New Insights into Typical Development and Attention Deficits Using Behavioural and Modelling Methods

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Abstract

The present thesis employs an interdisciplinary approach of behavioural and computational modelling methods to examine age- and ADHD-related differences in selective visual attention. Specifically, this thesis aims to investigate efficiency when individuals are required to allocate visual attention to a particular moment in time. Selective visual attention refers to the emergent property that arises from biased competition computations. ADHD is associated with differences in neural mechanisms that give rise to selective attention; however, this has been difficult to consistently identify at the behavioural level. Two visual search tasks, preview and preview gap search, as well as a neurocomputational model, the b-sSoTS model were used to examine differences in two time-based attention functions, visual marking and temporal binding. First, performance of typically developing children was compared against adults to establish baseline performance for children and identify developmental differences in the neural mechanisms underlying this performance (Chapter 2). This chapter thus provides a version of the b-sSoTS model that was subsequently used to reflect typically developing children with low levels of ADHD-traits and serve as a baseline to further model ADHD-related differences. In Chapter 3, typically developing children with low levels of ADHD-symptoms and high level of ADHD-symptoms were first compared on the visual search tasks. Performance at the behavioural level was then simulated by the model by implementing parameter changes to reflect hypothesized ADHD-related differences. Chapter 4 extended the investigation to adults with varying levels of differences. In a first behavioural study, adults with low, borderline and high levels of ADHD symptoms are compared using the visual search tasks. In a second behavioural study, levels of impulsiveness were also considered, as adults with low, borderline and high levels ADHD symptoms (but average impulsiveness) were compared with adults with high levels of ADHD symptoms and impulsiveness on the search tasks. Taken together, the outcomes of the present thesis suggest that while top-down visual marking is likely intact in ADHD, these individuals may experience differences in bottom-up temporal binding, at least in childhood. Furthermore, any temporal binding differences arise over and above developmental differences in the basic encoding of visual features. These findings thus serve as an interesting starting point for further research where an interdisciplinary approach using both behavioural and modelling methods can yield unique insights into selective attention in ADHD. Future research could further develop neurocomputational models to reflect the ADHD brain to draw stronger connections between the behavioural and neural levels. Research on selective visual attention in ADHD, particularly when using interdisciplinary methods, provides new insights into the neural mechanisms involved in this disorder, which can ultimately be used to develop better diagnostic and treatment procedures.

Keywords: selective attention, development, ADHD, visual search, computational model

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List of Abbreviations

ADHD	Attention-Deficit/Hyperactivity Disorder
AI	Artificial Intelligence
ANNs	Artificial Neural Networks
ANOVA	Analysis of Variance
ASRS	Adult Self-Report Scale
BCT	Biased Competition Theory
BOLD	Blood Oxygen Level Dependent
b-sSoTS	Binding-Spiking Over Time and Space
CD	Conduct Disorder
CNNs	Convolutional Neural Networks
CNS	Central Nervous System
CPT	Continuous Performance Task
DA	Dopamine
DAN	Dorsal Attention Network
DBH	Dopamine Beta-Hydroxylase
EEG	Electroencephalogram
ERP(s)	Event Related Potential(s)
FEF	Frontal Eye Fields
FIT	Feature Integration Theory
fMRI	Functional Magnetic Resonance Imaging
GAD	Generalised Anxiety Disorder
GSM	Guided Search Model
HDR	Hemodynamic Response

IFg	Inferior Frontal Gyrus
IOR	Inhibition-of-Return
IPS	Intraparietal Sulcus
LIF	Leaky Integrate-and-Fire
MANO	Multivariate Analysis of Variance
MFg	Middle Frontal Gyrus
ML	Machine Learning
MT	Middle Temporal
NE	Norepinephrine
ODD	Oppositional Defiance Disorder
PAC	Parietal Association Cortex
PB	Preview Benefit
PBG	Preview Gap Benefit
PFC	Prefrontal Cortex
PPC	Posterior Parietal Cortex
PPV	Positive Predictive Value
RF	Receptive Field
RT(s)	Reaction Time(s)
RSVP	Rapid Serial Visual Presentation
SNNs	Spiking Neural Networks
SNR	Signal-to-Noise Ratio
SPL	Superior Parietal Lobule
SSRT	Stop Signal Reaction Time
TD	Typically Developing

