simple transformation, and those falling into the complex span category. Further exploration suggested the ability to resist interference, or coordinate dual streams of information in complex-span tasks, does not necessarily reflect working memory capacity (Oberauer, Lange, & Engle, 2004). Our data suggest that in terms of inattention, a simple-span task is sufficiently demanding. This is even more important when considering that the present sample were not from a population with clinical diagnoses.

Diamond (2005) suggests that verbal presentation of material to children with PIT should be avoided, as it places particularly high demand on WM. She also suggests that PIT is often associated with superior spatial skills in a trade-off with linguistic skills, although we are not aware of any empirical evidence for this. Some take the view that there is no distinction between the processes used in verbal and spatial WM (Conway et al.

2005; Jones, Farrand, Stuart, & Morriss, 1995; Kane et al. 2004). As previously

mentioned, findings relating to ADHD and spatial working memory are mixed. Studies

making use of the Corsi Blocks task as a spatial working memory measure with child

participants have found no relationship between performance and inattention (Geurts,

Verté, oosterlaan, Roeyers, & Sergeant, 2005; Scheres et al. 2004). However, it is worth

noting that while these studies may have had non-significant p-values, without tests for the

strength of evidence for the null (e.g. Bayes), a conclusion that there is no relationship is

premature. Other research has observed a relationship between combined type or

unspecified ADHD and spatial working memory using the Corsi Blocks and similar tasks

(McInnes, Humprhies, Hogg-Johnson, and Tannock, 2003; Sowerby, Seal & Tripp, 2011;

Westerberg, Hirvikoski, Forssberg, & Klingberg, 2004). Unfortunately, findings from the

present study are not able to contribute to this debate with regard to inattention, as we

cannot confidently comment on its role. However, our results do suggest that impulsivity is

moderately correlated with Corsi blocks performance, and that it is a significant predictor

of performance. Impulsivity is therefore a likely contributor, and potentially sole generator,

of the relationship between ADHD and spatial working memory reported in the literature.

Conclusions drawn from the present data should be considered in light of some

potential methodological issues. Firstly, it should be noted that the Corsi blocks task is not

always regarded as a measure of working memory. Since the task has no concurrent

processing demands, it is regularly used as a measure of simple storage. This might be

responsible for the inconclusive results found in the present work. The task was used to

assess spatial working memory in this study on the grounds that when the sequence to be

recalled becomes longer than 3 or 4 items, so that memory load increases, central

executive resources are called upon (Vandierendonck, Kemps, Fastame, & Szmalec, 2004).

Also, along with similar tasks, it has been widely used as a spatial working memory

measure in research on ADHD symptoms (see above). However, we concede that there may be better measures of SWM, and that these might be more sensitive to variation.

Secondly, we note that participants in the current study found the mathematical component of the OSPAN task very difficult; more so than is usually observed in this task. Turner and Engle (1989) propose that the difficulty of the secondary task needs to be demanding enough to engage WM processes and reveal individual differences in task performance, but not be so difficult as to produce floor effects. Conway et al. (2005) recommend discarding data from participants who score less than 85% accuracy on the processing component of a task; accuracy is expected to be near ceiling. However, in the current study over 80% of participants failed to meet this criterion. The 5-second time limit to solve and answer the problem and read the word aloud should not have been an issue, as this was based on the average time to complete these operations found by Unsworth, Heitz, Schrock, and Engle (2005) in a sample of 296 students. The complexity of the equations themselves was no more difficult than standard versions of the task. Additionally, distribution of IQ scores in our sample was normal. Therefore, we can only speculate as to why this was, and say that further work on complex-span tasks and inattention is needed.

Experiment 2

The present study has so far provided support for the hypothesis that deficits in verbal WM are associated with inattention. The work also supports the idea that deficits associated with ADHD continue into adulthood, and that there are implications for un-diagnosed symptoms (regardless of DSM threshold) in the general population. Experiment 2 makes use of a novel task that in contrast to traditional measures of WM, focuses on the capacity to integrate aspects of instructions and avoid goal neglect. If as Diamond (2005) has suggested, inattention leads to difficulty with verbally presented material, it may not just be the verbal nature of the material that is relevant but the fact that instructions comprise

various components that need to be integrated. The letter-monitoring task described below requires the utilization of stored information and relies on representation integrity to guide behaviour. However, it is thought to tap a different form of attention than that assessed in traditional WM tasks (Duncan et al., 2008).

Duncan, Emslie, William, Johnson, and Freer (1996) describe a type of performance failure they call *goal neglect*. In goal neglect, participants are able to state a given rule, and yet behaviourally make no attempt to adhere to it. They developed a task sensitive to this failure, originally for use with frontal lobe damaged patients, but found the effect was also demonstrated in a normal population sample. On each trial of the task, a series of number-letter pairs are shown in quick succession in the centre of a computer screen. Participants are instructed to watch the characters on either the left or right side, and to read aloud the letters, but not the numbers they see on that side. An initial cue at the beginning of each trial directs participants to which side to read from; either "WATCH LEFT" or "WATCH RIGHT", is written in the centre of the screen. Then, immediately preceding the last three character pairs, a second cue directs them to which side to watch. The second cue is either a + or – symbol flashed in the centre of the screen. Irrespective of what side the participant started watching, + indicates watch right, and – indicates watch left. This determines whether the participant continues reading letters on the side they started on, or switches to reading letters on the opposite side. The +/- cue is often neglected, despite the fact it is not forgotten; participants are asked during and at the end of the task to relay the +/- rule in order to confirm understanding of it. Duncan et al. concluded that while participants were perfectly capable of obeying the rule, they were simply not doing so. They suggest that information competition is a key factor in neglect, i.e. because the switch rule comes chronologically later than other task relevant information, the quality of its representation in WM is poorer. The rule would be more likely followed if other task demands were not present, and so whilst the rule is

represented it is not fully integrated into what Duncan et al. refer to as the *Task Model*.
This is quite different to the secondary interference posed in complex-span tasks of
working memory, which is designed to increase demand on resources. Duncan et al. (2008)
conducted a series of experiments to determine what kind of attention or working memory
limit underlies goal neglect, and found that level of neglect is determined *not* by processing
demands during task execution, but by total complexity of the facts, rules, and
requirements in the task model. They suggest a WM limit in constructing and maintaining
the task model and that this underlies goal neglect. This WM limitation is different to those
tested in traditional span tasks in several ways. Firstly, Duncan et al. (2008) argue that the
quantity of information needed to be held in active storage for their task creates much
greater demands on capacity than do the few items on typical span task lists. Secondly, in
traditional span tasks, strings of information (digits, words etc.) are continually discarded
and updated as the task goes on meaning it is not necessary to hold them in active storage
for very long. The task model however, must be kept stable throughout the course of the
task, and be ready to respond to appropriate triggers. Duncan et al. (2008) suggest that this
is reflective of Baddeley's (2000) episodic buffer. Baddeley describes this as a limited-
capacity temporary-storage system that is capable of integrating information from a variety
of sources. Like the slave systems, it is controlled by the central executive, which is able to
retrieve information from it for the purposes of reflection, manipulation and modification.
The attention of the central executive is directed consciously, meaning that it influences
the content of the buffer by determining what sources of information are in focus. Duncan
et al. are not the only ones to make a connection between use of instructions and WM.
Other work has shown a clear link between instruction guided behaviour and working
memory, albeit in children (Jarowslawska, Gathercole, Logie, & Holmes, 2015; Yang,
Allen, & Gathercole, 2015).

     If goal neglect errors arise from attention control failures, this suggests the task

described by Duncan et al. will be a good measure of executive control. We would therefore expect performance on tasks assessing goal neglect to be related to inattention, but not hyperactivity or impulsivity. The existing literature on this is limited. There is evidence for an association between ADHD and goal neglect (Karatekin, 2006; van Lamblagen, van Kruistum, & Parigger, 2008; Kofman, Gidley Larson, & Mostofsky, 2008; Shue & Douglas, 1992; Pennington & Ozonoff, 1996;), and findings from a study using tasks designed to tap the episodic buffer suggested that ADHD was associated with an impaired ability to utilise the information processed by the buffer (Alderson et al., 2014). In terms of inattention specifically, Whyte, Schuster, Polansky, Adams, and Coslett (2000) found patients with traumatic brain injury associated with impairments of attention, demonstrated increased off-task behaviour, which they suggested could reflect a reduction in task-goal maintenance.

A second literature links goal neglect to *mind wandering* (Kane & McVay, 2012; McVay & Kane, 2009); the tendency to be distracted by thoughts unrelated to the task at hand. Mind wandering is also associated with ADHD (McVay et al. 2008; Shaw & Giambra, 1993), including non-clinical symptomology (Seli, Smallwood, Cheyne, & Smilek, 2015), and is reminiscent of the distraction and lack of sustained attention to tasks described in DSM criteria for inattention.

In order to extend previous findings, the present experiment aims to test whether this novel assessment of construction of working memory representations, is predicted by inattention in a non-clinical sample of adults. Again, whilst not directly predicted by Diamond (2005), the notion strongly chimes with her contention that verbally presented material is particularly problematic for those with inattention, although it is not the verbal nature of the instructions that is key under present predictions, but the requirement to fully integrate and to sufficiently maintain different components of a task model. We predicted that goal neglect errors will increase with higher levels of inattention, but not be related to

impulsivity or hyperactivity.

Method

Participants

The 95 participants from the previous study were invited back to complete an additional

WM measure; 66 accepted (Men: N = 24, Women: N = 42, Mean age = 22.09, SD = 4.73).

Materials

Letter monitoring task (Duncan et al. 1996). The task was administered as per

Duncan et al. Each block began with the word "READY" presented in the centre of the

screen. After the participant confirmed they were ready to proceed, the experimenter

pressed a key and the word disappeared and was followed by a blank interval of 500ms

before the instruction "WATCH LEFT/RIGHT" was presented in its place for 1 s. After a

further blank interval of 1 s the stimuli sequence began. This was a series of stimulus pairs

(numbers or letters) presented for 200ms and separated from the next by blank intervals of

200ms. Ten pairs appeared in turn and after the tenth a + or – symbol was presented in the

centre of the screen for 200ms. After a further blank interval of 200ms three more pairs

were presented. Of the first ten pairs a randomly selected 5 were letter pairs, and the rest

were numbers. Of the last three pairs, the first were always digits, and the second two were

letters. On half the trials participants were to stay on the side of the initial instruction, and

on the other half they were required to switch to the opposite side. For each trial digits

were selected randomly and independently from the set 1-8, and letters were selected

randomly without replacement from the alphabet but excluding D, I, O, V, and W. For

each trial a perfectly correct report would consist of five letters from the appropriate side

from the first ten stimulus pairs, and two from the appropriate side for the last three. A

prepared sheet was use to record responses for later scoring. Figure 1 shows an example of

stimuli for one trial. Each participant received the same instructions which described the three basic task requirements: a) to read aloud letters and ignore numbers, b) to begin on the side as instructed on screen, c) and to use the +/-symbols to guide responses for the final part of each trial. To ensure that the +/- rule would be remembered, pieces of paper were placed on the appropriate sides of the testing desk with either "PLUS" or "MINUS" written on them.

WATCH RIGHT

5	•	7
B	•	L
T	•	K
2	•	5
1	•	3
M	•	Y
6	•	2
F	•	J
P	•	H
3	•	8
	+	
4	•	2
G	•	A
E	•	N

Figure 1. An example of stimuli for one trial as per Duncan et al. 1996. Time runs from top to bottom. "WATCH RIGHT" is presented for 1 second, each proceeding stimulus is presented for 200ms separated by a blank interval of 200ms.

Participants were given at least one practice trial. Practice was repeated until at least one letter was reported (not necessarily from the correct side), and the +/- rule was described correctly.

The experiment consisted of three blocks of 12 trials. Each block contained four sub-blocks arranged so that one of each trial type (WATCH RIGHT followed by +, WATCH RIGHT followed by -, WATCH LEFT followed by -, and WATCH LEFT followed by +) appeared once per sub-block in random order (equating to two "switch" trials, and two "stay" trials per sub-block). Participants were asked to repeat the rule again between each block. Verbal prompts from the experimenter were controlled in the same manor as in Duncan et al.

Scores were awarded for the number of passed sub-blocks, meaning out of the four trials within each sub-block, participants had to correctly respond to one "switch" trial, and one "stay" trial to score a point. A correct trial response amounted to correctly reading at least three pre-+/- cue letters, and at least one post-+/- cue letter.

Results

The mean score on the letter-monitoring task was 7.02 ($SD = 2.50$, Range = 1-9). Correlations (see table 7) showed that, neither aspect of IQ was related to performance on the letter monitoring task ($ps > .05$). Performances on the three traditional tests of working memory (backward digit span, OSPAN, and Corsi blocks) were all significantly positively correlated with performance on the letter monitoring task ($ps < .01$). As expected, the ADHD symptom inattention was significantly negatively correlated with letter monitoring performance ($p = .032$), while there was no significant relationship between hyperactivity or impulsivity and the task ($ps > .05$).

Regression was used in the same manner as in Experiment 1, to assess the predictive value of inattention on letter monitoring task performance when the other symptoms of ADHD were accounted for (see table 8). As before, IQ was included as a covariate along with hyperactivity and impulsivity. Bayes Factors were used as per Experiment 1. Results suggest that data for IQ were insensitive ($p = .126$, $B_{H(0, .25)} = 0$)

Table 7

Correlations between IQ, CAARS subsets, and working memory scores

| | Mean | SD | Pearson Correlations | | | | | | | | |
			1	2	3	4	5	6	7	8	9
1. IQ gC	51.86	0.05	-								
2. IQ gF	48.67	9.47	0.139	-							
3. Inattention	54.58	10.81	0.006	0.126	-						
4. Hyperactivity	50.27	10.73	-0.109	0.08	.567**	-					
5. Impulsivity	47.97	8.9	-0.048	-0.039	.597**	.658**	-				
6. Digit Span	8.77	2.13	0.208	.306**	-.411**	-0.14	-.257*	-			
7. OSPAN	83.45	9.63	0.091	-0.15	-.344**	-0.081	-0.182	.305**	-		
8. Corsi Blocks	9.12	1.86	0.084	.593**	-0.089	-0.04	-0.184	0.194	0.124	-	
9. Letter-Monitoring	7.02	2.5	0.152	0.17	-.229*	0.057	-0.017	.296**	.352**	.313**	-

$*p < .05, **p < .01$

Table 8

Summary of regression for IQ, hyperactivity, impulsivity, and inattention on Letter-Monitoring scores.

	Variable	b	SEb	β	t	R^2	R^2 change	Semi-partial correlation
Step 1						0.036	0.036	
	IQ	0.039	0.025	0.19	1.551			0.19
Step 2						0.04	0.003	
	IQ	0.039	0.026	0.19	1.542			0.19
	Hyperactivity	0.013	0.029	0.057	0.464			0.057
Step 3						0.043	0.003	
	IQ	0.038	0.026	0.186	1.49			0.185
	Hyperactivity	0.025	0.038	0.108	0.654			0.081
	Impulsivity	-0.022	0.046	-0.077	-0.466			-0.058
Step 4						0.158	.116*	
	IQ	0.048	0.025	0.232	1.95			0.229
	Hyperactivity	0.056	0.038	0.242	1.485			0.174
	Impulsivity	0.029	0.047	0.104	0.62			0.073
	Inattention	-0.103	0.036	-0.447	-2.894*			-0.34

*$p < .01$

and that neither hyperactivity nor impulsivity contributed to variance in letter-monitoring scores ($p = .431$, $B_{H(0, .25)} = 0.16$; $p = .968$, $B_{H(0, .25)} = 0.27$ respectively). Inattention explained a significant amount of unique variance even after all other variables had been accounted for ($p = .005$).

Discussion

The aim of Experiment 2 was to build on the findings of Experiment 1, and show that symptoms of inattention but not hyperactivity or impulsivity are related to WM using a novel paradigm quite different to that used in traditional tests. Our findings support this; performance on the letter-monitoring task was predicted by inattention, but not by other symptoms of ADHD. This is the first study to show that inattention is a good predictor of goal neglect.

This has implications for our understanding of the way in which WM is deficient in inattention. Our findings suggest that inattention relates to the ability to integrate a task model thought to reflect the episodic buffer component of WM. While there appeared to be no problems in construction of this knowledge base (all participants were able to repeat task rules between blocks), it seems that in inattention, the quality of it was not sufficient in order to utilise the information while concurrently undertaking the task itself. This supports previous work linking attention problems to the episodic buffer (Alderson et al. 2014) and difficulties with task-goal maintenance (Whyte, et al. 2000). We suggest that this apparent difficulty with task model integration may explain why verbal presentation of information is particularly problematic for those with inattention, as highlighted by Diamond (2005).

Research has shown that construction and maintenance of the task model is strongly related to fluid intelligence (Duncan et al., 1996, 2008, 2012). The present work did not

find a significant correlation between either aspect of IQ and performance on the letter-monitoring task. However, Bayes values for the regression were insensitive meaning that our data does not rule out a relationship. Although our distribution for IQ was normal, we note that Duncan and colleagues have often sampled from both young and old populations to ensure enough variability in IQ in their samples, which could account for our inconclusive results. Notably, our results show that inattention predicts goal neglect independently of IQ and as such our results have implications for understanding goal neglect more generally.

General Discussion

The present research presents several important insights regarding the WM problems associated with inattention. Neither the mode (visual vs. spatial) nor the format (simple vs. complex) of presentation appears to be the factor determining the relationship between WM and inattention. Of the three ADHD symptoms, we can only be confident that inattention is associated with verbal WM deficits, which is broadly supportive of Diamond's hypothesis. However, only the goal neglect task clearly differentiated inattention from the other two core ADHD symptoms. Results for hyperactivity provided evidence for no contribution to the backward digit span and letter-monitoring verbal WM tasks, but were inconclusive for the Ospan verbal WM task. For impulsivity, the results provided evidence for no contribution to letter-monitoring, but were inconclusive for backward digit span and Ospan.

Both experiments suggest that use of a complex-span task (involving storage plus a secondary processing element) is unnecessary to show the WM deficit associated with inattention. Performance on a simple-span task was predicted by inattention in Experiment 1, and in Experiment 2 it predicted goal neglect errors, which Duncan et al. (2008) showed

are not affected by processing demands during task execution. However, as noted above, only the goal neglect task clearly differentiated the three core ADHD symptoms

Instead, construction of complex representations sufficient enough in quality to enable use of all represented information might be the key factor differentiating WM deficits associated with inattention from those associated with the other two core ADHD symptoms. This could explain why cumulatively, research has not found a distinction between verbal and spatial WM in ADHD using traditional tasks. Nevertheless, since the goal neglect task utilised in the present study was a verbal task, future research will need to be directed to investigating this possibility. Moreover, whilst task model complexity was shown to be related to inattention in Experiment 2, it cannot be the sole factor determining working memory deficits in those with inattention since the BDS task does not require the construction of a complex task model. Again though, our data do not allow us to differentiate between inattention and impulsivity in predicting performance on the BDS.

Finally, we provide evidence that symptoms of inattention experienced by adults from a community sample are associated with similar cognitive deficits as those seen in the childhood literature. It also shows that there is sufficient variation in symptomology within the general population to produce these effects. If we accept a dimensional view of ADHD and it's symptoms, our findings have relevance to understanding them in clinical groups. Awareness of the WM deficit associated with inattention even in a non-clinical sample may be of use in developing interventions for adults experiencing difficulties.

An important theoretical issue that should be noted with relation to our findings is that of direction of causation. We use regression to analyse data for both experiments with the primary purpose of looking at inattention independently from hyperactivity and impulsivity, a by-product of which is an imposition of direction on the data. However, we mean to make no judgement on whether inattention produces the problems seen in WM, or

whether WM underpins inattention. Either of these directions is reasonable. Holmes et al. (2014) suggest that high levels of inattentive and distractible behaviour may arise in part from a failure to maintain task goals in WM. Such a view proposes that inattention is the behaviour i.e. the final consequence that results from a cognitive deficit pathway. This seems to be the most common view in the literature, but then much of the research in the field of ADHD is pre-geared towards developing causal models for the disorder. Alternatively, it is possible that inattention leads to poor WM, as by its very nature it limits the information, or quality of information coming into the system through lack of focus. It is also likely that there are multiple pathways to poor working memory. In this work, inattention only explained a small portion of impaired WM performance. There might be another impaired process influencing performance. For example, Hofmann, Schmeichel, and Baddeley (2012) recently proposed that self-regulation (broadly defined as goal-directed behaviour) is connected to all three core executive functions, and is seen as facilitating WM in several ways; primarily through top-down control of attention toward goal-relevant stimuli, and away from irrelevant stimuli. It is possible that components of self-regulation may be driving the relationship between inattention and working memory, and that inattention may be better explained by a self-regulatory rather than specific executive function deficit. This has not been considered specifically in relation to inattention, but Shiels and Hawk (2010) suggest that ADHD may involve deficits in self-monitoring and adaptive control components of self-regulation, and the cognitive-energetic model of ADHD (Sergeant, 2000) comes closest to representing this theoretically. Both the second and third levels of the model (the energetic pools and the management/evaluation mechanism) involve self-regulatory functions that would play a role in constructing and utilising working memory representations. Shiels and Hawk suggest that such regulatory deficit models combine cognitive and motivational theories to offer a plausible alternative to core cognitive models that do not seem to fit with the heterogeneous nature of ADHD.

Limitations and Future Directions

Our research used self-report measures to assess inattention and the other symptoms of ADHD, but we note that it may be useful for future work to utilise objective measures. While no such measures address DSM defined inattention per se, there are tasks that tap various aspects of attention, for example the Attention Network Test (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002), which purports to tap three networks of attention. Redick and Engle (2006) found that WM was related to the *executive control* network (involved in resolving action conflict), and conclude that the ability to control attention is influenced by individual differences in WM capacity. It would be useful to understand whether and how the ANT relates to subjective estimates of inattention.

It is worth noting that there is evidence to suggest there may be gender differences in ADHD; both in presentation and diagnosis. Historically males have been more likely to receive a diagnosis than females, although some have blamed this on the propensity of females to have internalising symptoms without the more blatant externalising symptoms (Gershon & Gershon, 2002), or clinician gender bias (Bruchmuller, Margraf, & Schneider, 2012). However, data collected from university students suggested that males had a greater prevalence of both inattention and hyperactivity-impulsivity (Elisa & Parris, under review). The gender split in the current research was uneven. However, it was not the aim of the work to assess gender differences, but to establish a relationship between inattention and working memory. Future work may wish to take this further by looking at whether this relationship is mediated by gender and ensuring equal numbers in each group.

In summary, we have presented evidence that working memory is related to ADHD symptoms in adults without a clinical diagnosis of ADHD. However, results from both experiments suggest that inattention is the key symptom implicated in WM deficits. Whilst

inconclusive for spatial WM, inattention predicted performance on both simple and

complex-span traditional verbal tasks, as well as a novel task assessing WM for task rules.

Chapter 5: The Relationship Between Self-Regulation of "Cool" Cognitive Effort, Executive Functions and Inattention in a Community Sample

Continuing with the working memory and cognitive effort line of investigation, this chapter builds on the findings of chapters 3-4 to look at various components of the model and how they interact with each other. A number Stroop was chosen for its ability to tap cognitive effort with more stringent control than the CRT, whilst also measuring cognitive control variables.
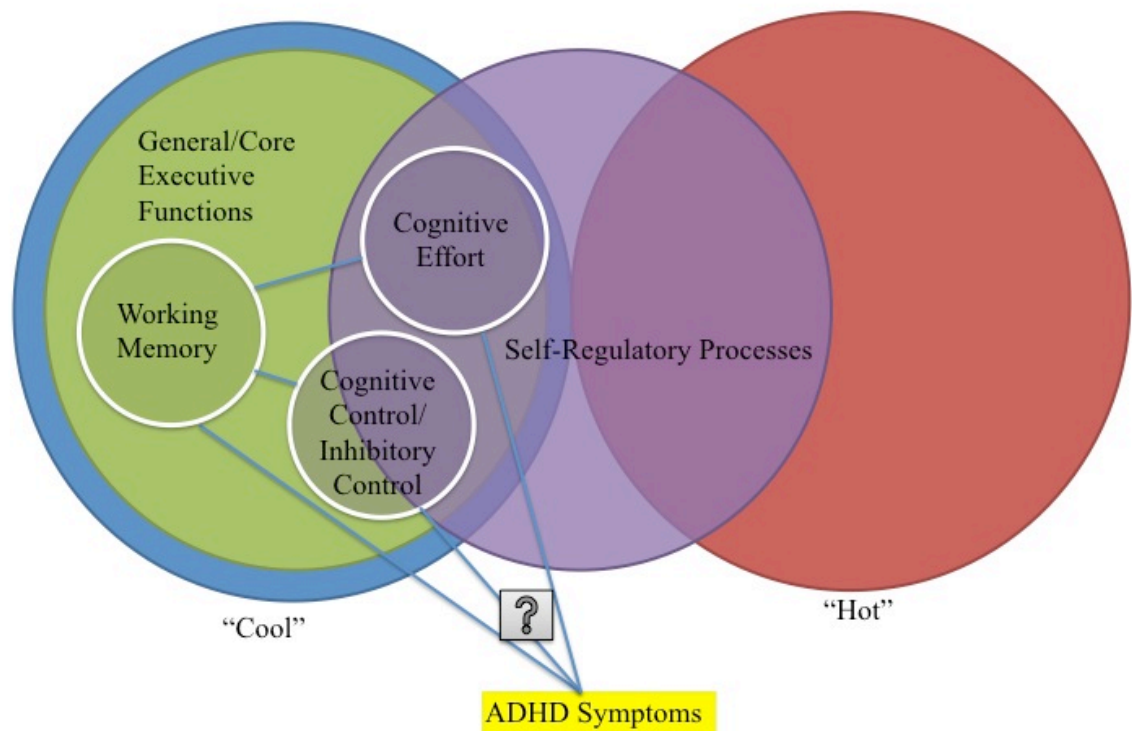
Abstract

Previous work has demonstrated a relationship between inattention and working memory (WM). Based on this and work theorising a link between working memory and self-regulation, we predicted a relationship between inattention and *cognitive effort*. 120 ADHD diagnosis free adults (aged 18-35) completed a self-report measure designed to assess ADHD symptoms, two measures of cognitive effort, a measure of inhibitory control and a measure of WM. Bayes analysis was used to evaluate the evidence in favour of the null hypothesis when *p* was above .05. We report strong evidence for no relationship between inattention and one measure of effort. Our results also provide strong evidence for no relationship between WM and cognitive effort or inhibitory control. The results are discussed in terms of current theory linking self-regulatory processes such as cognitive effort to core executive functions and in terms of their implications for understanding the role of self-regulatory processes in inattention and ADHD more generally.

The Relationship Between Self-Regulation of "Cool" Cognitive Effort, Executive

Functions and Inattention in a Community Sample

Inattention is one of the three core symptoms of attention deficit hyperactivity disorder

(ADHD). It is characterized by an inability to maintain task focus, distractibility,

forgetfulness and difficulties with organisation and planning. The remaining two

symptoms, hyperactivity and impulsivity, are characterized by excessive energy and

restlessness, disruptive and often inappropriate behaviour, and a lack of regard for social

rules. DSM-5 states that adults must rate positively for 5 out the 9 items listed on either or

both of the inattention or hyperactivity-impulsivity lists to meet criteria for one of three

diagnoses; the combined type (ADHD-C), the predominantly inattentive type (PIT) and the

predominantly hyperactive-impulsive type (ADHD-HI). However, a shift in opinion has

led many researchers to believe that this categorical approach is not the best fit for the data

on ADHD, a notion supported by taxometric (Frazier, Youngstrom, & Naugle, 2007

Haslam, Williams, Prior, Haslam, Gratetz, & Sawyer, 2006; Marcus & Barry, 2011) and

genetic (Crosbie, Arnold, Paterson, Swanson, Dupuis, & Li et al., 2013; Hudziak, Heath,

Madden, Reich, Bucholz, & Slutske et al. 1998; Nikolas & Burt, 2010) research. The

above description of inattentive symptoms is something many of us without an ADHD

diagnosis can relate to, and in fact it is now suggested that ADHD and its symptoms are

best viewed as dimensional as oppose to categorical, meaning clinical examples can be

regarded as being at the extreme end of normal expression. Using a reduced threshold of

DSM-5 criteria, we have shown that up to a third of the general population report

symptoms of inattention (Elisa & Parris, under review, see Chapter 2).

While historically ADHD is most commonly associated with children, evidence

suggests symptoms persist into adulthood in around 60% of cases (Elliott, 2002). In adults

symptoms of hyperactivity-impulsivity appear to diminish, while symptoms of inattention

persist to become the main characterisation of the disorder (Biederman, Mick, & Faraone,

2002; Millstein, Wilen, Biederman, & Spencer, 1997) meaning that it is difficult to generalise findings from research with children, to adults.

The focus of this research is on inattention in adults across the full spectrum of symptomology by using general population samples.

Executive Functions, Self-Regulation and ADHD

A primary deficit in executive functions (EFs) is one of the most prominent theories of attention deficit hyperactivity disorder (ADHD). It is generally agreed that there are three core separable but related EFs; working memory (WM), inhibitory control, and cognitive flexibility (Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000). These three core EFs are generally regarded as "cool" cognitive processes, as opposed to "hot" cognitive processes that involve emotion, motivation, and affect. Self-regulation refers broadly to ensuring behaviour is goal directed and overlaps with that of the "cool" general EFs. However, self-regulation refers to a collection of processes including the control processes of the EFs, cognitive effort and judgements based on utility, with the latter two involving emotion, motivation and affect. This means that self-regulation depends on both "cool" and "hot" aspects of cognition. However, there are contrasting opinions as to how self-regulatory and EF processes interact. Hofmann, Schmeichel and Baddeley (2012) suggest that the three core EFs facilitate self-regulatory processes of both "temperatures". For example, cognitive flexibility is required to enable switching between different means of sub-serving the same goal, as well as balancing multiple goals. Inhibitory control is required to avoid automatic unwanted responses that may conflict with a goal. However, the principal EF required for successful self-regulation according to Hofmann et al., seems to be WM. They suggest this is required to hold active representations of goals, control attention toward goal relevant stimuli and, away from goal irrelevant stimuli, shield goals from interference, suppress ruminative thoughts and regulate unwanted affect, desires and

cravings. Diamond (2013) shares the view that general EFs and self-regulatory processes are related but proposes that inhibitory control is the key EF in this relationship. Given these contrasting opinions, they make differential predictions as to which symptom of ADHD would result in an impairment in self-regulation.

In a meta-analysis Willcutt, Doyle, Nigg, Faraone and Pennington (2005) found that although EF deficits did not fully explain ADHD symptoms they were certainly an important component of the disorder. However, much of this has focused on the role of inhibitory control and is most relevant to sub-types of ADHD that include hyperactivity-impulsivity (i.e. Barkley, 1997). Diamond (2005) proposes that inattention is underpinned by a core deficit in WM, which does not apply to the other symptoms of ADHD and will be most obvious in PIT. Literature tends to support this view (Lui & Tannock, 2007; Martinussen & Tannock, 2006) and in our own work we have shown that WM deficits associated with inattention are present in a general population sample of adults (Elisa, Balaguer-Ballester, & Parris, 2016, see Chapter 4). If self-regulation is mainly supported by the EF of inhibition as per Diamond, we would expect to observe impaired self-regulation associated with hyperactivity-impulsivity only. If on the other hand, self-regulation is mainly supported by the EF of working memory, as per Hoffman et al., we would expect a self-regulation impairment to be associated with working memory. With regard to the "hot" / "cool" EFs distinction and ADHD symptoms, it has been suggested that there is a hot-hyperactive-impulsive/cold-inattentive distinction (Castellanos, Sonuga-Barke, Milham, & Tannock, 2006) but given that both "temperatures" are involved in self-regulation this particular suggestion does not help derive predictions in either direction.

Cognitive Effort and the Core Symptoms of ADHD

In the current work we focus on the *cognitive effort* aspect of self-regulation and its relationship to the symptoms of ADHD. Cognitive effort relates to the proportion of limited cognitive resources allocated to a task or decision and also to the tendency to apply such resources. As suggested by the name, this allocation of resources is effortful to the point that negative affect increases in line with level of effort (Garbarino & Edell, 1997). Thus the amount of cognitive effort required to perform a task or make a decision has an impact on the strategy used to do so (Bettman, Johnson, & Payne, 1990), producing individual differences in performance based on how willing or able individuals are to exert such effort to reach their goals. A detailed model of cognitive effort suggests that it is influenced by both "hot" and "cool" cognitive factors such as motivation, curiosity, memory and knowledge (Longo & Barrett, 2010). The multi-faceted nature of cognitive effort means it has been difficult to measure empirically. Attempts have included using physiological measures to assess workload (i.e. heart rate, blood pressure etc.), tasks to assess quality and quantity of performance and self-report measures to assess subjectively rated levels of effort.

The Cognitive Reflection Task (CRT) has been shown to reliably expose variation in cognitive effort and has merit in its ease of administration and ready availability. Whether the CRT assesses "cool" or "hot" aspects of cognitive effort is unclear; we suggest there is an argument for both. The task requires shielding or inhibition of a heuristic response i.e. "cool" cognition. However, the nature of the task could be argued to elicit an affective response (i.e. "hot"), as participants are often aware they have been presented with a "trick" question, which may motivate them to try harder. Research by Stupple, Gale, and Richmond (2013) concluded that performance on the CRT is better explained by variation in WM than cognitive effort. However, it is equally plausible given Hofmann et al.'s view, that working memory is a key mechanism in the application of

cognitive effort perhaps sustaining the motivation for effort. Our own work utilising the CRT has shown that inattentive symptoms in a community sample were uniquely predictive of task performance (Elisa & Parris, 2015, see Chapter 3). We employ the CRT in the present work to replicate our previous finding and to assess its relationship to our other measure of cognitive effort described below.

Another measure that has been used to measure cognitive effort, a variation on the number Stroop task (Robertson, Hiebert, Seergobin, Owen, & MacDonald, 2015), was designed to examine the effect of cognitive effort on reaction times (RTs) and error rates, and has the additional benefit of independently manipulating cognitive control. The repetitive lab based nature of the task means it is unlikely to elicit an affective response, and the processes required for accurate responding are primarily "cool" meaning it is useful for investigating inattention. The task presents a pair of single-digit integers on each trial and participants are asked to indicate which of the pair is physically larger (i.e. the largest font size). The numbers could differ in both physical size and numerical value and when these two dimensions are incongruent (i.e. the physically larger number is numerically smaller and vice versa), this provides the means for investigating cognitive control as in standard colour-word Stroop tasks. Congruent trials consist of number pairs where both physical and numerical dimensions agree (i.e. the physically larger number was also numerically larger and vice versa). Trials where numbers differ only in physical size and not numerical magnitude constitute a control condition. Varying the magnitude of the physical size difference between number pairs, allows investigation of cognitive effort. Robertson et al. cite research showing that longer RT's and increased error rates result from having to select between integers that are closer versus more distant in physical size (Kadosh, Henik, Rubinsten, Mohr, Dori & van de Ven et al., 2005; Kaufmann, Koppelstaetter, Delazer, Siedentopf, Rhomberg, & Golaszewski et al., 2005). They suggest that manipulation of congruency puts stress on cognitive control processes as well

as increasing cognitive effort demands, while differences in physical size magnitude increases cognitive effort but does not require additional cognitive control.

In summary the present work investigated the relationship between the self-regulatory process of cognitive effort and the core symptoms of ADHD using two measures of cognitive effort. Based on Hoffman et al.'s model and our previous work, we hypothesised a relationship between cognitive effort and inattention, which we also predicted would not be present for hyperactivity and impulsivity. Also included was a measure of working memory capacity and a measure of inhibition (the cognitive control component of the Stroop task) to test the conflicting proposals of Hofmann et al., (2012) and Diamond (2013) regarding the relationship between self-regulation and EFs. A relationship between WM and cognitive effort would be predicted by Hoffman et al., whilst a relationship between cognitive control and cognitive effort would be predicted by Diamond.

Method

Participants

120 individuals (105 females, 15 males) aged 18-35 ($M = 20.64$, $SD = 3.39$) participated in the experiment. Participants were recruited mainly from the Bournemouth University Psychology Undergraduate Participation Scheme whereby students receive course credits in return for participation. All participants were free from ADHD diagnosis. Participants gave full written, informed consent to take part. Ethical approval for the experiment was obtained from Bournemouth University ethics committee.

Materials and Procedure

ADHD symptoms. *Conners Adult ADHD Rating Scale–Self-Report: Short Version (CAARS-S:S; Conners et al.1999).* This is a 26 item self-report measure designed to assess

current ADHD symptoms in adults. Items are rated on a 4-point Likert-type scale, where 0 = *not at all* and 3 = *very much.* The measure contains 4 factor-derived subscales; A: inattention/memory problems, B: hyperactivity/restlessness, C: impulsivity/emotional lability, D: problems with self-concept, as well as E: an ADHD index comprised of items from the other subscales. For each subscale, a *T*-Score is derived. Guidelines suggest that a *T*-score of 45-55 is average for adults (using data from a normative sample). Scores range from 29-90. A *T*-score of above 65 is considered to be indicative of clinically elevated symptoms.

Working memory/goal neglect. *Letter monitoring task (Duncan, Emslie, Williams, Johnson, & Freer,. 1996).* The task was administered as per Duncan et al. (see Chapter 4 for a full description).

Intelligence quotient (IQ). A shortened version of the Wechsler Abbreviated Scale of Intelligence (WASI-II) was administered. This consisted of vocabulary and matrix reasoning subsets. From this measure a t-score for each relevant subscale (Gf & Gc) is calculated, and an approximate overall IQ score is obtained from an age-matched set of scores.

Cognitive Reflection Test (CRT; Frederick, 2005). The test is composed of three items as follows:

(a) A bat and ball cost £1.10 in total. The bat costs £1.00 more than the ball. How much does the ball cost?

(b) If it takes 5 machines 5 minutes to make 5 widgets, how long would it take 100 machines to make 100 widgets?

(c) In a lake, there is a patch of lily pads. Every day, the patch doubles in size. If it takes 48 days for the patch to cover the entire lake, how long would it take for the patch to cover half the lake?

In order to answer correctly it is necessary to suppress and/or evaluate the quick intuitive answer that immediately comes to mind (Frederick, 2005). The solution to the bat and ball problem is 5 pence, to the widget problem is 5 minutes and to the lily pad problem is 47 days.

Number Stroop task (Robertson, Hiebert, Seergobin, Own, & MacDonald, 2015). In each trial two numbers (from the set: 1, 2, 3, 7, 8, 9) appear on screen side by side in font Ariel. Font size (i.e. physical size) varied between 40, 55, 70, and 85. The task was to select the number that was the physically largest of the pair. Numerical magnitude served as an irrelevant/distracting dimension as responses were never made based on this information.

The experiment consisted of a single block of 132 randomly ordered trials that included 48 congruent (where physical size and numerical value are consistent), 48 incongruent (where physical size and numerical value are inconsistent) and 36 control (where the numbers differ in physical size but not numerical value) trials. For physical size, trials were considered to be "close" when the font size difference was 15 points and "far" when the difference was 45 points (as per Robertson et al. we also included in the experiment trials with an "intermediate" size difference of 30 points, but did not include theses the analyses). For numerical magnitude, trials were considered "close" when the difference between the number pair was 1 or 2 and as "far" when the difference was 6 or 7. Both physical and numerical dimensions were orthogonal and fully crossed with congruency to allow dissociation of their effects. For physical size there were 44 close, intermediate and far trials. For numerical magnitude there were 48 close and 48 far trials. The close-far variable on both the physical and numerical dimensions was fully balanced so there was an equal number of physical close – numerical close, physical close – numerical far, physical far – numerical close, and physical far – numerical far pairings.

Figure 1 shows the sequence of a single trial. Each trial began with a fixation cross displayed in the center of the screen for 500 milliseconds (ms), this is followed by a blank screen lasting 250 ms. The number pair is then presented, one on the left and one on the right. This screen lasted until the participant made their response, indicating by key press whether the physically larger number was on the left or the right. After selection had been made, a further blank screen was presented which lasted 525-7000 ms (mean = 2500 ms) before the fixation cross appeared again.

Participants were instructed to respond to the physically larger of the numbers as quickly and accurately as possible while ignoring the numerical values.

Each participant was individually administered for each test item. They were alone in a quiet testing room. Test administration order was counterbalanced.
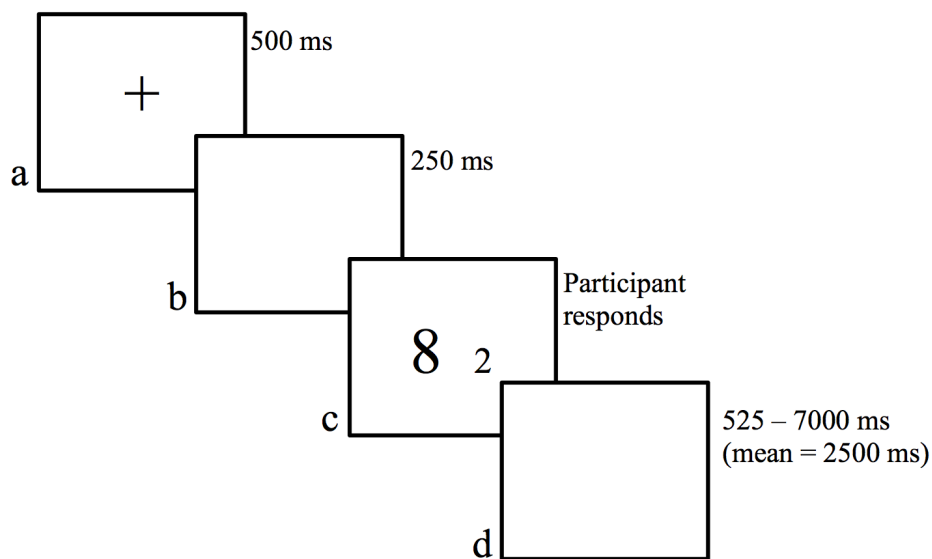
Figure 1. Stimuli order for one trial of the number Stroop as per Robertson, Hiebert, Seergobin, Owen, & MacDonald (2015)

Data Analysis

Initially, a full analysis in relation to the number Stroop task was carried out similarly to Robertson et al. to enable comparison and to affirm the efficacy of the task as a measure of

cognitive effort. Secondly, to address research questions, analysis was conducted on the relationships between ADHD symptoms, working memory and Stroop dependent measures. Two interference contrasts provided measures of cognitive control (incongruent – control, incongruent – congruent) and the physical size contrast (close – far) provided the measure of cognitive effort.