TEAch	Test of Everyday Attention for Children
TPJ	Temporo-parietal Junction
VAN	Ventral Attention Network
WASI-II	Wechsler’s Abbreviated Scale of Intelligence, Second Edition
WISC-IV	Wecshler’s Intelligence Scale for Children, Fourth Edition
WM	Working Memory
WRAT-4	Wide Ranging Achievement Test, Fourth Edition

COVID-19 Impact Statement

This statement is to bring attention to the impact of the COVID-19 pandemic on the present thesis. The government-mandated lockdowns that occurred as a response to the spread of COVID-19 in 2020 interrupted ongoing data collection for the first behavioural study presented in Chapter 4. In this study, three groups - adults with low, borderline and high levels of ADHD symptoms (according to their Adult ADHD Self Report Scale (ASRS; Kessler et al., 2005) scores were compared on preview and preview gap search. Importantly, this study was conducted in a traditional laboratory setting, such that participant met face-to-face with the researcher to undergo intelligence testing and complete the experiment. Accordingly, this study was cut short when this method of data collection was no longer feasible. As a result, the groups for this study were uneven (low ASRS n = 17; borderline ASRS = 30; high ASRS = 27). In order to address the statistical issues that accompany unequal sample sizes, a second study was conducted. In this second study, a completely online format was used. Participants were recruited via Birmingham City University's Research Participation Scheme (RPS; bcu.sona-systems.com) and Prolific (www.prolific.com). This study also further expanded the investigation to explore the effect of high levels of impulsiveness in those with high ADHD symptoms using the Barratt Impulsiveness Scale - Brief (BIS-B; Steinberg et al., 2013). The visual search task was conducted using Pavlovia (www.pavlovia.org), and the researcher supervised each experiment over Microsoft Teams (teams.microsoft.com) to ensure the validity of RTs. These COVID-19 lockdowns also restricted access particularly to potential participants who were under the age of 18, as these individuals were not able to be recruited online or through the university. Accordingly, the sample of children used in chapter 2 is also used in chapter 3. Similarly, the sample of adults used in chapter 2 is also used in the first behavioural study of chapter 4.

Chapter 1: Literature Review

The aim of the present thesis is to investigate age- and ADHD-related differences in time-based selective visual attention using both behavioural and computational modelling methods. The thesis begins with a review of relevant literature on selective visual attention and on ADHD. In the first section of this chapter, the neural mechanisms of selective visual attention are described, and these neural-level observations are then further linked to influential psychological theory. Furthermore, the development of these attentional mechanisms is reviewed. Next, the existing literature characterising cognitive and neural differences in ADHD is evaluated and reconsidered within the context of selective attention. The third section introduces computational modelling of visual search and outlines how these models can provide unique insight into the neural mechanisms that give rise to complex cognitive functions. The concluding section of this chapter puts forth a proposal for an interdisciplinary project where behavioural and modelling techniques complement each other to provide a deeper understanding of typical and atypical attention.

1.1 Selective Attention

At any given moment, our senses are bombarded with an endless amount of incoming information. To interact with this crowded environment, we must filter through the available information in an efficient manner to determine what is (and is *not*) important. This describes the critical function of *selective attention*. Selective attention refers to the ability to selectively prioritise behaviourally relevant information while ignoring other, potentially distracting information (Broadbent, 1958; Buschman & Kastner, 2015; Desimone & Duncan, 1995; Driver, 2001; Lindsay, 2020). The idea of selective attention as a filter that protects our limited-capacity cognitive resources from overload was first detailed by Broadbent (1958) in light of his findings from dichotic listening tasks. Since then, a large body of research has been dedicated to understanding the nature and mechanisms underlying selective attention, and this topic continues to be widely popular across a range of disciplines (Carrasco, 2011; Kristjánsson & Egeth, 2020; Lee & Choo, 2013).

In the visual domain, attention has famously been likened to a spotlight (Posner et al., 1980) that enables enhanced processing of stimuli that falls within the location of its "beam." This idea was subsequently expanded by Feature Integration Theory (FIT; Treisman & Gelade, 1980), which proposed attention binds separable visual features (i.e., colour, shape) into whole objects. Wolfe and colleagues (Wolfe, 1994; Wolfe et al., 1989) developed this further with their model of visual search, which suggested that an observer's prior knowledge of the target item's features, as well as its inherent saliency and similarity to other items, serve as top-down and bottom-up signals (respectively) that guide attention across space (Wolfe, 2015a, 2020). Around this same time, neuroscience research showed that attention arises as a consequence of biasing sensory competition between features, objects, or locations (Beck & Kastner, 2009; Desimone & Duncan, 1995; Kastner & Ungerleider, 2001).