Bayes factors were calculated using the procedures outlined in Dienes (2014), for all p values greater than .05, to assess the strength of evidence in support of hypotheses. Proposed cut-offs for acceptance of a hypothesis (Jeffreys, 1998), states a B above 3 as providing substantial support for the alternative hypothesis, whilst below 1/3 provides substantial support for the null hypothesis. A B that falls between 1/3 and 3 deems the data insensitive as to whether the alternative or null hypothesis should be accepted. We modelled the predictions of the theory of an absence of evidence for a relationship with a half-normal whose mean and standard deviation values reflected what could reasonably be expected in the circumstance of a significant result. For example Bayes factors for non-significant correlations concerning ADHD symptom variables were calculated using the figures from the relationship between inattention and letter-monitoring performance (previously identified as a significant relationship as per Elisa et al., 2016). $B_{H(0, X)}$ refers to the Bayes Factors testing each hypothesis, where 'H' indicates a half-normal distribution, and 'X' the predicted standard deviation of this half-normal, against a null hypothesis of no difference. Where p values and Bayes factors conflict, the Bayes factor is taken as conclusive. A p value of > .05 does not necessarily indicate that there is no effect, simply that one was not found in the current data set. The use of Bayes factors increases researcher confidence in concluding that there is no effect.

Results

Number Stroop Task Analysis

Analyses of the number stroop task data deliberately mirrored those of Robertson et al. to

enable comparison. Table 1 shows mean RT's and error rates sorted by congruency,

physical size, and numerical magnitude. One sample t-tests showed significant RT slowing

for all contrasts (see Table 2).

Table 1
Mean RT's and error rates for trials sorted by congruency, physical size, and numerical size.

Congruency	Physical Size	Numerical Magnitude	RT	RT SEM	Error	Error SEM
Incongruent	-	-	537.15	8.54	1.19	0.21
	Close	-	622.71	10.80	2.95	0.51
	Intermediate	-	520.59	8.97	0.47	0.21
	Far	-	472.63	7.46	0.16	0.09
	-	Close	521.46	8.63	0.98	0.20
	-	Far	552.77	8.84	1.41	0.28
	Close	Close	599.29	11.46	2.63	0.52
	Close	Far	645.62	11.13	3.29	0.71
	Intermediate	Close	500.60	8.88	0.31	0.23
	Intermediate	Far	540.65	9.84	0.64	0.30
	Far	Close	467.23	7.66	0.00	0.00
	Far	Far	477.86	7.96	0.33	0.19
Congruent	-	-	488.63	7.63	0.23	0.06
	Close	-	536.61	9.79	0.26	0.11
	Intermediate	-	471.21	6.93	0.10	0.07
	Far	-	459.60	7.67	0.31	0.12
	-	Close	494.75	7.96	0.24	0.09
	-	Far	482.43	7.56	0.21	0.08
	Close	Close	558.18	10.76	0.31	0.18
	Close	Far	514.91	10.00	0.21	0.15
	Intermediate	Close	471.32	7.40	0.21	0.15
	Intermediate	Far	471.08	7.00	0.00	0.00
	Far	Close	456.83	8.03	0.21	0.15
	Far	Far	462.35	7.87	0.42	0.21
Control	-	-	493.50	7.39	0.26	0.08
	Close	-	549.51	9.70	0.38	0.20
	Intermediate	-	477.38	7.62	0.21	0.12
	Far	-	455.66	6.56	0.21	0.12
-	Close	-	570.73	9.60	1.29	0.21
-	Intermediate	-	490.71	7.50	0.27	0.09
-	Far	-	463.26	7.03	0.23	0.07
-	-	Close	508.05	8.12	0.61	0.12
-	-	Far	517.28	7.94	0.81	0.15

Effects of interference and facilitation can be seen in figure 2 and effects of

physical size and numerical magnitude can be seen in figure 3. Significant response

slowing was seen in both the interference contrasts and significantly increased response times were seen in the congruent – control contrast.

Table 2.
One sample *t*-tests (theoretical mean 0) for all contrasts

Contrast	*t*	*p*
Incongruent - Control	19.259	< .001
Incongruent - Congruent	16.907	< .001
Congruent - Control	-2.144	0.034
Physical Close - Physical Far	25.623	< .001
Numerical Close - Numerical Far	-3.792	< .001

A one-way ANOVA showed significant differences in magnitude of response slowing between interference and close-far contrasts ($F_{(2.35, 279.32)} = 295.37, p < .001$). Bonferroni corrected post-hoc tests show the greatest cognitive effort was required for physical size differences, followed by incongruent – control and incongruent – congruent. The least cognitive effort was required for numerical magnitude (see Table 3).

Table 3,
Bonferroni corrected post-hoc t-tests for differences in magnitude between interference and close-far contrasts

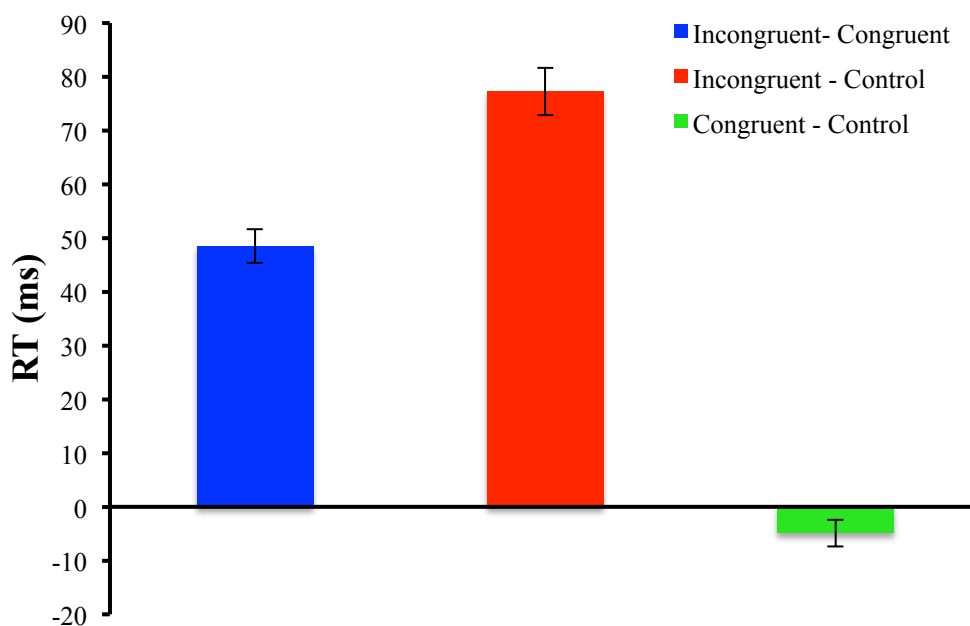| Contrasts		Mean Difference	*t*	*p*
incongruent-control	incongruent-congruent	28.74	8.94	< .001
	phycial close - far	-30.21	-9.021	< .001
	numerical close - far	86.49	18.29	< .001
incongruent-congruent	phycial close - far	-58.95	-13.964	< .001
	numerical close - far	57.75	15.46	< .001
phycial close - far	numerical close - far	116.7	23.485	< .001

Figure 2. Average RT differences for number Stroop contrasts. One-sample t-tests showed significant differences for all three.
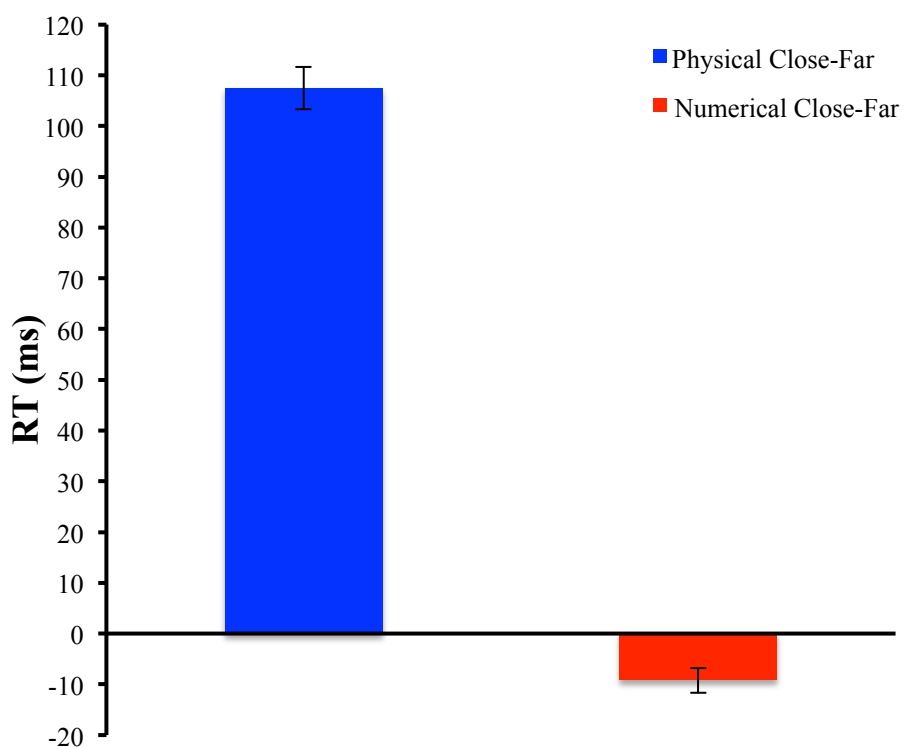
Figure 3. Average RT differences for physical and numerical close – far contrasts. One-sample t-tests showed significant differences for both.

A 3 x 2 ANOVA determined the effect of congruency and physical size differences on RT's. Significant main effects for congruency ($F_{(2, 238)} = 148.19$, $p < .001$) and physical size ($F_{(1,119)} = 634.03$, $p < .001$) were found. We also found a significant interaction between these variables ($F_{(2, 238)} = 74.39$, $p < .001$).

Bonferroni corrected post-hoc *t*-tests showed participants were slower during incongruent than congruent ($t_{(119)} = 16.91$, $p < .001$), and control trials ($t_{(119)} = 15.86$, $p < .001$). Control trials were also significantly slower than congruent trials ($t_{(119)} = -2.14$, $p = .034$). Investigation of the interaction showed that physical size produced significant differences in magnitude of slowing across all three levels of congruency (incongruent $t_{(119)} = 26.94$, $p < .001$; congruent $t_{(119)} = 14.42$, $p < .001$; control $t_{(119)} = 16.12$, $p < .001$), with close trials slower than far trials. There was a significantly larger effect of physical size seen in incongruent relative to congruent ($t_{(119)} = 11.74$, $p < .001$), and control ($t_{(119)} = -2.849$, $p < .015$).

Analogous analysis was performed for numerical magnitude. A 2 x 2 ANOVA showed main effects for congruency ($F_{(1,119)} = 283.27$, $p < .001$) and numerical magnitude ($F_{(1,119)}$ 8.75, $p < .001$) trials. A significant interaction was also found ($F_{(1,119)} = 92.77$, $p < .001$). The effect of the difference of numerical magnitude on response time was significant for both incongruent ($t_{(119)} = -8.52$, $p < .001$) and congruent ($t_{(119)} = 4.21$, $p < .001$) trials but was significantly greater for incongruent trials ($t_{(119)} = -9.63$, $p < .001$). Interestingly effects for incongruent and congruent trials were in the opposite direction; for incongruent trials far discriminations were slowest and for congruent trials close discriminations were slowest.

We next investigated the effects of our variables on error rates. A 3 x 2 ANOVA with congruency and physical size as within-subjects variables showed main effects of congruency ($F_{(1.35, 160.99)} = 18.10$, $p < .001$), and physical size ($F_{(1,119)} = 23.64$, $p < .001$). We also observed an interaction between the two ($F_{(1.39,165.59)} = 22.45$, $p < .001$).

Bonferroni corrected post-hoc t-tests showed participants made more errors during incongruent than congruent ($t_{(119)} = 5.38$, $p < .001$), and control ($t_{(99)} = 4.924$, $p < .001$) trials. However, there was no significant difference in error rates between congruent and control trials ($t_{(119)} = -.803$, $p = .423$, $B_{H(0,5.8)} = .09$). Investigation of the interaction showed that physical size only produced a significant effect on error rates for incongruent trials ($t_{(119)} = 5.50$, $p < .001$). There was no difference between close and far for congruent ($t_{(119)} = -.30$, $p = .764$, $B_{H(0,5.56)} = .04$), or control ($t_{(119)} = .728$, $p = .468$, $B_{H(0,5.56)} = .08$) trials. The effect of physical size was significantly greater for incongruent trials relative to congruent ($t_{(119)} = 5.38$, $p < .001$), and control ($t_{(119)} = 4.69$, $p < .001$) trials. There was no difference between congruent and control trials ($t_{(119)} = -.80$, $p = .423$, $B_{H(0,5.8)} = .09$).

Analogous analysis was performed for numerical magnitude. A main effect for congruency ($F_{(1,119)} = 21.90$, $p < .001$) was found, and results for numerical magnitude showed no effect ($F_{(1,119)} = 1.88$, $p = .173$, $Bs_{H(0,40.27)} < .33$). There was no significant interaction between congruency and numerical magnitude ($F_{(1,119)} = 2.67$, $p = .108$, $B_{H(0,49.62)} = .03$). This suggests error rate was not significantly affected by the difference in numerical value of the number pairs.

Results regarding the variable "numerical magnitude" for both this work and that of Roberston et al. (who found no main effect of numerical magnitude on RTs) contradict what is predicted in the literature i.e. that number pairs that are numerically closer will be more difficult (Moyer & Landauer, 1967). Results from this work and Robertson et al. also conflict. This raises concerns about the usefulness of numerical magnitude difference as a measure of effort. Therefore no further analysis is reported on this variable and focus will be on the physical size differences as a measure of effort.

Tables 4 and 5 show correlations between ADHD symptoms, working memory scores, and variables from the Stroop task for RT's and error.

Table 4.
Pearson Correlations between all variables (Stroop RT's)

	Gf	c A	c B	c C	c E	L-M	I-Control	I-C	pClose-Far	nClose-Far	CRT
Gf	-	0.016	-0.108	-0.119	-0.025	0.149	-0.121	-0.094	-0.156	0.05	.254*
Inattention		-	.310*	.483*	.696*	-.367*	0.094	-0.011	0.158	0.043	0.083
Hyperactivity			-	.364*	.508*	-0.096	-0.009	0.008	-0.011	0.058	0.131
Impulsivity				-	.622*	-.248*	0.074	-0.042	0.157	0.107	-0.106
ADHD composite					-	-.257*	0.029	-0.007	0.076	0.02	0.087
Letter-Monitoring						-	0.022	-0.046	-0.027	-0.068	-0.026
Incong – Cont(stroop)							-	.608*	.668*	-0.018	-0.116
Incong - Cong								-	.333*	0.015	-0.029
Physical Close-Far									-	-0.058	-0.15
Numerical Close-Far										-	0.003
CRT											-

* $p < .01$

Table 5.

Pearson Correlations between all variables (Stroop error rate)

	Gf	c A	c B	c C	c E	L-M	I-Control	I-C	pClose-Far	nClose-Far	CRT
Gf	-	0.016	-0.108	-0.119	-0.025	0.149	-0.064	-0.09	-0.049	0.024	.254**
Inattention		-	.310**	.483**	.696**	-.367**	-0.073	-0.131	-0.156	.228*	0.083
Hyperactivity			-	.364**	.508**	-0.096	-0.017	-0.006	0.132	0.072	0.131
Impulsivity				-	.622**	-.248**	-0.14	-0.17***	-0.147	-0.014	-0.106
ADHD composite					-	-.257**	-0.144	-0.17	-0.158	0.122	0.087
Letter-Monitoring						-	0.067	0.102	0.001	-.239**	-0.026
Incong-Cont(stroop)							-	.843**	.585**	-.322**	-0.047
Incong-Cong								-	.631**	-.226*	-0.057
Physical Close-Far									-	-0.077	-0.002
Numerical Close-Far										-	0.104
CRT											-

$* \ p < .05, \ ** \ p < .01, \ *** \ B > 3$

Working Memory, Cognitive Effort, and Cognitive Control

Our data was insensitive with regards to the relationship between working memory and cognitive effort as assessed by the CRT ($p = .779$, $B_{H(0,0.8)} = 1.17$). For the physical close-far measure of effort and working memory our data provides strong evidence for no relationship for both RTs and error rates ($ps < .05$, $Bs_{H(0,0.8)} < .33$). Results relating to working memory and cognitive control (both interference contrasts) also suggested strong evidence for no relationship for both RTs and error rates ($ps < .05$, $Bs_{H(0,0.8)} < .33$). Cognitive control was unrelated to cognitive effort as measured by the CRT for RTs ($ps > .05$. $Bs_{H(0,0.8)} < .33$) and data for error rates was insensitive ($ps > .05$, $Bs_{H(0,0.8)} > .33 - < 3$). We also provide strong evidence that our two measures of effort (physical size contrast and the CRT) were not correlated ($p = .102$, $B_{H(0,0.8)} = .31$) suggesting either that they assess different aspects of cognitive effort, that one of them may not be a good measure of effort, or indeed that neither of them is a good measure of effort.

Analysis Relating to ADHD Symptoms

On the CAARS questionnaire 17.5% of participants had elevated symptoms (i.e. a t-score of 60 or above) on the composite subscale for ADHD. For individual symptoms; 30% of participants had elevated scores for inattention, 5.83% had elevated scores for hyperactivity, and 6.67% had elevated scores for impulsivity.

Working memory. In line with our previous work and a "cool" description of inattention, we see a correlation between working memory and inattention ($p < .001$). Unexpectedly and inconsistent with a "hot" description of the other ADHD symptoms, this was also true for impulsivity ($p = .006$).

Cognitive effort. Contrary to our previous findings, we found evidence for no correlation between cognitive effort as assessed by the CRT and inattention ($p = .366$, $B_{H(0,0.8)} = .33$). For RT's and error rates, results relating to inattention and the Stroop

measure of cognitive effort (physical close-far) were inconclusive as Bayes suggested data were insensitive ($ps > .05$, $Bs_{H(0,0.8)} = > .33 - < 3$). Correlations between the other two ADHD symptoms and this measure of cognitive effort were also insensitive for both RT's and error rates ($ps < .05$, $Bs_{H(0,0.8)} > .33 - < 3$) and this was also the case for results relating to the CRT ($ps < .05$, $Bs_{H(0,0.8)} > .33 - < 3$)..

Cognitive control. Correlations between inattention and both interference contrasts were insensitive for both RTs and error rates ($ps > .05$, $Bs_{H(0,0.8)} > .33 - < 3$). We saw strong evidence for no correlation between hyperactivity and both interference contrasts for RTs ($ps > .05$, $Bs_{H(0,0.8)} < .33$) and errors ($ps < .05$, $Bs_{H(0,0.8)} > .33 - < 3$). For impulsivity Bayes analysis yielded insensitive values for both contrasts ($ps > .05$, $Bs_{H(0,0.8)} > .33 - < 3$). For impulsivity and incongruent – control Bayes was insensitive ($p < .05$, $B_{H(0,0.8)} > .33 - < 3$). However, Bayes suggested that impulsivity was significantly correlated with incongruent-congruent for error rates ($p = .063$, $B_{H(0,0.8)} = 3.59$).

Discussion

The present experiment investigated the relationship between the self-regulatory process of cognitive effort and the core symptoms of ADHD using two measures of cognitive effort. Based on Hofmann et al.'s model and our previous work, we hypothesised a relationship between cognitive effort and inattention, not hyperactivity or impulsivity. Also included was a measure of working memory capacity and a measure of inhibition (the cognitive control component of the numerical Stroop task) to test the conflicting proposals of Hofmann et al., (2012) and Diamond (2013) regarding the relationship between self-regulation and EFs. A relationship between WM and cognitive effort would be predicted by Hofmann et al., whilst a relationship between cognitive control and cognitive effort would be predicted by Diamond. Results were not as expected. We observed strong evidence for no relationship between inattention and CRT performance; our other measure

of effort resulted in insensitive results. For results relating to cognitive control both inattention and hyperactivity were insensitive but there was some evidence to suggest a relationship with impulsivity. Regarding Hofmann's proposal, results showed strong evidence for no relationship between WM and cognitive effort as assessed by the Stroop; data relating to the CRT was insensitive. Regarding Diamond's proposal, we found strong evidence for no relationship between inhibitory control and cognitive effort as measured by the CRT. Furthermore, results provide strong evidence for no relationship between WM and the cognitive control in the Stroop task..

Comparison to Findings of Robertson et al. (2015)

Our use of the number Stroop task employed by Robertson et al. gives us the opportunity to test the effectiveness of their paradigm on a larger sample of participants (their sample consisted of only 16) and confirm the dissociability of measures of cognitive control and cognitive effort. As in Robertson et al., participants had slower RT's and higher error rates during incongruent relative to congruent and control trials and for close relative to far physical size differences. We also found an effect of numerical magnitude on RT's (but not error rates), which was not found by Robertson et al. In fact this component of the task produced some curious results. The main effect was in the opposite direction to that which we would expect i.e. far trials elicited slower RT's and investigation of the interaction between numerical magnitude and congruency for RT's showed that this was being driven by incongruent trials; in congruent trials RT's were in the expected direction with close slower than far. Attempting to discern the reason behind this puzzling result would be a departure from the aims of the research. Suffice to say we did not treat the numerical magnitude difference contrast as an important variable in our analysis relating to inattention and working memory. Robertson et al. describe research that has shown that RT's and error rates were increased as a result of reducing the numerical difference

between integers (Moyer & Landauer, 1967) but indeed their own results did not support this.