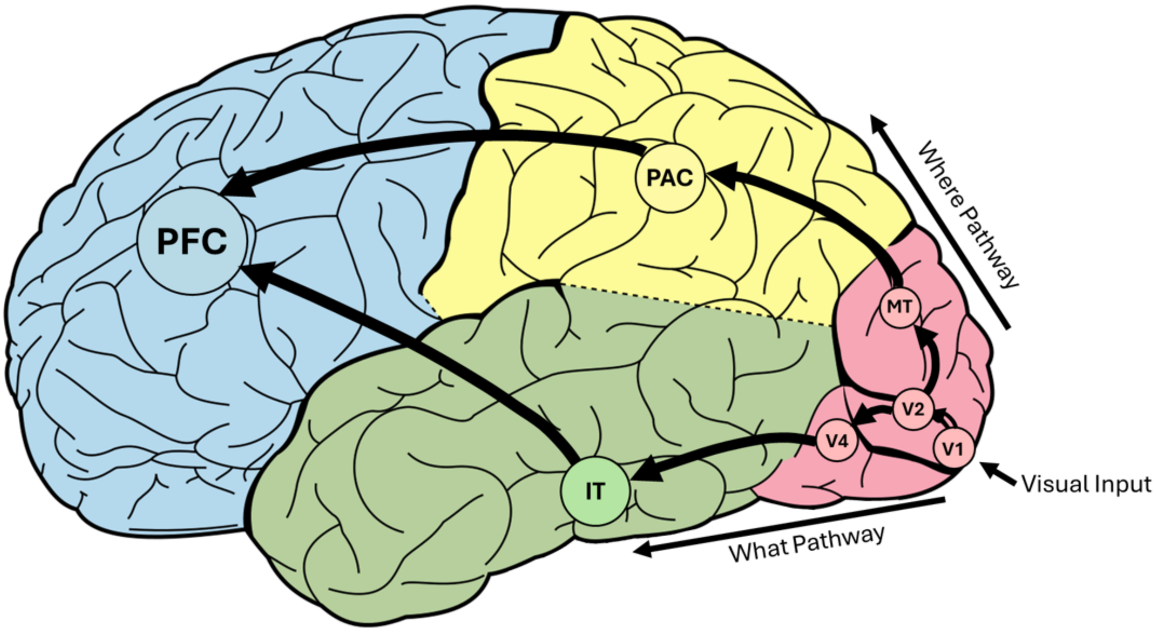
Ultimately, selective visual attention is inextricably linked with both the lower-level processes of perception (Carrasco, 2018; Carrasco & Barbot, 2019) as well as higher-level functions such as learning, planning, memory, and decision-making (Friedman & Robbins, 2022; Nigg, 2017; Panichello & Buschman, 2021). Indeed, one of the reasons Broadbent's (1958) filter model of attention was initially popular is due, in part, to its conceptualisation of attention as a distinct mechanism that exists directly between these lower- and higher-level processes (Zivony & Eimer, 2022). However, the question of where the mechanism of attention occurs within the visual hierarchy has been a subject of debate for decades (Kanwisher & Wojciulik, 2000; Serences & Kastner, 2014). Two models of the visual hierarchy help to illustrate the complexities of this discussion: the classic visual hierarchy (Hubel & Wiesel, 1959, 1962) and the re-entrant hierarchical model (Felleman & Van Essen, 1991; Lamme & Roelfsema, 2000).

1.1.1 Selective Attention in the Visual Hierarchy

According to the classic hierarchical model of visual perception, information is constructed across a series of increasingly complex stages along a feedforward pathway from low- to high-level cortex (Barlow, 1972; Lamme & Roelfsema, 2000; see Figure 1.1). Visual input is first received by neurons in primary visual cortex (also referred to as area V1) where receptive fields are small and selectively tuned, responding best to lines of particular size/shape, orientation and/or direction of motion (Hubel & Wiesel, 1959, 1962). From primary visual cortex, visual information then travels along two functionally distinct processing streams, commonly referred to as the “what” and “where” visual pathways (Ungerleider & Mishkin, 1982). The ventral “what” pathway (V1/V2, V4, IT) is primarily concerned with *what* a particular object is, and thus is an important site for object recognition (Conway, 2018; DiCarlo et al., 2012). In contrast, the dorsal “where” pathway (V1/V2, MT, PAC) is concerned with objects’ spatial properties, and is therefore thought to be important in mediating object-related actions such as reaching, grasping, etc. (Goodale & Milner, 1992; Husain & Nachev, 2007; Milner & Goodale, 2008). Within the ventral “what” pathway, basic visual features are combined in successive stages of visual cortex, eventually culminating in complex representations of objects and categories (Conway, 2018; Grill-Spector & Weiner, 2014). This hierarchical processing is reflected in changes of the receptive fields, which become larger and more selective for complex properties like pattern and shape in area V4 and even for categorical representations in inferior temporal cortex (Grill-Spector & Malach, 2004; Pasupathy et al., 2020).

Figure 1.1

Classic Model of the Visual Hierarchy

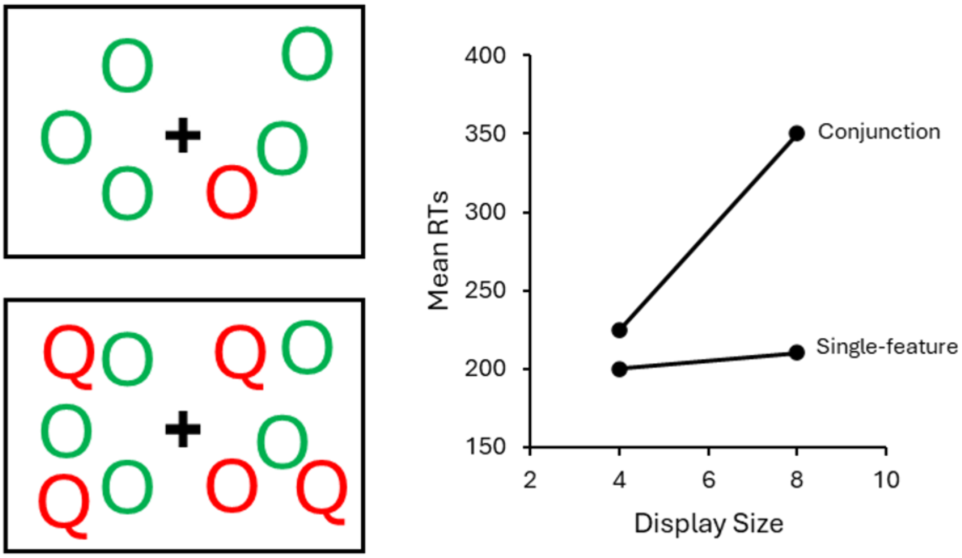


Note. Visual input first enters the cortical hierarchy at area V1. From here, it is sent to the “what” pathway (V4, IT) and the “where” pathway (MT, PAC; Ungerleider & Mishkin, 1982) to analyse its featural and spatial properties (respectively). Finally, the input is sent forward to the PFC, where it can be represented in working memory (Barbas et al., 2005). Adapted from “Mechanisms of Visual Attention in the Human Cortex” by S. Kastner and L. G. Ungerleider, 2000, *Annual Review of Neuroscience*, *23*(1), p. 318 (https://doi.org/10.1146/annurev.neuro.23.1.315). Copyright 2000 by Annual Reviews.