Also in contrast to the findings of Robertson et al., our results showed an interaction between congruency and physical size; the largest effect of physical size was during incongruent trials. However, as physical size affected RT's across all levels of congruency we can still be confident in it's serving as a measure of cognitive effort.

Working Memory, Cognitive Effort, and Cognitive Control

Results provided strong evidence for no relationship between cognitive effort as measured by the number Stroop and WM. This is a surprising result given the theory put forward by Hofmann et al. (2012), which makes a persuasive argument for WM's role in self-regulation, although we note that this is very general and may need to be refined with respect to different aspects of self-regulation, i.e. cognitive effort. Previous work has suggested that WM is strongly implicated in CRT performance (Stupple et al. 2013; Toplak, West, & Stanovich, 2011); insensitive results in the current work regarding these variables mean we are unable to add to this. The result that WM and cognitive control were not related, even modestly, is also somewhat surprising given their proposed relationship in EF models (Diamond, 2005; Hofmann et al., 2012; Miyake et al. 2000). Research looking at the relationship between WM and inhibitory control using the colour-word Stroop task clearly supports their relationship (Kane & Engle, 2003), however, the Stroop paradigm is not standard across experiments, and there is research to suggest the relationship may be dependent on the specific design (Long & Prat, 2002). Therefore it is possible that our results are a reflection of the number Stroop paradigm used in this work, which was designed foremost to enable independent manipulation and cognitive effort and cognitive control as per the aims of Robertson et al.

With regard to Diamond's (2013) proposal that inhibitory control is the key facilitator of self-regulation, we provide strong evidence against it (RT's). However, we only tested this in relation to the CRT, due to the overlap between the Stroop measures of control and effort.

Performance on the CRT was not correlated with the measure of cognitive effort provided by the number Stroop task, suggesting either that they measure independent facets of cognitive effort, or that one or both of them is not a good measure of cognitive effort. This may not be surprising given the complexity of the concept and the numerous measures used in attempt to tap it in the past (Longo & Barrett, 2010) and as previously mentioned the hot/cool status of the CRT is unclear.

ADHD Symptoms

Working memory. The relationship between inattention and WM found in previous work (Elisa et al. 2016, see Chapter 4) proved to be robust, supporting a "cool" description of inattention. However, this was not unique to inattention; impulsivity was also significantly negatively correlated with WM performance. This does not support a "hot" description of hyperactivity-impulsivity and is inconsistent with Diamond's (2005) theory that WM and inattention are exclusively related.

Cognitive effort. We predicted that inattention but not hyperactivity or impulsivity would be related to cognitive effort as measured by both the Stroop and the CRT. Results relating to both hyperactivity and impulsivity were insensitive for both measures of effort. This was also the case for data relating to inattention, although for the CRT the Bayes factor indicates we have strong evidence for no effect. This means that findings from our previous work showing that performance on the CRT was predicted by inattention but not hyperactivity or impulsivity (Elisa & Parris, 2015, see Chapter 3) are not supported.

Cognitive control. For RTs results were insensitive for the relationship between impulsivity and both of the interference contrasts, however, for error rates Bayes suggested evidence for a relationship between this ADHD symptom and the contrast incongruent – congruent (results for incongruent – control were insensitive). Given Barkley's (1997) theory of ADHD that puts behavioural inhibition as the primary cognitive deficit related to hyperactivity-impulsivity, the latter is what we would expect. These results therefore provide some support for Barkley's theory. Data regarding hyperactivity for both RTs and error rates were insensitive for both interference contrasts. Regarding inattention, data for both RTs and error rates were also insensitive for both interference contrasts and thus no conclusions can be drawn. In contrast to Barkley's theory, for a hot/cool – hyperactivity-impulsivity/inattention distinction, we would expect to have seen a relationship between inattention and cognitive control that did not exist for hyperactivity-impulsivity. Unfortunately insensitive results mean that we are not able to add to the commentary on this. Results from the wider literature regarding ADHD and inhibitory control are also mixed; a meta-analysis of studies using Stroop colour-word paradigms concluded that interference control is consistently compromised in ADHD (Lansbergen, Kenemans, & Van Engeland, 2007), while another meta-analysis on the same task showed evidence to the contrary (Schwartz & Verhaeghen, 2008). In a study that used several different measures to assess cognitive control, results suggested inattention and hyperactivity-impulsivity were negatively related to performance separate tasks (Polner, Aichert, Macare, Costa, & Ettinger, 2015). An explanation for our own findings may lie with our sample demographic. As previously noted symptoms of hyperactivity-impulsivity diminish with age past childhood and research suggests this is also the case for problems with cognitive control (Luna, Padmanabhan, & O'Hearn, 2010). Thus given that our sample consisted of adults we may be less likely to see evidence of a relationship between these two.

Summary and Conclusions

A strength of the current work is the use of Bayes factors to allow confident acceptance of the null hypothesis. However, a number of insensitive results means that our data does not allow us to make firm conclusions regarding many of the relationships explored in this study. The relationship between inattention and cognitive effort as measured by the number Stroop task was a key motivator for the present study but an insensitive result means that we cannot draw any conclusions about it. However, the Bayes factor for the correlation between inattention and the CRT provides strong evidence for no relationship between these two variables suggesting inattention is not related to the self-regulation of cognitive effort. Nevertheless, given our previous finding is in direct contrast to this (Elisa & Parris, 2015, see Chapter 3), further work is needed on the CRT and inattention. This may involve using samples with clinical level symptom severity. However, if ADHD symptoms are on a continuum as the literature suggests, effects should still be observable in community samples. It might also require using a 7-item version of the CRT (Toplak, West, & Stanovich, 2014) to provide greater variation in performance to be accounted for by inattention than the 3-item version used here. The two very different methods of tapping cognitive effort used in this research were shown to be un-related to each other which attests to the difficulty of defining and measuring cognitive effort. Future work using different measures of effort might produce different results.

Overall results make it difficult for us to comment with clarity on the "hot"/"cool" distinction proposed for ADHD symptoms. We reliably find that WM and inattention are related, which is inline with the theory, but there was no evidence for a relationship between inattention and cognitive control. Furthermore impulsivity (which should be related to "hot" cognition as per the theory) was shown to be negatively related to WM. Results relating to hyperactivity and impulsivity and both measures of effort were insensitive. Impulsivity was shown to be related to cognitive control, which refutes the

hot/cool – hyperactivity-impulsivity/inattention distinction and supports an inhibitory control explanation of this symptom as per Barkley (1997). Results relating to hyperactivity provided strong evidence for no relationship for RTs (and was insensitive for error).

There was strong evidence against a relationship between WM and cognitive effort, as well as evidence for no relationship between cognitive control and cognitive effort). Overall these findings do not support a relationship between EFs and self-regulatory processes using the current measures, meaning neither Diamond's (2013) nor Hofmann et al.'s (2012) models are supported, with the caveat that more research is needed on how effort is best measured and defined.

Chapter 6: Self-Regulatory Processes and ADHD Symptoms in a Community Sample of Adults: Evidence for a Hot/Cool Distinction

The findings from Chapter 5 did little to clarify our understanding of the relationships between ADHD symptoms and self-regulatory processes. In Chapter 6 we approach the issue with a new task that allows us to look at several aspects of self-regulation, including locus-coeruleus norepinephrine system activity in response to the exploit/explore trade-off. A categorical rather than dimensional approach is taken in this study, although DSM thresholds are lowered to include symptomology representative of the general population. A dimensional approach was ruled out due to the necessarily small sample size (owing to time restraints resultant from the nature of the experiment) that was deemed inappropriate for analysis using regression.
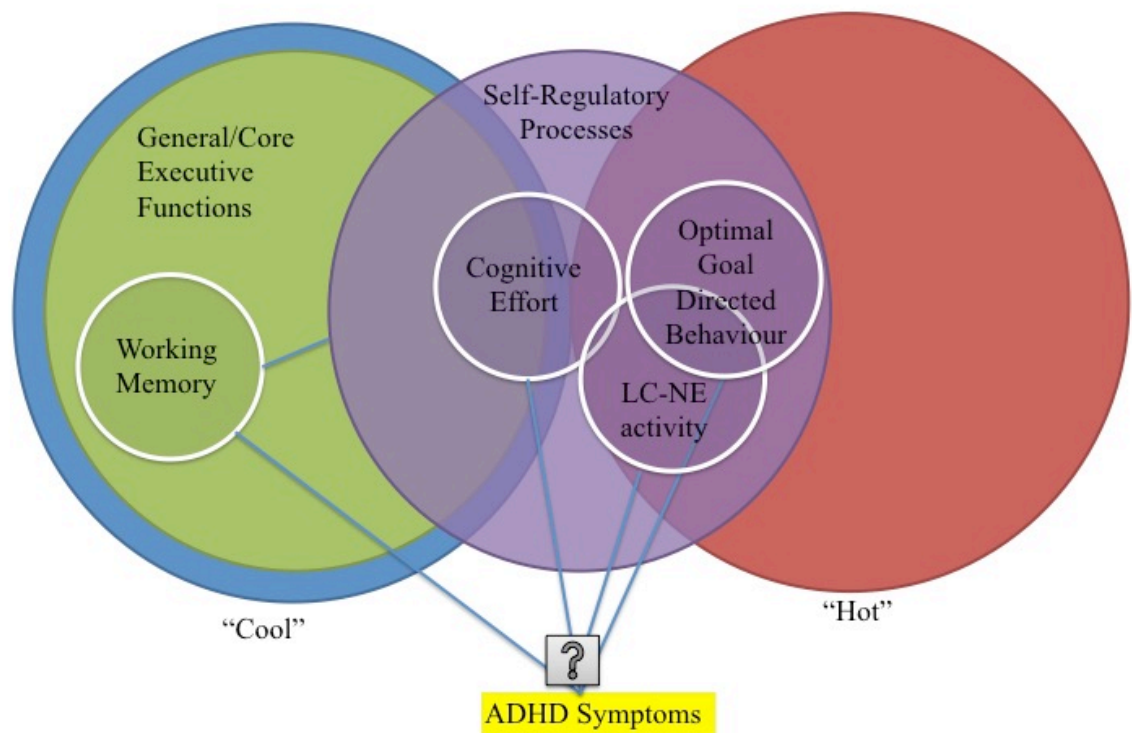
Abstract

Recent work has suggested that changes in pupil diameter relate directly to changes in locus-coeruleus norepinephrine (LC-NE) system activity (Rajkowski, Kubiak, & Aston-Jones, 1993). Two modes of LC-NE firing are represented by different pupillary responses that promote either task engagement and "exploitation" (LC phasic mode), or task disengagement in favour of "exploration" (LC tonic mode). A relationship between attention deficit hyperactivity disorder (ADHD) symptoms and "hot" self-regulatory processes modulated by norepinephrine activity has been predicted; specifically that there would be a tendency towards pupillary responses representing LC tonic mode. The nature of this possible relationship is investigated in the current work with consideration for a) theories relating to a hot/cool – hyperactivity-impulsivity/inattention distinction, and b) the relationship between executive functions and self-regulatory processes. 55 diagnosis free adults were screened for ADHD-type symptoms using DSM-5 criteria and comprised three groups; predominantly inattentive (N = 15), combined (N = 17), and control (N = 23). Pupils were tracked during a task that enables behavioural disengagement when the utility of continuing is diminished. Results provided strong evidence against a relationship between LC-NE activity and any of the ADHD symptoms. However, we show behavioural evidence for dysfunction of "hot" self-regulatory processes related to utility judgements related to hyperactivity-impulsivity. Results are discussed in relation to theories of executive function in ADHD, and findings from wider literature.

Self-Regulatory Processes and ADHD Symptoms in a Community Sample of Adults:

Evidence for a Hot/Cool Distinction

Attention deficit hyperactivity disorder (ADHD) is a childhood-onset developmental

disorder with three core symptoms; inattention, hyperactivity and impulsivity. Inattention

is characterised by an inability to focus on tasks, difficulty with planning and organisation,

forgetfulness, and high levels of distractibility. Hyperactivity and impulsivity (often

grouped together as in the Diagnostic and Statistical Manual [DSM]) are characterised by

excessive energy levels, impatience, and disruptive, often inappropriate behaviour, with a

lack of regard for social rules. Symptoms often persist into adulthood (Elliott, 2002,

Wender et al. 2001), although hyperactivity-impulsivity tends to diminish leaving

inattention as the most prominent (Biederman, Mick, & Faraone, 2000). Recent work has

established the prevalence of ADHD symptoms, particularly inattention, in community

samples of adults (Alloway, Elliott, & Holmes, 2010; Faraone & Biederman, 2005), which

fits with the now commonly accepted notion of symptoms as existing along a continuum

(Barkley & Murphy, 2006). The present study was designed based on the notion that the

key causal impairments associated with the clinical expression of ADHD are detectable in

community samples (Elisa & Parris, 2015; 2016 see Chapters 3 & 4).

A prominent theory of ADHD symptoms suggests a role for catecholamines such

as dopamine (DA), epinephrine, and norepinephrine (NE) in the modulation of attention

and impulse control (Mercugliano, 1995; Oades et al. 2005; Pliszka, McCracken, & Maas,

1996). In rats, low levels of stimulants such as methylphenidate and amphetamine produce

increases in NE and DA in the pre-frontal cortex (PFC) resulting in improved focus and

executive function (Berridge et al. 2006). Both DA and NE contribute towards maintaining

alertness, attention, focus, arousal, effort, and motivation, and are structurally quite similar.

However, each has distinct origins and projections in the brain, and selective alterations

have different behavioural effects, suggesting discrete complimentary roles for these

neurotransmitters. Both NE and DA have marked effects on the function of the PFC, with optimum levels of each required for proper control of behaviour and attention (Arnsten, 1998, 2005). Rosseti & Carboni (2005) conclude that while DA is associated with reward expectancy, NE is involved in the active maintenance of task information. Evidence for the involvement of catecholamines in ADHD comes primarily from drug studies where many of the medications used successfully to treat symptoms of ADHD alter catecholamine transmission (Arnsten, 2006; Oades et al. 2005; Mercugliano, 1995). More work is needed however to identify whether there is an association between DA, NE and the ADHD subtypes. Research suggests that DA may be less relevant to ADHD in adults given the prominent symptom in this age group is inattention. For example, issues associated with the dopamine transporter gene DAT1 have been specifically linked with hyperactive-impulsive symptoms of ADHD but not with inattention (Gizer et al. 2008; Waldman et al. 1997). DAT1 is abundant in the striatum, an area that Diamond (2005) suggests is the primary site for neurobiological dysfunction in ADHD-combined type. The present research will focus on exploring the role of NE in ADHD and its subtypes with particular interest in its role as an attention modulator. Although it is unlikely that a single neurotransmitter can explain all symptoms of ADHD fully, a review article by Biederman and Spencer (1999) suggests that neurobiological and pharmacological research provides compelling support for a noradrenergic explanation of ADHD.

The Locus-Coeruleus Norepinephrine System

NE is synthesised and projected from the locus-coeruleus (LC), a small nucleus located near the pons in the brainstem. The wide and diffuse projection from the LC is known as the LC-NE system which has two modes of function; phasic and tonic, which affect online task attention. Phasic firing typically occurs in response to a stimulus event during moderate baseline LC activity. This mode of function indicates engagement with a task,

and is associated with heightened task performance (Aston-Jones, Rajkowski, Kubiak, & Alexinsky, 1994). Elevated tonic mode firing occurs with increased baseline LC activity, and an absence of phasic responses. This mode of function indicates task disengagement, and is associated with poorer performance, and distractibility (Aston-Jones et al., 1994). There is an inverted-U relationship between LC activity and performance, meaning that performance is optimal with moderate levels of tonic activity, combined with stimulus-evoked phasic activation. This can be thought of as the goldilocks level of activation; performance is worse with too little or too much arousal (see fig 1; Aston-Jones, Rajkowski, & Cohen, 1999).
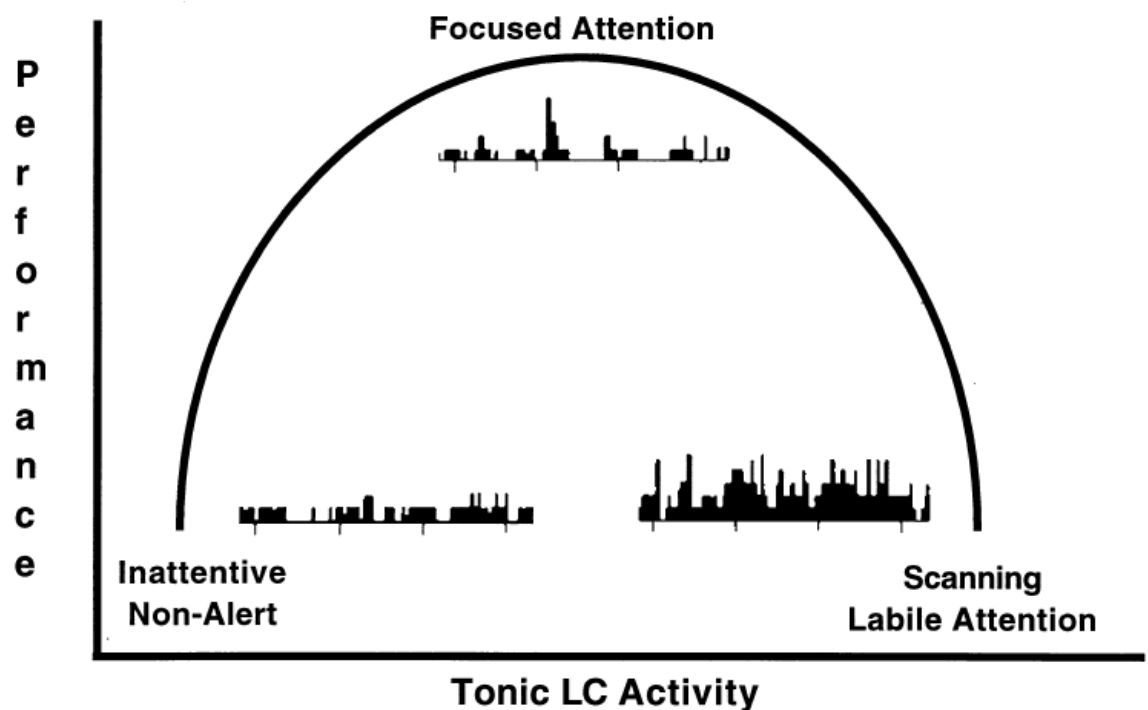

Figure 1. The inverted-U relationship between LC tonic activity and task performance as per Aston-Jones, Rajkowski, and Cohen, (1999).

Recent research has suggested that changes in firing mode of the LC are indicative of control state. The adaptive gain theory (AGT; Aston-Jones & Cohen, 2005) explains how the LC-NE system regulates control state for engagement versus disengagement. This

is known as the *exploit/explore trade-off* and illustrates the balance between pursuing known sources of reward (exploitation), and exploring new ones (exploration). AGT proposes that the LC-NE system responds to changes in task utility by modulating the gain (responsivity) of processing in appropriate cortical circuits. It is suggested that the anterior cingulate and orbitofrontal cortex play a critical role in evaluating costs and rewards, and jointly provide the LC with on-going evaluations of task utility (Nieuwenhuis & Jepma, 2011). The system then adjusts between firing modes in order to maximise utility (Aston-Jones & Cohen, 2005).

Executive Function and Self-regulation: Links to LC-NE Activity, and ADHD Symptoms

Self-regulation is a multifaceted concept, but can be broadly defined as sub-processes of general executive functions (EFs) that regulate emotional, motivational, and cognitive arousal, and ultimately behaviour towards a goal (Diamond, 2013). Research has identified several components of self-regulation including cognitive control, cognitive effort, and optimal goal directed behaviour. The last of these is of particular interest in relation to LC-NE functioning, and refers to behaviours that maximise utility inline with goal representations. The exploit/explore trade-off is an example of this. A self-regulatory explanation of LC-NE function is supported in the literature; norepinephrine is thought to enable adaptive control based on utility, and it has been shown that phasic responses reflect error processing and facilitate the phenomenon of post-error slowing (Nieuwenhuis, Aston-Jones, & Cohen, 2005; Shiels & Hawk, 2010).

A link has already been made between ADHD symptoms and self-regulatory processes. Most notably the cognitive-energetic model of Sergeant (2000) proposes that inhibitory control deficits can be explained by energetic and state factors. The models' energetic pools "arousal" and "activation", reflect tonic and phasic responses to task

demands and stimuli, while "effort" is related to the cognitive demands of a task. Whilst the research on self-regulation in ADHD has produced mixed results (Schachar, Mota, Logan, Tannock, & Klim, 2000; Scheres et al. 2003; Schwartz & Verhaeghen, 2008; Vaidya et al. 1998), the theories of Barkley (1997) and Sergeant (2000) suggest that specific cognitive control deficits may be related to hyperactivity-impulsivity. Despite this theoretical leaning, we note that much of the research in this area does not account for ADHD subtype.

Several researchers have predicted that ADHD is associated with the explore/exploit component of self-regulation underpinned by dysfunctional LC-NE activity (Aston-Jones, Rajkowski, & Cohen, 2000; Howells, Stein, & Russell, 2012; Ressler & Nemeroff, 2001). More specifically, it has been suggested that ADHD would be characterised by a tendency towards overly tonic activity (exploration), and an absence of phasic bursts (exploitation). This is supported by the finding that the cognition enhancing effects of low doses of methylphenidate, probably involve modest alterations in LC discharge (Devilbiss & Berridge, 2006). However, this facet of self-regulation is yet to be investigated in the context of ADHD and its subtypes. Research has shown that adults with ADHD score higher on a novelty seeking scale than controls (Downey, Stelson, Pomerlau, & Giordani, 1997) suggesting a tendency for exploration, but this work did not look at differences between ADHD symptoms. The concept of exploration could fit with either or both the notion of distractibility and lack of focus associated with inattention, and the impulsive behaviour associated with hyperactivity-impulsivity.

A separate but related body of literature argues for a dissociation between "hot" affective decision-making, and "cool" EF processes, and for their separable contributions to ADHD. The term "cool" cognition refers primarily to the three core EFs (working memory, inhibitory control, and cognitive flexibility; Miyake et al., 2000). "Hot" cognition refers to the type of EF processes required to make judgements in the face of emotional

and motivational factors. The distinction also applies to the self-regulatory sub-processes so that there are "hot" and "cool" aspects of self-regulation. For example, judgements based on utility towards optimal goal directed behaviour as described above, would be considered "hot", while cognitive control aspects of self-regulation (i.e. shielding from or overriding irrelevant information) would be considered "cool". It is proposed that inattention is associated with "cool" cognition, and hyperactivity-impulsivity with "hot" cognition (Castellanos, Sonuga-Barke, Milham, & Tannock, 2006; Toplak, Jain, & Tannock, 2005). This is supported by research suggesting that deficits in the "cool" EF working memory (WM) are unique to inattention (Diamond, 2005; Elisa & Parris, 2016, see Chapter 4). In research utilising a task designed to tap "hot" cognition Toplak et al. (2005) found that adolescents with ADHD performed less optimally than controls, and that WM ability did not influence performance. Importantly, they found that performance on the task was correlated with symptoms of hyperactivity-impulsivity, and not with inattention.

A possible conflict with the idea of a distinction between ADHD symptoms and the "temperature" of their underlying cognition arises depending on the theoretical leaning towards the direction of the relationship between general EFs, particularly WM, and self-regulatory processes. There is evidence to suggest that "cool" EFs facilitate both "temperatures" of self-regulatory processes (Diamond, 2013; Hofmann Schmeichel, and Baddeley, 2012). If the relationship were in this direction then a distinction between "hot" and "cool" cognition in ADHD would still fit theoretically. However, it is suggested that LC-NE activity (which we associate with "hot" self-regulation) influences WM function through modulation in the PFC (Arnsten & Li, 2005; Oades et al. 2005; Rosseti & Carboni, 2005), which would mean inattention (assuming its relationship with WM as previously evidenced) should be related to this "hot" cognition. Findings from studies using NE drugs to look at the effects on WM are mixed, but a link between the two has been reported

(Chamberlain, Muller, Blackwell, Robbins, & Sahakian, 2006). This potential relationship would support the relationship between executive functions as proposed by Hofmann et al. since they propose a role for working memory in self-regulation. In contrast, Diamond (2013) restricts this relationship to the executive function process of inhibition, eschewing a role of working memory in self-regulation.

Measuring LC-NE Activity

Seminal work in the 1960's showed that task evoked pupillary responses reflected changes in cognition related to task difficulty and corresponding mental effort (Hess & Polt, 1964, Kahneman & Beatty, 1966). However, until more recently pupillometry was not widely employed in the field of psychology due to its lack of face validity as a measure of brain function (Beatty & Lucero-Wagoner, 2000). It has now been shown that changes in pupil diameter directly relate to changes in LC-NE activity. Rajkowski, Kubiak, and Aston-Jones (1993) published an abstract suggesting that baseline pupil diameter closely tracked NE activity from direct LC neuronal recordings in monkeys while they performed a target detection task. Larger baseline pupil diameters reflected LC tonic mode and task disengagement, while smaller baseline pupil diameters reflected LC phasic mode and engagement with the task. This finding was confirmed and extended by Joshi, Li, Kalwani, and Gold (2016) who concluded that changes in pupil diameter accurately reflect neural activity in the LC, and that LC-mediated arousal may coordinate activity throughout the brain. Task evoked pupillary dilations are thought to be indicative of an LC phasic response to salient stimulus (Einhauser, Stout, Koch, & Carter, 2008). Gilzenrat, Nieuwenhuis, Jepma, and Cohen (2010) tested human participants using a similar target detection task to that used with monkeys, and found that in line with LC-NE-pupillary-response theory, small baseline pupils coupled with larger task evoked dilations were associated with improved task performance. Large baseline pupils were associated with

poorer task performance and smaller task evoked dilations. They also investigated the relationship between pupil diameter and control state, and found evidence in support of AGT. In their *diminishing utility task* (DUT) participants were able to make a behavioural indication of change in control state by actively disengaging (electing to escape) from the task if the perceived utility of maintaining engagement began to decline. Pupil data accurately tracked decline of task engagement preceding escape, and building again post-escape. Specifically increasing baseline pupils and diminished stimulus evoked dilations were seen in trials leading up to escape. This parallels the relationship between patterns of LC activity and control state predicted by AGT (an inverted-U shape).

There is very little research looking at the pupillary response in ADHD. Karatekin, Bingham, and White (2009, 2010) found evidence suggesting there may be group differences between ADHD children and controls in ability to apply effort (as measured by pupillary response) when needed. However, Kara, Turkbay, Urdem, Congologlu, and Ilhan (2012) found no differences in pupil diameter between ADHD children and controls.

The Present Research

The DUT has several practical applications for use in ADHD symptom research. It can be used to tap into two aspects of self-regulatory processes; cognitive effort (the allocation of resources to a task or decision), and optimal goal directed behaviour via adaptive control, as well as measuring LC-NE activity by proxy of pupil diameter while participants complete a task requiring assessment of utility. We set out to look at whether groups with ADHD-type symptoms (predominantly inattentive, and combined) differed from controls on measures derived from the DUT. Specifically we were interested in whether there would be any differences in the pattern of pupil responses between adults with and without ADHD-type symptoms.

Regarding behavioural variables measuring self-regulatory processes, we were interested in whether there were any differences between groups in explore/exploit behaviour ("hot") that might show ADHD-symptoms to be related to impairments in judgements based on utility. Optimal goal directed behaviour would be to exploit known sources of reward until utility is diminished. It was expected that participants with ADHD symptoms would be more inclined to explore, even if this is not the optimum behaviour. This tendency towards exploration would also be indexed by completing trials with easier tone discriminations, suggesting an avoidance of trials requiring increased cognitive effort. Cognitive effort is influenced by both "hot" and "cool" cognitive factors (Longo & Barrett, 2010), so could apply to both of our ADHD-type groups. Previous work looking at "cool" aspects of cognitive effort and ADHD symptoms has produced mixed findings (Elisa & Parris, 2015; Elisa & Parris, in preparation, see Chapters 3 & 5). We might also expect to see slower reaction times in the trials leading up to an escape in our ADHD-type groups compared to controls, as the requirement for cognitive effort increases. In both ADHD groups and a control group behavioural disengagement should be reflected by pupillary responses indicating elevated tonic mode firing, replicating Gilzenrat et al. (2010). However, it was expected that ADHD groups will have larger baseline pupils, and smaller stimulus evoked dilatations relative to controls both over the course of the task and particularly in the trials surrounding a behavioural escape. This finding would support Aston-Jones and Gold's (1999) suggestion that ADHD symptoms are associated with elevated tonic activity and an absence of phasic LC activation. It is assumed that any differences between the ADHD groups will be attributable to hyperactivity-impulsivity-related impairments.

The study was designed to enable us to assess the relationships between "hot" and "cool" cognitive processes and the different ADHD symptoms. On the one hand we have evidence for a relationship between self-regulatory processes (both "hot" and "cool") and

"cool" WM, which is consistent with Hofmann et al.'s proposal, and on the other we have the notion of separable contributions for each temperature of cognition to ADHD symptoms; "hot" to hyperactivity-impulsivity, and "cool" to inattention. If the former were true we might expect (depending on the direction of the relationship) self-regulatory deficits associated with LC-NE activity to be related to inattentive symptoms (given the evidence for a relationship between inattention and WM) and thus be present in both our ADHD-type groups. If the latter were true we would expect such deficits to be present only in the group with hyperactive-impulsive symptoms, a finding that would also support Diamond's notion that self-regulation is primarily supported by inhibition.

Method

Materials and Tasks

ADHD screening. Screening for ADHD symptoms was completed using a questionnaire based on the Adult ADHD Rating Scale-IV (Barkley, 2011), but adapted to reflect DSM-5 criteria. The scale contains the 18 items (9 for inattention, 9 for hyperactivity-impulsivity) from the DSM-5 criteria for ADHD with each item answered on a 4-point scale (from 0-3; *not at all*, *sometimes*, *often* and *very often*). As per DSM criteria, items were taken to be indicative of a symptom if they were rated often or very often; this is referred to as a positive rating. Participants were asked to read each question carefully and consider to what extent they had experienced each item description over the last 6 months. They completed the questionnaire either in paper or electronic format.

The DSM threshold is 5 positively rated items on either or both the inattention and hyperactivity-impulsivity subscales. For this research the threshold was lowered to 4 to include a wider range of symptomology reflective of the general population. A score of 2 or less positively rated items on either of the subsets suggests the symptom is not present.

Participants who scored three on either subsets were considered sub-threshold and therefore not included in the research.

Working memory. The *letter-monitoring task* (Duncan et al., 1996) assesses task integration through measuring goal-neglect, is thought to tap the episodic buffer component of WM, and correlates strongly with traditional measures of WM (Elisa & Parris, 2016). This task was chosen for its demonstrated relationship with inattention.

Intelligence quotient (IQ). A shortened version of the Wechsler Abbreviated Scale of Intelligence (WASI-II) was included. From this measure a t-score for each relevant subscale (Gf & Gc) is calculated, and an overall IQ score is obtained from an age-matched set of scores.

Diminishing utility task (Gilzenrat et al. 2010, see fig 2). Participants performed a number of pitch discriminations, for which points were earned for correct judgement. On each trial, participants first heard a reference tone, followed shortly by a comparison tone. They were instructed to make a speeded response to whether the comparison tone was higher or lower in pitch than the reference tone, using buttons on a gamepad. For correct responses, the value of that trial was added to the participant's total score, the proceeding trial's value increased by 5 points, and the difficulty of the pitch discrimination was increased. For incorrect responses, participants earned no points, the value of the subsequent trial was reduced by 10 points (with a floor of 0 points), and difficulty remained the same. In order to measure behavioural disengagement, participants were given the option to escape from the current block of discriminations without penalty at the beginning of each trial, moving to a new block of trials reset to the easiest level of difficulty. Participants were instructed to try and earn as many points as possible over the 30-minute duration of the task.

On the first trial of each block, the difference in pitch between the reference and comparison tones was 64 Hz (50/50 higher and lower). For each block the reference tone

stayed the same, and the difference between this and the comparison tone was halved following a correct response. If participants correctly discriminated a 0.25 Hz difference, tones became impossible to discriminate on the subsequent trial (i.e. 0 Hz difference). This means there were 9 discriminable tones for each block, with the tenth set impossible to discriminate between. For these indiscriminable trials there was a 50/50 chance of earning points. Indiscriminable trials continued until participants elected to escape. After an escape, a new block was chosen randomly without replacement from a set of four reference tones (400, 550, 700, and 850 Hz), which was replenished once all tones had been exhausted.

At the start of each trial participants were shown a score/value screen that displayed the total number of points earned so far, and the points value of the proceeding trial. Participants then indicated whether they wanted to accept or escape the trial using the gamepad. If a participant chose to accept, a 250-msec reference tone followed after a 5-sec delay. This was followed by an interval of 4-secs, and a 250-msec comparison tone. Participants then indicated as quickly and accurately as possible whether the comparison tone was higher or lower in pitch than the reference tone. 3-secs post response a 250-msec feedback (for accuracy) sound was played. After a delay of 4-secs, a score/value screen for the next trial was shown. If participants elected to escape, a 250-msec escape sound was played, and a score/value screen for the first trial of the new block was shown.

Participants were seated 60cm from the display monitor displaying a blank medium grey field. They were instructed to hold their gaze within a central fixation circle delineated by a thick black border subtending 4° of visual angle. Trials did not proceed unless gaze was maintained within this circle. Participants were also asked to limit blinking throughout each trial, and were encouraged to blink in-between trials at the score/value screen before pressing to accept/escape. Participants completed several practice trials to familiarise themselves with the format before the experiment started.

Practice was repeated until participants indicated that they were comfortable with the task. Stimuli were played through speakers either side of the monitor.
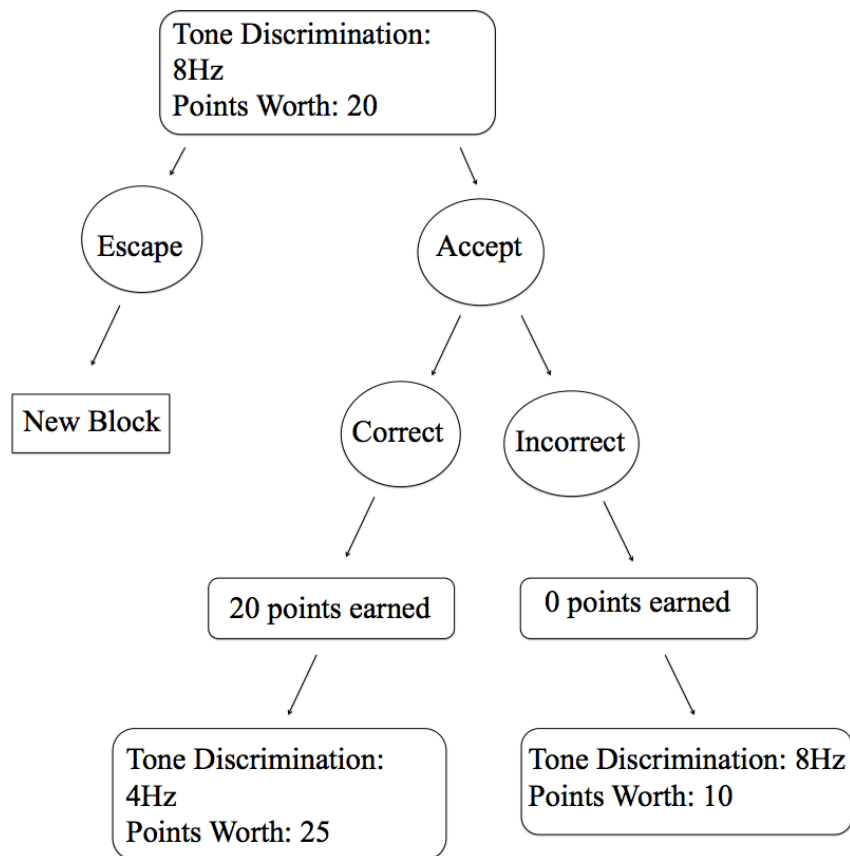
Figure 2. An example of play for one trial of the DUT.

Stimuli were programmed and are delivered using Experiment Builder (SR Research). Pupil diameter was recorded using the head-mounted EyeLink 1000 eyetracker (SR Research). Eye images were sampled by infrared camera at 1000 Hz. The dominant eye of each participant (determined before recording, and tested during practice trials) was recorded throughout the experiment.

Baseline pupil diameter was recorded before every trial, and is defined as the average diameter during the 1-sec interval prior to the onset of the score/value screen (note that these are pre-trial baselines not pre-experimental baselines). Peak dilations of the pupil were measured as the maximal deviation from this baseline in the 2.5 secs following onset

of the comparison tone. As in Gilzenrat et al., in order to look at pupil data relative to behavioural disengagement, trials were averaged as a function of their position relative to escape events. Gilzenrat et al. only considered escape events preceded and followed by at least four accepted trials to ensure sufficient levels of task engagement. In the current research we reduced this to three as we found that restricting it to four greatly reduced the number of trials eligible to be included in the analysis.

As our analysis included investigation of group differences, we took a closer look at the behavioural dependent variables from the DUT. A description of each of these and their relation to either "hot" or "cool" self-regulatory processes can be seen in Table 1.

Table 1.

Descriptions of behavioural dependent variables for the diminishing utility task

Dependent Variable	Description
Reaction time (RT): "Cool" self-regulatory processes	The time in ms taken to respond (higher or lower) to the comparison tone. Indiscriminable trials included. Reaction times are expected to slow in response to trial difficulty thus reflecting "cool" processes of cognitive effort.
% Escapes: "Hot" self-regulatory processes	The percentage of times a participant elected to escape across all trials in the task. An escape represents making a decision to "explore" rather than "exploit" thus reflecting "hot" optimal goal directed behaviour.
% Indiscriminable trials: "Hot" self-regulatory processes	The percentage of indiscriminable trials played over the task. This measure gives an indication of participants' perseverance with tones that were impossible to discriminate between and relates to "hot" optimal goal directed behaviour.
% Zero point trials: "Hot" self-regulatory processes	The percentage of trials played for where no points could be won. This measure gives an indication of participants' perseverance with a block even if some trials had no worth, and relates to "hot" optimal goal directed behaviour.
Frequency difference: "Hot" self-regulatory processes	The average frequency difference between the reference and comparison tones. This is a measure of the average difficulty of the trials played over the task, and should reflect choices regarding "hot" cognitive effort based on utility.
Expected Value: "Hot" self-regulatory processes	This was computed to estimate the probability that participants would get trials of each difficulty level correct. Looking at this variable in conjunction with behavioural disengagements gives a measure of "hot" optimal goal directed behaviour.
Total score	The total score from the 30 minute playing time. Indiscriminable trials not included.
Average points played for	The average number of points played for on each trial.
Average points won	The average number of points won on each trial. Indiscriminable trials not included.

Two variables measure cognitive effort (frequency difference and reaction time), and three tap into our assessment of optimal goal directed behaviour (percentage of escapes, percentage of indiscriminable trials, and percentage of zero point trials). As in Gilzenrat et al. we also computed an estimate of expected value for each of the 6 trials surrounding an escape and the escape trial itself. This was calculated for each participant by multiplying the potential value of a trial by the expected accuracy on a trial of that difficulty for that participant. This was determined by averaging the accuracy of all trials with the same frequency difference, resulting in the probability the participant would get a trial of that difficulty correct. The measure of expected value allowed us to look at whether participant's behaviour was optimal and based on on-going assessments of task utility.

Data Analysis

Bayes Factors (B) were used to assess the strength of evidence in support of hypotheses where the p value indicated no significant result. These were calculated using the procedures outlined in Dienes (2014). Proposed cut-offs for acceptance of a hypothesis (Jeffreys, 1998), states a B above 3 as providing substantial support for the alternative hypothesis, whilst below 1/3 provides substantial support for the null hypothesis. A B that falls between 1/3 and 3 deems the data insensitive as to whether the alternative or null hypothesis should be accepted. We modelled the predictions of the theory of an absence of evidence for a relationship with a half-normal whose mean and standard deviation values reflected what could reasonably be expected in the circumstance of a significant result. For example Bayes factors for non-significant behavioural dependent variables were calculated using the mean difference and standard deviation from a significant behavioural dependent variable. $B_{H(0, X)}$ refers to the Bayes Factors testing each hypothesis, where 'H' indicates a half-normal distribution, and 'X' the predicted standard deviation of this half-normal, against a null hypothesis of no difference. Where p values and Bayes factors conflict, the

Bayes factor is taken as conclusive. A p value of $> .05$ does not necessarily indicate that there is no effect, simply that one was not found in the current data set. The use of Bayes factors increases researcher confidence in concluding that there is no effect.

Participants

Participants were identified through prior screening as part of a wider research programme. A total of 55 male (N = 17) and female (N = 38) participants aged 18-35 participated in the research. Participants were allocated to one of three groups based on their ADHD screening scores. A primarily inattentive-type group (N = 15) consisted of participants who scored four or more positively rated items on the inattention subset, and 2 or less on the hyperactivity-impulsivity subset; and a combined-type group (N = 17) consisted of participants who scored 4 or more on both the hyperactivity-impulsivity subset and the inattention subset. Finally a control group (N = 23) consisted of participants who scored 2 or less on both subsets. Groups differed significantly on inattention scores [$F_{(2.52)} = 172.53$, $p < .00$, see Table 2] with the control group being significantly lower than both the combined-type ($p < .00$) and inattentive-type groups ($p < .00$) and the combined-type group reporting higher scores on inattention than the inattentive-type group ($p < .00$). There were also significant group differences in hyperactivity-impulsivity scores [$F_{(2.52)} = 113.239$, $p < .00$] with the control and inattentive-type groups being significantly lower than the combined-type group ($ps < .000$), but with no difference between the control and inattentive-type groups ($p < .131$). Participants were reimbursed £8 for their time.

Procedure

Participants complete all tasks individually in a quiet room. The order of tasks is counter-balanced, but participants complete either the DUT followed by IQ and WM tasks, or the other way around.

Ethical approval for this research was obtained from Bournemouth University ethics committee.

Table 2.

DSM scores for inattention and hyperactivity-impulsivity across groups

Group	DSM subset	Mean	SD
Control	Inattention	0.48	0.67
	Hyperactivity-impulsivity	0.65	0.78
Combined-type	Inattention	6.41	1.54
	Hyperactivity-impulsivity	5.47	1.33
Inattentive-type	Inattention	4.87	0.83
	Hyperactivity-impulsivity	1.33	1.05

Results

Results are split into two sections. Firstly we looked at data pertaining to the whole sample and replicated the analysis conducted by Gilzenrat et al. (2010). Secondly we conducted analysis between our ADHD-type groups.

Average t-scores for fluid and crystallised intelligence along with letter-monitoring scores can be seen in Table 3. In the diminishing utility task participants completed on average 74.58 trials (range 59-96), and elected to escape 6.64 times (range 0-21) over the course of the 30-minute playing time. The average epoch contained 7.64 trials. The average game score was 633.18 (range 130-1270). The average point value played for on a single trial was 16.74, and the average point value attained was 10.91. The average frequency difference between the reference and comparison tones was 15.31.

We now look at measures as observed leading up to and following an escape. Figure 3 shows average RTs and accuracy for trials surrounding escapes. As in Gilzenrat et al., on average RTs were slower [2382.68 vs. 1442.38 msec; $F_{(1,48)} = 49.353$, $p = .00$] and performance less accurate [13.01% vs. 87.57%; $F_{(1,48)} = 254.116$, $p = .00$] prior to an escape than afterwards. However, unlike Gilzenrat we only see a trending increase in RT

across trials immediately post-escape [$F_{(1,48)}$ = .817, p =.430, comparisons: $ps > .05$, $Bs_{H(0,.17)} > .33 - < 3$], and in the trials leading up to an escape [$F_{(1,48)}$ = 1.848, p = .163, comparisons: $ps > .05$, $Bs_{H(0,.17)} > .33 - < 3$], although RT peaked on the trial immediately prior to escape.

Table 3.
Means and SD's for crystallised and fluid intelligence t-scores, and letter monitoring scores

Dependent Variable	Mean	SD
Gc	52.6364	7.47431
Gf	48.7091	7.522
Letter-Monitoring	7.9273	1.46382
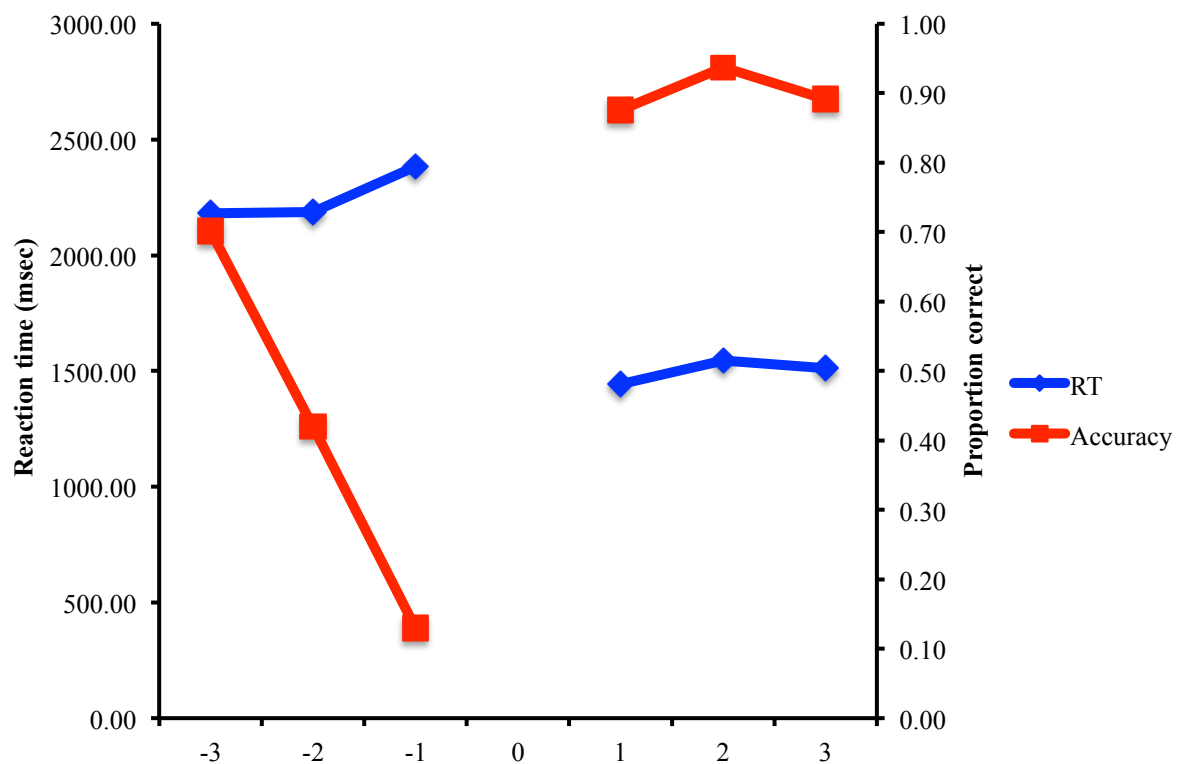
Figure 3. RTs and accuracy for trials surrounding escapes.

We also only saw a trending decrease in accuracy immediately post-escape [$F_{(1,48)}$ = 1.379, p = .256, comparisons: $ps > .05$, positions -3 vs. -2; $B_{H(0,.17)} > .33 - < 3$, positions -3 vs. -1;

$B_{H(0,.17)}$ = .26, positions -2 vs. -1; $B_{H(0,.17)}$ > .33 - < 3], but a significant decrease in the trials leading up to the escape [$F_{(1,48)}$ = 3.995, p = .00].

Figure 4 shows pupil measures (BPD & SED) for trials surrounding escapes. As in Gilzenrat et al., BPD significantly increased across the trials leading up to an escape as revealed by linear trend analysis [$F_{(1,48)}$ = 6.914, p = .011], and significantly decreased over the trials immediately post-escape as participants started a new epoch [$F_{(1,48)}$ = 24.743, p = .00]. We also replicated the overall inverted-U shaped trend centered on the escape trial which was significant as indicated by quadratic trend analysis [$F_{(1,48)}$ = 12.780, p = .001].

As expected by Gilzenrat et al., we saw a significant decrease in SED across the trials leading up to an escape [$F_{(1,48)}$ = 8.390, p = .006], as well as a significant increase over the trials immediately post-escape as a new epoch was started [$F_{(1,48)}$ = 26.607, p = .00].

Figure 4. BPD and SED over trials surrounding escapes.

Figure 5 shows expected value across the trials surrounding escapes. As in Gilzenrat et al., participants on average elected to escape when exp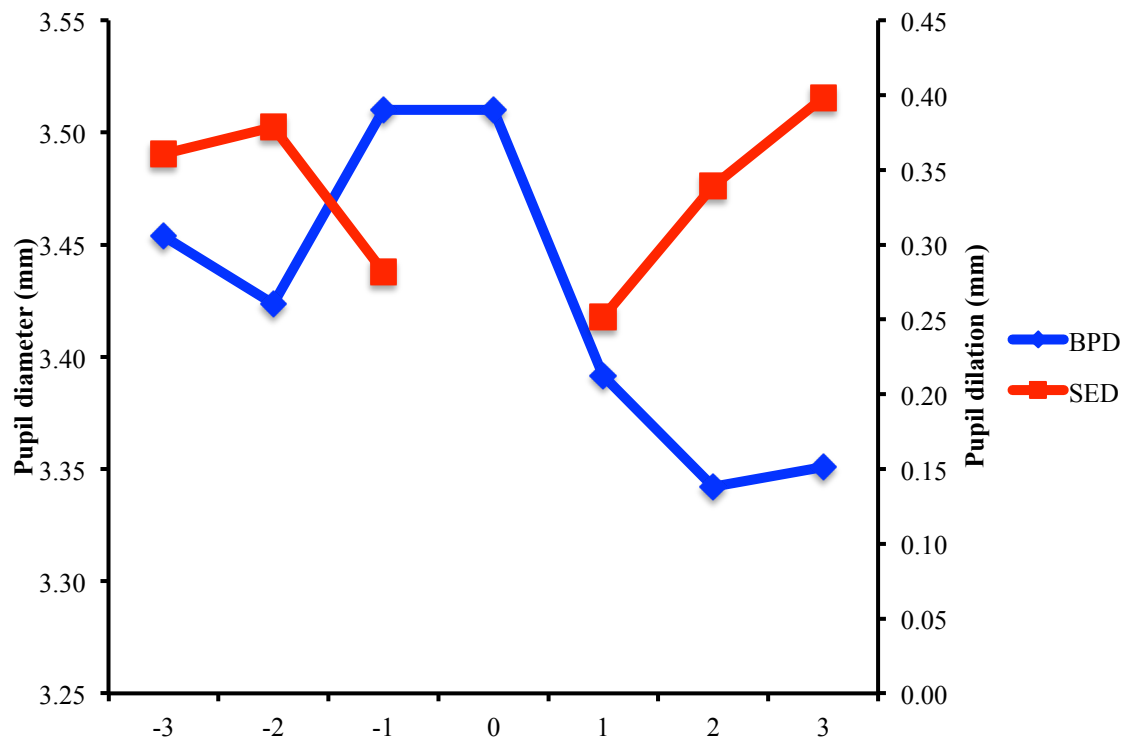ected value was at a minimum. We also see the same significant quadratic trend centered on the escape that mirrors the pattern observed in BPD [$F_{(1,48)}$ = 130.654, p = .00, see fig 6]. However, our results diverge from Gilzenrat et al. in our regression analyses for predictors of pupil diameter (both BPD and SED). When we regressed our four performance metrics (expected value, actual value, expected accuracy, and actual accuracy) onto BPD, all were insensitive (expected value: r^2 = .046, p = .141, $B_{H(0,.17)}$ = 2.44; actual value: r^2 = .033, p = .213, $B_{H(0,.17)}$ = 1.74; expected accuracy: r^2 = .025, p = .282, $B_{H(0,.17)}$ = 1.42; actual value: r^2 = .001, p = .863, $B_{H(0,.17)}$ = 1.34), although we note that expected value was closest to the threshold. When these variables were regressed onto SED expected value and actual value showed evidence for no effect (r^2 = .0001, p = .952, $B_{H(0,.17)}$ = .24; r^2 = .001, p = .806, $B_{H(0,.17)}$ = .20 respectively), and expected accuracy and actual accuracy were insensitive (r^2 = .0001, p = .957, $B_{H(0,.17)}$ = 1.32; r^2 = .001, p = .820, $B_{H(0,.17)}$ = 1.35 respectively). We also regressed our measures of effort onto BPD and SED. Neither RT nor frequency difference were good predictors of either pupil measure (BPD: r^2 = .013 p = .433, $B_{H(0,.17)}$ = .99, SED r^2 = .002, p = .771, $B_{H(0,.17)}$ = .27, BPD: r^2 = .012, p = .451, $B_{H(0,.17)}$ = .01, SED: r^2 = .000, p = .890, $B_{H(0,.17)}$ = .01 respectively).

Finally we also regressed our fluid intelligence and working memory measures onto pupil diameter. Neither fluid intelligence nor working memory predicted BPD (r^2 = .003, p = .687, $B_{H(0,1.60)}$ = .059; r^2 = .002, p = .754, $B_{H(0,1.60)}$ = 1.32 respectively) or SED (r^2 = .005, p = .594, $B_{H(0,1.60)}$ = .019; r^2 = .008, p = .513, $B_{H(0,1.60)}$ = 1.06 respectively), with Bayes values being either at the low end of insensitive or providing evidence for no effect.

Table 4 shows correlations between letter-monitoring performance, and self-regulation variables from the DUT. Results show clear evidence for no relationship between WM and any of the aspects of self-regulation as measured behaviourally (*ps* >

.05, $Bs_{\text{H}(0,.50)} < .33$). Results for both BPD and SED were insensitive $ps > .05$, $.33 < Bs_{\text{H}(0,.50)} < 3$).
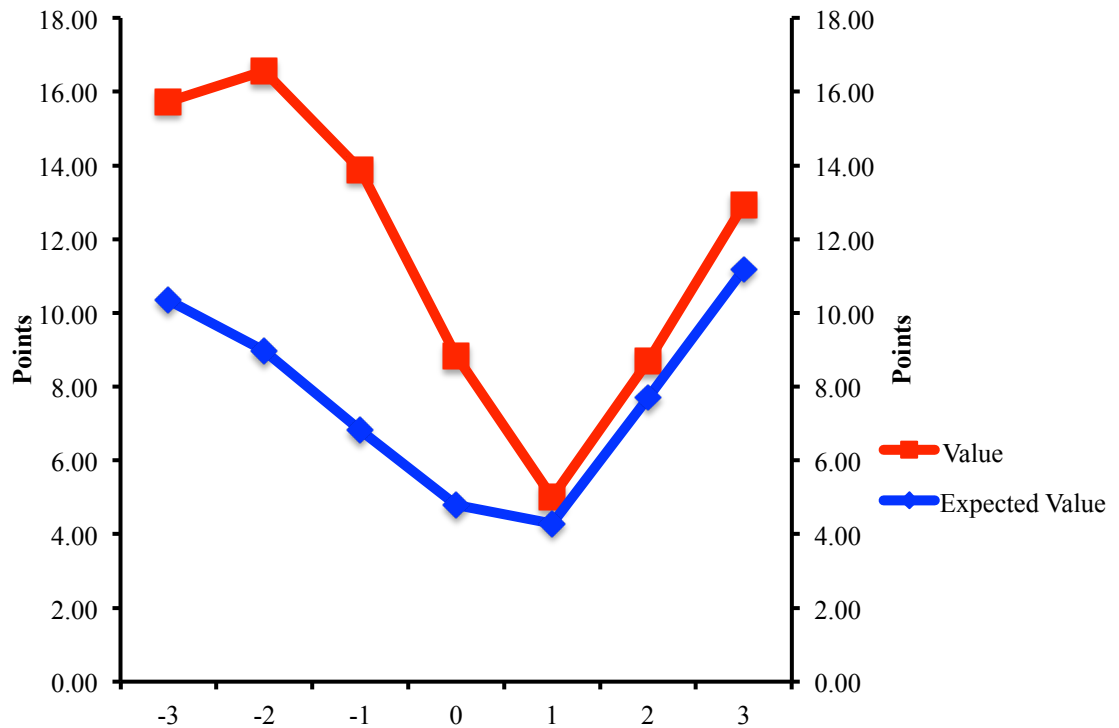

Figure 5. Expected value and actual value across trials surrounding escapes.
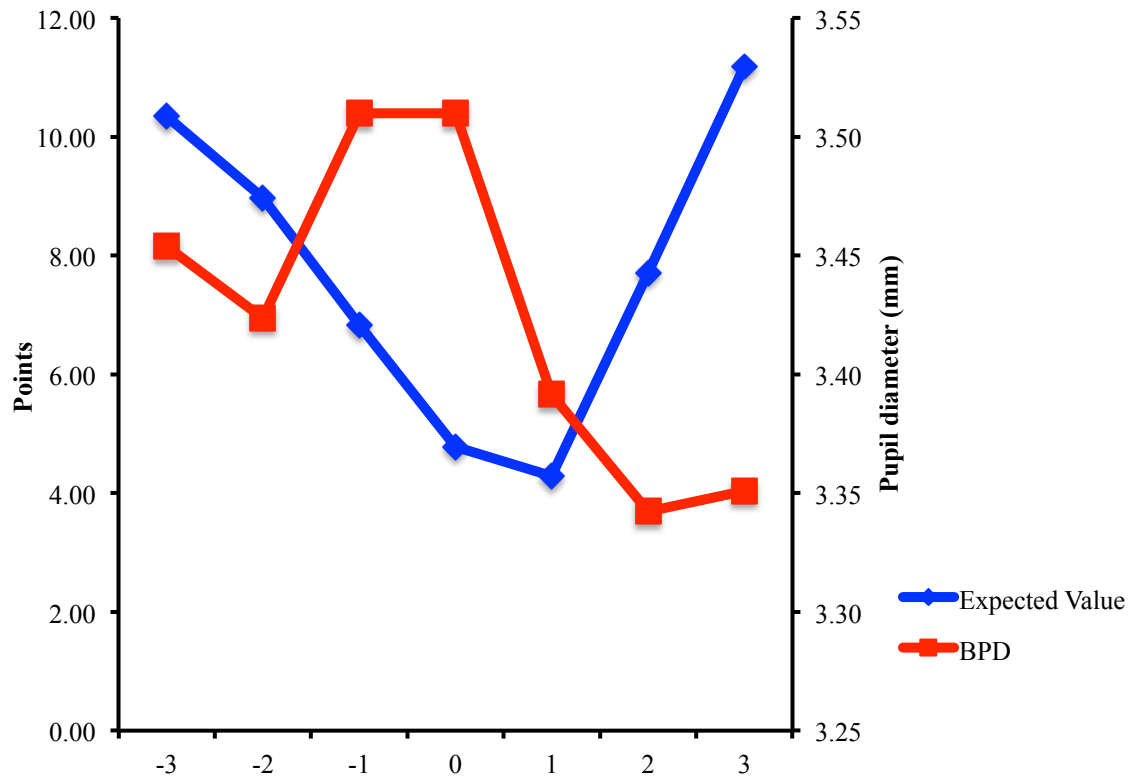

Figure 6. BPD and expected value across trials surrounding escapes.

ADHD-Type Group Differences

Table 5 shows means and SD for our IQ and WM measures across groups. ANOVA's

showed significant group differences in both crystallised [$F_{(2.52)}$ = 3.174, p = .05], and fluid

intelligence[$F_{(2.52)}$ = 6.655, p = .006]. In both cases this was driven by the combined-type

group having a significantly lower score than both the control and inattentive-type groups

(comparisons: Gc control vs. combined; p = .082, $B_{H(0,14.04)}$ = 3.51, control vs. inattentive;

p = .970, $B_{H(0,14.04)}$ = .20, combined vs. inattentive; p = .081, $B_{H(0,14.04)}$ = 3.93, Gf control

vs. combined ; p =.019, control vs. inattentive; p = .855, $B_{H(0,14.04)}$ = .26, combined vs.

inattentive; p = .010). There were also significant group differences on our working

memory measure, the letter-monitoring task [$F_{(2.52)}$ = 8.693, p = .001]. Pairwise

comparisons showed that as expected performance by the inattentive-type group was

significantly lower than controls (p < .001). The data for the control and combined-type

groups, and the combined-type and inattentive-type groups was insensitive (p = .364,

$B_{H(0,14.04)}$ = .33; p = .127, $B_{H(0,14.04)}$ = .59 respectively).

Table 6 shows means and SD for each of our DUT dependent variables averaged

across all trials.

Cognitive effort. Results for *RTs* across all trials played were insensitive [$F_{(2.52)}$ =

1.498, p = .233, comparisons: *ps* > .05, control vs. combined; $B_{H(0,25.41)}$ = 1.35, control vs.

inattentive; $B_{H(0,25.41)}$ = 1.58, combined vs. inattentive; $B_{H(0,25.41)}$ = 1.61], while results for

frequency difference, which represents the difficulty of the trials played, provided clear

evidence for no group differences [$F_{(2.52)}$ = .004, p = .996, comparisons: *ps* > .05, control

vs. combined; $B_{H(0,25.41)}$ = .09, control vs. inattentive; $B_{H(0,25.41)}$ = .11, combined vs.

inattentive; $B_{H(0,25.41)}$ = .10].

Table 4

Correlations between working memory and measures of self-regulation

	1	2	3	4	5	6	7	8
1. Working Memory	-	-0.105	0.151	0.183	-0.028	0.18	-0.043	-0.09
2.% Escapes		-	-.869**	-.379**	.759**	-0.16	-.296*	-0.064
3. % Indiscriminable Trials			-	.402**	-.633**	0.166	.332**	0.033
4. % Zero Point Trials				-	-0.113	.367**	.532**	0.009
5. Frequency Difference					-	-0.114	-0.125	-0.041
6. Reaction Time						-	.264*	0.011
7. BPD							-	.273*
8. SED								-

* $p < .05$ ** $p < .01$

Table 5.

Means and SD's for crystallised and fluid intelligence t-scores, and letter monitoring scores across ADHD-type groups

Dependent Variable	ADHD-type group	Mean	SD
Gc			
	1 Control	54.04	8.85
	2 Combined	49	4.57
	3 Inattentive	54.6	6.73
Gf			
	1	50.3	8.13
	2	44.06	6.37
	3	51.53	5.4
Letter-Monitoring			
	1	8.65	0.65
	2	7.88	1.22
	3	6.6	1.84

Table 6.

Averages for DUT behavioural variables across groups

Dependent Variable	ADHD-type group	Mean	SD
RT			
	1 Control	2096.83	833.86
	2 Combined	2100.81	645.63
	3 Inattentive	1733.48	482.96
Frequency Difference			
	1	15.26	9.19
	2	15.26	7.57
	3	15.31	6.29
% Escapes			
	1	7.43	5.3
	2	8.1	5.35
	3	10.55	5.44
% Indiscriminables			
	1	29.02	24.09
	2	22.14	25.97
	3	16.8	17.72
% Zero point trials			
	1	10.34	13.44
	2	15.86	15.8
	3	3.91	5.28
Total Score			
	1	618.48	286.45
	2	592.65	264.72
	3	701.67	188.68
Points Played for			
	1	17.7	8.07
	2	14.69	5.83
	3	17.59	4.34
Points Won			
	1	11.43	5.16
	2	9.77	4.37
	3	11.39	2.99

Results also showed a significant interaction between RT and group [$F_{(4,92)} = 4.203$, $p = .004$] on the trials surrounding an escape. Further exploration of this suggested that there were significant group differences (as indicated by Bayes factors) at two of the three positions: position -3 [$F_{(2,45)} = 2.551$, $p = .089$; comparisons: control vs. combined; $p = .106$, $B_{H(0,1958.85)} = 3.49$, control vs. inattentive; $p = 1.00$, $B_{H(0,1958.85)} = .17$, combined vs.

inattentive; $p = .231$, $B_{H(0,1958.85)} = 1.77$]; position -1 [$F_{(2,45)} = 4.377$, $p = .018$; comparisons: control vs. combined; $p = .075$, $B_{H(0,1958.85)} = 5.26$, control vs. inattentive; $p = 1.00$, $B_{H(0,1958.85)} = .36$, combined vs. inattentive; $p = .018$, see fig7) with the combined-type group being significantly slower than the control group suggesting greater cognitive effort was required for a response.
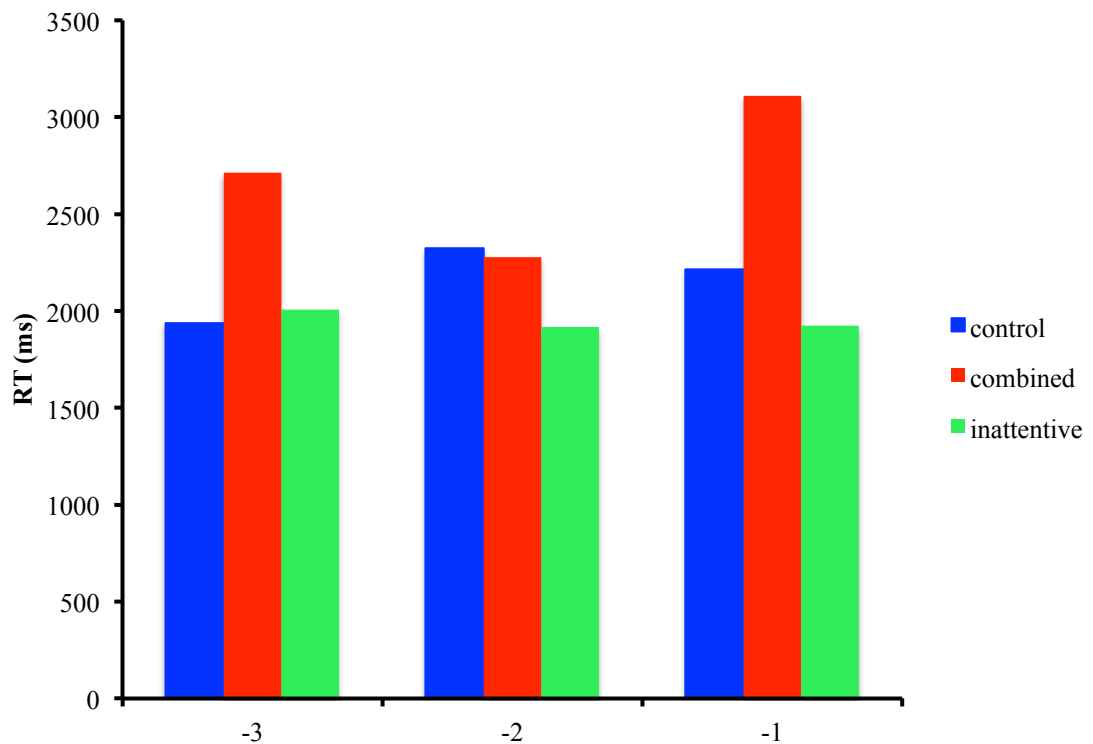
Figure 7. Average RTs across groups over the three trials leading up to an escape.

There were no differences (or there was insensitivity) at position -2 [$F_{(2,45)} = .644$, $p = .530$; comparisons: control vs. combined; $p = 1.00$, $B_{H(0,1958.85)} = .29$, control vs. inattentive; $p = .807$, $B_{H(0,1958.85)} = .52$, combined vs. inattentive; $p = 1.00$, $B_{H(0,1958.85)} = .26$].

There was strong evidence for no difference between groups across trials post-escape [$F_{(2,46)} = .344$, $p = .710$, comparisons: $ps > .05$, $Bs_{H(0,1958.85)} < .33$], and no

interaction between RT position and group [$F_{(4.92)} = .302$, $p = .876$, comparisons: $ps > .05$, $Bs_{H(0,1958.85)} < .33$].

Optimal goal directed behaviour. Results for *percentage of behavioural escapes* over all trials were mixed but leaning towards evidence for no effect [$F_{(2.52)} = 1.590$, $p = .214$, comparisons: $ps > .05$, control vs. combined; $B_{H(0,25.41)} = .09$, control vs. inattentive; $B_{H(0,25.41)} = .29$, combined vs. inattentive; $B_{H(0,25.41)} = .58$]. Results for *percentage of indiscriminable trials* played for were insensitive [$F_{(2.52)} = 1.307$, $p = .279$, comparisons: $ps > .05$, control vs. combined; $B_{H(0,25.41)} = .72$, control vs. inattentive; $B_{H(0,25.41)} = .57$, combined vs. inattentive; $B_{H(0,25.41)} = 1.95$]. The only dependent variable in this category for which there were significant group differences was the *percentage of zero points trials* played for [$F_{(2.52)} = 3.541$, $p = .036$] with the combined-type group playing more of these trials than the inattentive-type group, and differences between the other groups being insensitive (control vs. combined; $p = .369$, $B_{H(0,25.41)} = .71$, control vs. inattentive; $p = .286$ $B_{H(0,25.41)} = .97$, combined vs. inattentive; $p = .027$).

Other variables included in the analysis were; *total score* for which results were insensitive [$F_{(2.52)} = .784$, $p = .462$, comparisons: $ps > .05$, control vs. combined; $B_{H(0,25.41)} = 1.37$, control vs. inattentive; $B_{H(0,25.41)} = 1.59$, combined vs. inattentive; $B_{H(0,25.41)} = 1.60$], *number of points played* for in a given trial which were mixed but leaning towards no effect [$F_{(2.52)} = 1.203$, $p = .309$, comparisons: $ps > .05$, control vs. combined; $B_{H(0,25.41)} = .40$, control vs. inattentive; $B_{H(0,25.41)} = .34$, combined vs. inattentive; $B_{H(0,25.41)} = .08$], and *number of points won* in any given trial for which results showed clear evidence for no group differences [$F_{(2.52)} = .810$, $p = .451$, comparisons: $ps > .05$, control vs. combined; $B_{H(0,25.41)} = .18$, control vs. inattentive; $B_{H(0,25.41)} = .17$, combined vs. inattentive; $B_{H(0,25.41)} = .06$].

There was strong evidence for no group differences on any of our other behavioural dependent variables for trials leading up to or post-escape [accuracy pre-escape: $F_{(2.46)} =$

.174, $p = .841$, comparisons: $ps > .05$, $Bs_{H(0,1958.85)} < .33$, accuracy post-escape: $F_{(2.46)} = $

.718, $p > = .493$, comparisons: $ps > .05$, $Bs_{H(0,1958.85)} < .33$, expected accuracy pre-escape:

$F_{(2.46)} = .084$, $p = .920$, comparisons: $ps > .05$, $Bs_{H(0,1958.85)} < .33$, expected accuracy post-

escape: $F_{(2.46)} = .628$, $p = .538$, comparisons: $ps > .05$, $Bs_{H(0,1958.85)} < .33$, trial worth pre-

escape: $F_{(2.46)} = .817$, $p = .448$, comparisons: $ps > .05$, $Bs_{H(0,1958.85)} < .33$, trial worth post-

escape: $F_{(2.46)} = .225$, $p = .799$, comparisons: $ps > .05$, $Bs_{H(0,1958.85)} < .33$, expected value

pre-escape: $F_{(2.46)} = .512$, $p = .603$, comparisons: $ps > .05$, $Bs_{H(0,1958.85)} < .33$, expected

value post-escape: $F_{(2.46)} = .157$, $p = .855$, comparisons: $ps > .05$, $Bs_{H(0,1958.85)} < .33$].

Pupillometry variables. Analysis for pupil measures also showed strong evidence

for no group differences for either BPD [$F_{(2.52)} = 1.509$, $p = .231$, comparisons: $ps > .05$,

$Bs_{H(0,25.41)} < .33$], or SED [$F_{(2.52)} = .497$, $p = .611$, comparisons: $ps > .05$, $Bs_{H(0,25.41)} < .33$]

across all trials. We also saw strong evidence for no group differences in pupil dilation pre

or post-escape for either BPD [pre-escape: $F_{(2.46)} = .253$, $p = .778$, comparisons: $ps > .05$,

$Bs_{H(0,1958.85)} < .33$, post-escape: $F_{(2.46)} = .295$, $p = .746$, comparisons: $ps > .05$, $Bs_{H(0,1958.85)}$

$< .33$] or SED [pre-escape: $F_{(2.46)} = .462$, $p = .633$, comparisons: $ps > .05$, $Bs_{H(0,1958.85)} < $

.33, accuracy post-escape: $F_{(2.46)} = .020$, $p = .980$, comparisons: $ps > .05$, $Bs_{H(0,1958.85)} < $

.33].

Discussion

This research used the *diminishing utility task* (DUT; Gilzenrat et al. 2010), to assess self-

regulatory processes (both "hot" and "cool"), and specifically the modulation of control

state and the exploit/explore trade-off in a community sample of adults reporting either

purely inattentive, both inattentive and hyperactive, or no ADHD symptoms. Principally

our aim was to investigate whether and which ADHD-type symptoms were associated with

atypical patterns of norepinephrine (NE) activity and/or atypical self-regulatory

explore/exploit behaviour. Overall, our data provide strong evidence for no difference

between the ADHD groups and controls in terms of pupillometric/NE measures despite

reporting differences in the experience of ADHD symptomatology and in working memory. However, we did observe behavioural differences associated with hyperactive-impulsive-type symptoms suggesting a "hot" self-regulatory deficit.

Control State, NE and Pupillometry in the DUT

Before considering the results as they related to ADHD symptoms in detail it is important to note that our results pertaining to the whole sample largely mirror the findings of Gilzenrat et al. (2010). Behavioural measures pre and post-escape reflect the level of difficulty (i.e. frequency difference between reference and comparison tones) of those trials; accuracy dipped in the trials leading up to an escape and was significantly higher post-escape, and RTs trend towards slowing in the trials leading up to an escape and increasing in the trials post-escape, with the peak immediately before escape. The patterns observed in the pupil data reflect these behavioural patterns reinforcing evidence for the relationship between pupillary response and control state. Like Gilzenrat we also observed increasing baseline pupil diameters (BPD) in the trials leading up to an escape with the peak BPD at the escape, coupled with diminished stimulus evoked dilations (SED). On post-escape trials we observed a decrease in BPD coupled with an increase in SED. The pattern of BPD was an inverted-U as predicted by AGT. Taken together these results parallel LC tonic mode in the trials leading up to an escape, and LC phasic mode in the trials immediately post escape reflecting levels of task engagement and providing further support for the link between pupil diameter and LC-NE activity.

AGT suggests that decisions on whether task engagement or disengagement is most adaptive are aided by online assessments of utility that drive control state. As in Gilzenrat et al. we computed a measure of expected value to test whether this was reflected in pupillary responses. Participants demonstrated optimal decision making behaviour on the whole; escaping when the expected value of the trials began to decline. When plotted

across trial position relative to escape, expected value mirrored the U-shape of BPD suggesting that evaluations of trial worth were related to engagement. When Gilzenrat et al. regressed expected value onto BPD they found a significant effect, however our own results, while close to the threshold for Bayes to indicate evidence for an effect, were insensitive. Indeed when expected value was regressed onto SED we found evidence for no effect, in direct contrast to previous findings. Gilzenrat et al. do concede that the metric of expected value has some flaws; it assumes unrealistically that participants have knowledge of both future and past trials, and it does not take into account perceptual differences between tones with the same frequency differences (between reference and comparison) but different frequencies (i.e. a reference tone of 400 Hz vs. a reference tone of 850 Hz). In spite of these things, they still found expected value to be a reliable predictor of both BPD and SED, and this is key in their conclusion that pupillary responses, and by inference LC activity, track utility. Unfortunately our data cannot provide support for this.

In an effort to establish what task factors were influencing pupil size, we also regressed frequency difference and RT (our metrics of effort) onto BPD & SED, along with letter-monitoring task performance (working memory), and fluid intelligence. None were good predictors of either pupil measure. In fact Bayes values provided clear evidence that effort was not related to task-evoked dilations, which is a stark contradiction of findings from previous work. Beatty (1982) concludes that the task-evoked pupillary response accurately reflects all aspects of variations in processing demands. It is therefore more likely that our finding is due to limitations in design rather than that there is no relationship between pupil dilation and effort. Our pupil dilations follow the pattern we would expect to reflect changes in effort (decreasing in the trials preceding an escape as trials get more difficult, and increasing at the start of a new epoch), however it may be that variation in difficulty is not sufficient across the 3 trials pre and post-escape to elucidate an

effect. Ideally we would have more trials both pre and post escape included in the analysis, however the nature of the task, in that it was participant driven, negated this.

Further analysis looked at the relationship between fluid intelligence and working memory, and pupil size. Unfortunately we are unable to draw firm conclusions as Bayes values were largely insensitive. Research reviewed by Solanto (1998) showed that the noradrenergic effects of stimulants were useful in enhancing working memory performance, so we would reasonably expect a relationship with pupil size. Tsukahara, Harrison, & Engle (2016) provide evidence showing a strong relationship between pupil size and both working memory capacity and fluid intelligence, although this was found using pre-experimental baseline measures of pupil size which may explain why we did not find such an effect.

Working Memory and Self-regulation

Contrary to the proposal of Hofmann et al. (2012) we found clear evidence for no relationship between WM and self-regulation as measured behaviourally with the DUT. However, results for WM and pupil measures were insensitive meaning we cannot rule out a relationship between WM and LC-NE activity.

ADHD-Type Group Differences

We first tested whether we had group differences in IQ so this could be considered in the proceeding analysis. We found significant group differences for both crystallised and fluid intelligence, with the combined-type group scoring lower than both controls and the inattentive-type group. There was no difference between the control group and the inattentive-type group. The association between ADHD symptomology and IQ is well

evidenced in the literature for both clinical (Crosbie & Schachar, 2001; Mariani & Barkley, 1997; Rucklidge & Tannock, 2001) and community (Fergusson, Horwood, & Lynskey, 1993; Goodman, Simonoff, & Stevenson, 1995; Rapport, Scanlan, & Denney, 1999) samples (although we note that this is not accepted c.f. Schuck & Crinella, 2005), and it is suggested that there is a genetic origin to this (Kuntsi et al. 2004). Our results support this notion but only in cases where hyperactivity-impulsivity is present.

As expected we observed significant group differences in performance on our working memory (WM) measure, the letter-monitoring task, which were independent of IQ. Participants in the inattentive-type group scored significantly lower than controls. This corroborates previous work suggesting that WM impairments in ADHD are specific to symptoms of inattention (Diamond, 2005; Elisa & Parris, 2016). However, given that our combined-type group was just as inattentive as our inattentive-type group, we would reasonably have expected them to also have significantly poorer performance than controls; Bayes values indicated data was insensitive so we are unable to conclude whether there was or was not an impairment in this group.

Self-regulatory processes. Findings from previous work looking at ADHD symptoms and cognitive effort have been mixed (Elisa & Parris, 2015; Elisa & Parris, in preparation). In the current work we used two measures from the DUT to index effort: RTs ("cool"; reflecting slowing due to increased effort) and trial difficulty (the frequency difference between the reference and comparison tones reflecting the choice to engage in effort; "hot"). Contrary to what was expected, results suggested there were no differences between groups in the difficulty of trials played suggesting that participants with ADHD-type symptoms were no more inclined to play trials which required less cognitive effort that controls. For RT, we observed significant group differences at two of the three positions prior to an escape with the combined-type group being significantly slower than the control group.

Results suggested neither of our ADHD-type groups elected to escape any more frequently than the controls meaning our hypothesis that ADHD-type symptoms would lead to differences in control state, i.e. a greater tendency to "explore" rather than "exploit", was not supported. Two of our dependent variables indexed poor game strategy; playing an indiscriminable trial or a trial that was worth no points represents the opposite of a decision based on utility. Results regarding indiscriminable trials were insensitive, but we saw significant group differences in the percentage of zero point trials played over the course of the game, with the combined-type group playing more of these trial types than the inattentive-type group. However, we note that without IQ-matched groups we cannot rule out that the group differences observed in IQ may account for the result.

Taken together our findings on self-regulatory processes suggest that hyperactivity-impulsivity symptoms were associated with heightened expenditure of effort in trials with the same level of difficulty as those played by controls, who did not experience the same level of effort expenditure. It could therefore be argued that their assessment of utility is not optimal, (i.e. that "hot" goal directed behaviour is not optimal) as the most sensible strategy of behaviour in this scenario would be more frequent behavioural disengagements coupled with an associated reduction in overall trial difficulty; which we do not see. This interpretation supports the notion that hyperactive-impulsive symptoms are associated with modified "hot" EF processes.

Pupil measures. Pupillometry was used as a proxy for LC-NE activity. Drug studies and genetic research have suggested a link between norepinephrine and ADHD (Biederman & Spencer, 1999; Bymaster et al. 2002; Comings et al. 2000; Kako et al. 2007), and this seemed an ideal way to investigate any differences between those with ADHD-type symptoms and those without. We predicted ADHD-type symptoms would lead to an increase in tonic mode activity, and an accompanied decrease in phasic activity represented by larger pre-trial baselines and smaller SEDs, and indicating lower task

engagement. The analysis provided strong support for the null hypothesis of no group differences. Over all trials we observed no group differences in either BPD or SED, with Bayes values clearly showing evidence for no effect. This was also the case when we considered only trials surrounding an escape, suggesting that under strategic gameplay conditions (i.e. requiring assessment of task utility and with an escape option) ADHD-type symptoms did not affect (or were not affected by) LC-NE activity. This is not hugely surprising in light of our finding that ADHD-type symptoms did not lead to an increase in exploratory behaviour, which is what we would expect to accompany elevated tonic LC firing and it's associated pupil reactions.

Before concluding we must consider whether our ADHD-type groups, which were drawn from a community, not a clinical, population, are sufficient to elucidate any differences in LC-NE activity related to ADHD symptoms. As indicated by our results, our experimental groups were significantly higher than controls in ADHD symptomology, although this almost certainly would not have reached clinical levels. Importantly, we did see a significant difference between groups in performance on a working memory measure, and in response slowing pre escape, suggesting that if group differences on any other measure existed, our data would have revealed it. Moreover, if the clinical disorder is best described as being on a continuum, as ADHD is, any effect observed in a community sample would confirm the importance of the mechanisms causing the effect in the clinical population. That is, if an effect is present even in the community sample then it is likely to be key in the associated clinical disorder. Likewise, if an effect is not present in a community sample, it is unlikely to be of import at the clinical level unless it is assumed that the causal mechanisms at the clinical level are different, but this would violate the assumptions inherent in defining the disorder as being continuum based. Therefore, whilst we cannot draw conclusions from results where Bayes values were within the insensitive range, we

can draw conclusions both where significant differences and strong evidence for no difference are reported (i.e. pupillometric measures, measures of effort, total game score, accuracy, and number of points played for and won).

Conclusion

The most prominent findings of this work were strong evidence for no differences between ADHD-type groups and controls in pupil/NE measures (despite significant group differences in symptoms and working memory) and evidence for slowed response times pre-escape associated with hyperactive-impulsive symptoms suggesting a deficit "hot" self-regulatory processes, namely goal directed behaviour. If we accept the link between changes in pupil diameter and LC-NE activity (which our data supports) then our findings suggest that ADHD symptoms are not related to activation of norepinephrine. However, we note that while this is evidence against a noradrenergic explanation of ADHD, this does not rule out a role for norepinephrine; it is still feasible that there is a relationship but that LC-NE activity is not the mechanism for it. For example, it is thought that the mechanism by which drugs used to treat ADHD (such as stimulants and antidepressants) work is by blocking the reuptake of catecholamines into the presynaptic neuron, thereby increasing levels of these monoamines in the extraneuronal space. This is not necessarily connected to the activity of the relevant neuronal circuits. This mechanistic explanation is also relevant to the potential relationship between WM and NE, which our data do not support. Indeed our findings relating to response times pre-escape are more consistent with developmental models that assert separable contributions of "hot" and "cool" executive function processes to ADHD manifestation (Sonuga-Barke, 2002; Sonuga-Barke, Dalen, and Remington, 2003) with modified "hot" control mechanisms associated with hyperactive-impulsive symptoms. This also supports the direction of the relationship between EFs and self-regulation being as Diamond (2013) and Hofmann et al. (2012) suggest, which is bolstered

by our results showing clear evidence for no relationship between inattention and "hot" LC-NE activity.

With regard to methodology, we note that there is an argument that while the DUT gives the options of exploit or disengage, it does not actually give participants an "explore" option in the true sense. Further work may wish to look at exploration behaviour in relation to ADHD symptoms more closely using a task such as that developed by Jepma & Nieuwenhius (2011), who address this limitation; we may yet find greater differences in tendency to explore using a more sensitive task.

Chapter 7: Thesis Discussion

The overarching aim of this thesis was to investigate the cognitive underpinnings of the symptom inattention as defined in the DSM under criteria for attention deficit hyperactivity disorder (ADHD). This necessitated looking at the other two core symptoms of ADHD (hyperactivity and impulsivity), in order to establish whether differences existed between them. Inattention was identified as a worthwhile area of investigation due to its under-representation in ADHD literature and it's relevance to adults, who as a population are also under-represented in the literature. Based on the latest evidence (see Chapter 1), this work took the approach that ADHD symptoms exist along a continuum, with the high end of severity representing those appropriate for clinical diagnosis and treatment. On the whole this thesis took a dimensional approach to investigating ADHD symptoms, by utilizing a self-report measure (Connor's adult ADHD rating scale) and regression techniques in analysis. In contrast, the final experimental chapter (Chapter 6) of the thesis categorizes participants into DSM ADHD-type groups, but lowers the threshold for criteria in order to maintain a sample representative of the general population. The study in Chapter 2 represents a break from the overall aims in order to validate the approach proposed in the thesis. Chapters 3-6 focus on addressing the relationships between ADHD symptoms and various components of an executive function (EF) model based on an interpretation of the literature in this area.

Theoretical Context

Five key theoretical approaches drove the work in this thesis. Firstly, that of the three core EFs (working memory, inhibitory control, and cognitive flexibility); the one theorized to be principally and uniquely related to inattention is working memory (WM; Diamond, 2005). The literature is generally (but not definitively) supportive of this claim, although there are several issues that make it difficult to apply findings to our population of interest

(adults from a community population), including samples disproportionately of children, and a primarily categorical approach with low regard for ADHD subtypes. There is also an argument for the role of inhibitory control in hyperactivity-impulsivity (Barkley, 1997), as well as a substantial body of literature that links all three of the core EFs to ADHD symptoms generally, which may or may not be relevant to inattention (depending on the research design), but which is related to the second theoretical point; the proposal that EFs are related to self-regulatory processes. The work of Diamond (2013), and Hofmann, Schmeichel, and Baddeley (2012) is most influential here. Both theories suggest that all three core EFs (by nature of their own relationships) facilitate successful self-regulation, but differ in which they see as being most important. Diamond argues that inhibitory control overlaps considerably with self-regulation, but provides little in the way of an argument or evidence for this view. In Hofmann et al.'s far more comprehensive review, WM is identified as being most important in self-regulation, although a role for all three core EFs is acknowledged. If we accept the first theoretical approach, both of these views support the third; the potential for a relationship between ADHD symptoms and self-regulatory processes. However, before a review of relevant literature could take place it was necessary to define what is meant by "self-regulatory processes". This was complicated by a fourth literature on distinctions between "hot" and "cool" cognition. A definitive model of "hot" and "cool" cognition does not exist, but it is generally accepted that "cool" cognition refers to the three core EFs, and that "hot" cognition refers to processes involving reward, motivation, and emotion etc. Based on our interpretation of the literature this thesis took the stance that "hot" cognition reflects "hot" self-regulatory processes, "cool" cognition refers to both the three core EFs and "cool" self-regulatory processes, and that both "temperatures" of self-regulation are facilitated by the three core EFs (see model in Chapter 1 p 34). By these definitions, there is evidence in the literature to support a relationship between ADHD symptoms and both "hot" and "cool" self-

regulatory processes. However, the fifth literature key to this thesis, which suggests a hot/cool – hyperactivity-impulsivity/inattention distinction, further complicates this. Assuming our interpretation of the literature on EFs and self-regulatory processes is correct, this would mean only inattention would be related to any of the three core EFs, which refutes the well-established literature linking hyperactivity-impulsivity to inhibitory control.

Based on these five approaches the aim of this thesis was primarily to look at the relationships between components of the model (hot/cool, EFs, self-regulatory processes) with ADHD symptoms, while simultaneously attempting to clarify the relationships between the facets of cognition themselves.

Summary of Main Findings

Chapter 2. Symptom prevalence. The research in this chapter was a partial replication and extension of previous work by Faraone and Biederman (2005). Our sample was deliberately specific; a community sample of university students, as it was our intention to recruit mainly from this population in future work (however note that findings from previous work suggest such data from university students is generalizable to non-academic populations). We conducted a comprehensive analysis that looked at ADHD symptom prevalence both dimensionally and categorically, and found that inattention was the most prevalent symptom in the sample. The findings from this research clearly supported the work of Faraone and Biederman, as well as validating the approach and methodology used throughout the thesis.

Chapter 3. ADHD symptoms and performance on the CRT. This chapter reflects the starting point for addressing the main aim of the thesis. The cognitive reflection test (CRT) was used to assess a self-regulatory component believed to be facilitated by the three core EFs: cognitive effort. This easy to administer task was used to generate data

quickly in order to inform the direction of the thesis. Results showed that all three ADHD symptoms were negatively correlated with CRT performance, but inattention uniquely accounted for variance in a regression model.

Chapter 4. ADHD symptoms and working memory. At the end of Chapter 3 we noted evidence suggesting that CRT performance may well be explained by variance in WM, which would fit with Hofmann et al.'s theory on WM's relationship to self-regulatory processes. The aim of Chapter 4 therefore was to rigorously test Diamond's (2005) theory on inattention and WM. This was done using three traditional WM tasks; two verbal (one simple one complex-span) and one spatial-span task in Experiment 1. Experiment 2 utilized the letter-monitoring task (Duncan, Emslie, Williams, Johnson, & Freer, 1996) that assesses goal-neglect and is purportedly related to the episodic buffer component of WM. Results from Experiment 1 showed that inattention uniquely predicted performance on both the simple and complex-span verbal tasks (results for hyperactivity and impulsivity were inconclusive), refuting the hypothesis made by Diamond (2005) that only complex-span tasks would be sufficient to uncover variance in inattention. Results relating to spatial WM and inattention were inconclusive, leaving us unable to confirm or refute its relationship, however impulsivity was a good predictor of performance on this task. Results from Experiment 2 suggested that the performance on the letter-monitoring task was uniquely predicted by inattention and that this task clearly differentiated inattention from the other two ADHD symptoms. Overall findings from both experiments broadly support Diamond's hypothesis of a unique relationship between inattention and WM.

Chapter 5. ADHD symptoms, cognitive effort, and working memory. The work in this chapter represents a reflection on the findings from Chapters 3 and 4, with a view to tightening the methodology and refining our understanding of the relationships already established. A task that enables independent manipulation of cognitive effort and cognitive

control was utilized allowing us to look at both of these "cool" processes in relation to ADHD symptoms. The letter-monitoring task from Chapter 4 was used to assess WM due to its unique relationship with inattention. The CRT from Chapter 2 was also used to enable comparison between the two quite different measures of cognitive effort. Unfortunately results were largely inconclusive and we were unable to support a relationship between cognitive effort and either inattention (refuting a "cool" description of inattention) or WM (refuting Hofmann et al., 2012). Results suggested a relationship between impulsivity and cognitive control, which supports Barkley's (1997) theory. However, the finding was not consistent across both stroop interference contrasts or both RTs and errors (i.e. some were insensitive), did not apply to hyperactivity, and should be considered in light of the additional finding that impulsivity was also related to WM. Overall this makes it difficult to comment on the "temperature" best used to describe these symptoms.

Chapter 6. ADHD symptoms and LC-NE activity. The inconclusive results from Chapter 5 prompted us to take a change of approach in our assessment of self-regulatory processes. Indeed the concept of self-regulation is so vast that a conclusion on its relationship to any variable would require using measures to test various facets of it. In this chapter we looked at the exploit/explore trade-off in relation to locus coeruleus norepinephrine (LC-NE) activity, considered to be a "hot" component of self-regulation. We utilized a task that enabled participants to make a behavioural disengagement (i.e. to explore) when the utility of continuing was diminished. Using eye-tracking technology, we were able get a proximate measure of LC-NE activity through changes in pupil diameter evoked by task stimuli. Along with this the task allowed measurement of a number of behavioural variables relating to "hot" and "cool" self-regulatory processes of cognitive effort, and optimal goal directed behaviour. Contrary to predictions results provided strong evidence against a relationship between LC-NE activity and any of the ADHD symptoms.

However, there was behavioural evidence for dysfunction of "hot" self-regulatory processes related to utility judgement related to hyperactivity-impulsivity. Both findings are in line with a hot/cool – hyperactivity-impulsivity/inattention distinction.

Implications for Theory

Findings from the research in chapters 3-6 of this thesis are now reviewed collectively in an attempt to assimilate them into the theory outlined above.

The relationship between inattention and working memory. Our investigation of this relationship was mainly motivated by Diamond's (2005) predictions. While primarily addressed in Chapter 4, the main finding of a significant relationship was replicated in Chapters 5 and 6. Diamond predicted that complex-span tasks specifically would be particularly sensitive to inattention. Our findings do not support this; the relationship between performance on a simple-span task (the backward digit span) and inattention was just as strong as for a complex-span task (the operation span). As noted in Chapter 4, this finding adds to debate in the literature on what constitutes a WM task, and whether the secondary element of the task needs to include new stimuli (as in operation span), or whether mental transformation of target items is sufficient; our work supports the latter. Secondly, Diamond suggests that verbal presentation of material places a particularly high demand on WM. Based on this it was predicted that a spatial-span task would not necessarily be related to inattention. Unfortunately results were inconclusive, although we note there are methodological issues with the task used (the Corsi blocks) that may not make it ideal for use in this context (see Chapter 4). However, we did find that the letter-monitoring task (which is heavily reliant on the assimilation and amalgamation of complex verbal material) was best at differentiating inattention from the other two ADHD symptoms, which lends support to Diamond's theory.

Overall our findings on inattention and WM support conclusions made in the wider literature using child and adult samples, from clinical and non-clinical populations (Gansler et al. 1998; Gathercole et al. 2008; Klingberg et al. 2005; Kim, 2004; Martinussen & Tannock, 2006). The fact that the relationship observed in community samples was robust across studies in this thesis further highlights the relevance of the finding to clinical populations.

The relationship between general executive functions and self-regulatory processes. Chapters 5 and 6 addressed Diamond's (2013) and Hofmann et al.'s (2012) proposals regarding which EF(s) facilitate self-regulatory processes. Results provided clear evidence that WM was not related to cognitive effort as assessed by the number Stroop task, or by behavioural measures from the diminishing utility task (DUT). Wider literature supports a relationship between WM and CRT performance (Stupple, Gale, & Richmond, 2013; Toplak, West & Stanovich, 2011), however our own results were insensitive meaning we are unable to add to the commentary. Results regarding WM and LC-NE activity (as measured with pupillometry) were also insensitive meaning we neither support nor rule out a relationship. WM was not related to interference contrasts in the number Stroop task, however distinguishing between whether this represents inhibitory control as one of the three core EFs, or as cognitive control as a facet of self-regulation is difficult as they are most likely synonymous in this context. Regardless, results also clearly showed that this variable was not related to cognitive effort as measured by the CRT.

Although inconclusive, results from both chapters tend to refute (but not conclusively rule out) both Diamond and Hofmann in that no compelling evidence for any relationship between either WM or inhibitory control, and self-regulatory processes was found (reflecting a mixture of strong evidence against and insensitive results). Although testing relationships between these variables was not the primary aim of the thesis, we do concede that methodology could be refined, particularly with respect to inhibitory control.

Indeed, in their work on the CRT Toplak et al. (2011) note the importance of comprehensive measurement of inhibition.

Self-regulatory processes and ADHD symptoms. Based on the EF model outlined in Chapter 1, we tested the relationship between ADHD symptoms and various facets of self-regulation with consideration for theory suggesting a hot/cool – hyperactivity-impulsivity/inattention distinction. Based on this we expected to see symptoms of hyperactivity-impulsivity related only to "hot" self-regulatory processes, and inattention related only to "cool" self-regulatory processes. However, if "cool" inhibitory control deficits were key to hyperactivity-impulsivity as suggested (Barkley, 1997), we might also see hyperactivity-impulsivity related to "cool" self-regulatory processes, particularly if Diamond's view of inhibitory control facilitating self-regulation were true. In Chapter 2 we show evidence that all three ADHD symptoms were negatively correlated with performance on the CRT, but that only inattention was a significant predictor of variance. This finding could be taken as support for self-regulatory deficits in ADHD generally but with an emphasis on inattention. As we note in Chapter 2, the "temperature" of the CRT as a self-regulatory task is unclear and perhaps mixed; which indeed could explain why all three symptoms of ADHD were related. However, although there was not strong evidence against them, these findings were not replicated in Chapter 5, where evidence for the relationship between ADHD symptoms and "cool" cognitive effort was inconclusive. Findings from Chapter 6 partially support the hot/cool – hyperactivity-impulsivity/inattention distinction by showing evidence for hyperactivity-impulsivity's relationship with deficits in "hot" self-regulatory processes, specifically that group-specific increases in effort were not responded to optimally. Results regarding other "hot" self-regulatory variables were insensitive. Results for the relationship between inattention and "cool" cognitive effort as measured by the number Stroop were also insensitive. In Chapter

3 we found that impulsivity was a good predictor of "cool" spatial WM, which goes directly against the hypothesis.

While inconsistent, collectively these results provide partial support for a relationship between ADHD symptoms and self-regulatory processes generally. With consideration for our findings relating to WM and inattention, results also provide support for a hot/cool – hyperactivity-impulsivity/inattention distinction as suggested by Castellanos, Sonuga-Barke, Milham, and Tannock (2006).

Relevance to the General Population

Findings from Chapter 2 fully support the existence of ADHD symptoms existing at less severe levels than those meriting clinical diagnosis in the general population. This means that cognitive issues identified to be related to ADHD symptoms in clinical groups will also be experienced in the general population; indeed findings from this thesis suggest this is the case. Given the high degree of heredity in ADHD (Faraone, & Doyle, 2001; Fliers, Franke, & Buitelaar, 2005) this could be particularly relevant to family members of those diagnosed with ADHD, who do not meet diagnostic threshold, but who still experience symptoms.

Relevance to Clinical Groups

Findings from Chapter 2 support a dimensional approach to ADHD symptoms, meaning that the findings from Chapters 3-6 are relevant to clinical groups that experience ADHD symptoms. We would expect that the decrease in symptom severity associated with a community sample means that effects found in this work would represent a minimum for clinical groups. For example, adults experiencing clinical levels of inattention will experience increased deficits in WM. Equally, where we found strong evidence for no relationships regarding EF components (i.e. self-regulatory processes related to LC-NE

activity), it is unlikely that these are relevant to clinical level expression of ADHD symptoms.

Future Directions

This thesis represents the first work to look at EFs and self-regulatory processes, within a model acknowledging "hot" and "cool" cognition distinctions, related to ADHD symptoms in a community sample of adults. The model included in Chapter 1 represented a best interpretation of the literature, and attempted to define and characterize aspects of cognition operationally in order to test them in relation to ADHD symptoms. Ideally a firm model of EF function would exist prior to testing in relation to symptomology. Future work should look at refining definitions and distinctions in the model. For example, this thesis accepted a premise that the three core EFs are predominantly "cool" in nature. However, it is possible that there is more overlap between "hot" and "cool" processes than models of cognition allow for. This would certainly complicate testing aspects of EF, as paradigms that isolate either "hot" or "cool" would be required. Indeed, it is likely that development of models of EF have been influenced by the use of laboratory-based tasks that are inherently devoid of "heat". The model was also based heavily on the work of Diamond (2013) and Hofmann et al. (2012) suggesting that EFs facilitate self-regulatory processes, and the findings in this thesis do not support this. However, the thesis does not represent a comprehensive test of these theories and therefore does not rule them out. It would be highly useful to have clarification of the relationships between the concepts in the model before further work is carried out on how ADHD symptoms relate to them. As noted with regard to inhibitory control above, future work could consider extensive EF testing using multiple measures. Further work utilizing the letter-monitoring task as a measure of WM would be useful, in order to clarify what about it's nature makes it unique in its relationship to inattention.

Conclusion

The studies in this thesis set out to investigate the cognitive underpinnings of inattention, with a view to supporting research suggesting a qualitative distinction between this symptom and those of hyperactivity-impulsivity. Overall findings are very mixed, although some notable contributions to the literature have been made. The main finding from the work relates to the relationship between inattention and WM, which was shown to be robust and reliable across three studies, and differentiated inattention from hyperactivity-impulsivity. An aspect of "hot" self-regulation was also found to be related uniquely to hyperactivity impulsivity. Findings relating to the relationships between core EFs and self-regulatory processes do not on the whole support the positions of Diamond (2013) and Hofmann et al. (2012) that the three core EFs facilitate self-regulatory processes, although we are not in a position to rule them out. With regard to the hot/cool – hyperactivity-impulsivity/inattention distinction we show evidence for a relationship between specific components of "cool" cognition with inattention, and "hot" cognition with hyperactivity-impulsivity. However, results relating to other aspects of both were inconclusive.

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Appendices

Appendix A. Connors Adult ADHD Rating Scale-Self-Report: Short Version

(Connors, Edhardt & Sparrow, 1999)

Instructions: Listed below are items concerning behaviors or problems sometimes experienced by adults. Read each item carefully and decide how much or how frequently each item describes you recently. Indicate your response for each item by circling the number that corresponds to your choice. Use the following scale: 0 = Not at all, never; 1 = Just a little, once in a while; 2 = Pretty much, often; and 3 = Very much, very frequently.

	Not at all, never	Just a little, once in a while	Pretty much, often	Very much, very frequently
1. I interrupt others when talking.	0	1	2	3
2. I am always on the go, as if driven by a motor.	0	1	2	3
3. I'm disorganized.	0	1	2	3
4. It's hard for me to stay in one place very long.	0	1	2	3
5. It's hard for me to keep track of several things at once.	0	1	2	3
6. I'm bored easily.	0	1	2	3
7. I have a short fuse/hot temper.	0	1	2	3
8. I still throw tantrums.	0	1	2	3
9. I avoid new challenges because I lack faith in my abilities.	0	1	2	3
10. I seek out fast paced, exciting activities.	0	1	2	3
11. I feel restless inside even if I am sitting still.	0	1	2	3
12. Things I hear or see distract me from what I'm doing.	0	1	2	3
13. Many things set me off easily.	0	1	2	3
14. I am an underachiever.	0	1	2	3
15. I get down on myself.	0	1	2	3
16. I act okay on the outside, but inside I'm unsure of myself.	0	1	2	3
17. I can't get things done unless there's an absolute deadline.	0	1	2	3
18. I have trouble getting started on a task.	0	1	2	3
19. I intrude on others' activities.	0	1	2	3
20. My moods are unpredictable.	0	1	2	3
21. I'm absent-minded in daily activities.	0	1	2	3
22. Sometimes my attention narrows so much that I'm oblivious to everything else; other times it's so broad that everything distracts me.	0	1	2	3
23. I tend to squirm or fidget.	0	1	2	3
24. I can't keep my mind on something unless it's really interesting.	0	1	2	3
25. I wish I had greater confidence in my abilities.	0	1	2	3
26. My past failures make it hard for me to believe in myself.	0	1	2	3

Appendix B. DSM-5 Adult ADHD Rating Scale (based on Barkley, 2011)

How often in the last 6 months	Never	Sometimes	Often	Very frequently
have you failed to give close attention to details or made careless mistakes at work or in other activities?	0	1	2	3
have you had difficulty sustaining attention in tasks or recreational activities?	0	1	2	3
have you had trouble keeping up with a conversation with someone, or with someone speaking to you directly?	0	1	2	3
have you failed to follow through on instructions or complete chores, duties in the workplace/assignments at college/university?	0	1	2	3
have you had difficulty organizing tasks and activities?	0	1	2	3
have you avoided or disliked engaging in tasks that require sustained mental effort? i.e. college/university assignments, tasks at work	0	1	2	3
have you lost things necessary for tasks or activities at college/university/work?	0	1	2	3
have you been distracted by activity or noise around you?	0	1	2	3
have you lost things necessary for tasks or activities (e.g., work/college materials, tools, wallets, keys, paperwork, eyeglasses, mobile telephones).	0	1	2	3
have you fidgeted with hands or feet, or squirmed in your seat?	0	1	2	3
have you left your seat in meetings or other situations where your are expected to remain seated?	0	1	2	3
have you felt restless inside, or expressed restlessness by behaving inappropriately?	0	1	2	3
have you had difficulty unwinding, relaxing or engaging in leisure activities quietly?	0	1	2	3
have you talked excessively?	0	1	2	3
have you felt 'on the go' or as if 'driven by a motor'?	0	1	2	3
have you had difficulty waiting your turn in situations where turn taking is required?	0	1	2	3
have you found yourself finishing the sentences of people you are talking to before they can finish themselves, or blurted out the answers to questions before they have been completed?	0	1	2	3
have you interrupted or intruded on others when they are busy?	0	1	2	3

Appendix C. Table showing a summary of post-publication regression analysis for

Chapter 3. Variables entered as in Chapter 4 (with inattention last rather than first).

Summary of regression for IQ, hyperactivity, impulsivity and inattention on CRT scores.

Variable	b	SEb	β	t	R^2	F for change in R^2
Step 1					0.023	1.879
WTAR IQ	0.013	0.009	0.151	1.437		
Step 2					0.051	2.781
WTAR IQ	0.009	0.009	0.108	1.018		
Hyperactivity	-0.030	0.012	-0.262	-1.472		
Step 3					0.089	.573
WTAR IQ	0.008	0.009	0.95	.886		
Hyperactivity	-0.13	0.015	-.202	-.849		
Impulsivity	-0.011	0.015	-0.102	-0.757		
Step 4					0.161	6.325**
WTAR IQ	0.011	0.009	0.125	1.193		
Hyperactivity	-0.006	0.016	-0.37	-0.258		
Impulsivity	-0.004	0.015	-0.033	-0.250		
Inattention	-0.031	0.012	-0.314	-2.515**		

**p < .01