The classic view of the visual hierarchy aligns with FIT (Hochstein & Ahissar, 2002; Treisman & Gelade, 1980). FIT proposes that, during an initial “pre-attentive” stage, perceptual information is processed in parallel and basic visual features are automatically encoded in different parts of the visual cortex. In a subsequent “attentive” stage, the serial application of selective attention facilitates the binding of these visual features in a “master map,” thus allowing the selected features to be identified as a perceptual object at higher levels of processing. Support for FIT is provided primarily by visual search tasks (see Figure 1.2), which require subjects to search a display of randomly positioned “distractor” items to identify a pre-determined target (Eckstein, 2011; Nakayama & Martini, 2011). The number of distractors surrounding a target in a display, referred to as the display size (or set size) varies from trial to trial. Performance in visual search tasks are measured by the mean reaction time (RT) as a function of the display size, i.e., the slope of the RT function (Wolfe, 1998, 2020). FIT uses two types of visual search conditions, known as single-feature and conjunction, as evidence of pre-attentive and attentive stages, respectively. In single-feature search, the target item appears to “pop out” from the search display, as it is defined by a difference of one feature from its distractors (e.g., a red letter “O” target among green letter “O” distractors). In a conjunction search, the target is a conjunction of two features, and distractors belong to one of two groups that are defined by one of the target features (e.g., a red letter “O” target among green letter “O” and red letter “Q” distractors). According to FIT, the stage of processing at which search operates in is reflected in the search slope. In a single-feature search, slopes are typically quite flat, as RTs are not affected by the number of distractors present. This reflects the pre-attentive stage, where there is an absence of any focused attention. In conjunction search, slopes are steep, as RTs increase linearly with the number of distractors, implying the application of effortful attention (Humphreys, 2016; Kristjánsson & Egeth, 2020; Wolfe, 2015a).

Figure 1.2

Single-feature and Conjunction Search Displays and Slopes



Note. In the single-feature search (top left), the target letter “O” appears to pop out from the green letter “O” distractors in the display. In the conjunction condition (bottom left), the target red letter “O” is more difficult to find among the green letter “O”s and red letter “Q” distractors. On the right are the typical flat and steep slopes of the RT function for these search conditions (respectively). Adapted from “Visual Search: How Do We Find What We Are Looking For?” by J. M. Wolfe, 2020, *Annual Review of Vision Science*, *6*(1), p. 541 (https://doi.org/10.1146/annurev-vision-091718-015048). Copyright 2020 by Annual Reviews.

Notably, FIT posits that the placement of attention across space is random (Treisman & Gelade, 1980). However, in such a cluttered environment, this method of visual search would often be incredibly inefficient. Furthermore, this assumption overlooks both the role of a stimulus' inherent saliency and of the observer, who brings their unique attentional capacity and internally-held goals to each search (Lynn et al., 2024; Redden et al., 2023). To account for these factors, the

Guided Search Model (GSM) provides a critical revision to FIT in its proposal that, rather than random allocation, attention is guided to the most likely location of the target item (Wolfe, 2020, 2021). According to GSM, different types of information collectively contribute to guide attention using a priority map. A priority map consists of a topographical map of space where all the objects within the visual field compete for selection. Each object within this map is assigned a unique priority level, and the object with the highest level of priority is selected (Bisley & Mirpour, 2019; Fecteau & Munoz, 2006; Rust & Cohen, 2022).

One source of information that contributes to priority is bottom-up salience (Itti & Borji, 2015; Soltani & Koch, 2010; Treue, 2003). Bottom-up salience refers to the distinctiveness of a stimulus. There are a number of different physical qualities that make one object more salient relative to the surrounding objects, including colour, orientation, size, motion and onset (Wolfe, 2020; Wolfe & Horowitz, 2004, 2017). Furthermore, the property of salience is relative (Becker, 2010; Becker et al., 2017). This is best highlighted by the similarity rule, which states that a stimulus' saliency depends on its level of similarity to the target and the other distractors in the display, with the most saliency yielded from a target that is maximally different from distractors that are highly similar to one another (Duncan & Humphreys, 1989; Wolfe, 1994, 2021). In addition to bottom-up salience, priority level is also determined by "top-down" guidance based on behavioural goals (Baluch & Itti, 2011; Boshra & Kastner, 2022; Noudoost et al., 2010). Top-down guidance can be generated from knowledge of the target's basic features (Wolfe, 1994, 2021). Expected target features are held online in working memory (WM), and this representation guides attention to the most likely target (Carlisle et al., 2011; Olivers et al., 2011). For example, in a search where the observer is searching for a red letter "H" target among red letter "A" and black letter "X" distractors, attention can be guided by the colour red and the letter "H," thus making search significantly more efficient (Egeth et al., 1984). Ultimately, bottom-up (stimulus-driven) and top-down (goal-driven) guidance are combined to yield an overall level of priority for each item within the visual scene, and attention is directed to the item with the highest level of priority (Bisley & Mirpour, 2019; Fecteau & Munoz, 2006; Wolfe, 2021).

Collectively, the classic view of the visual hierarchy, FIT and GSM suggest that selective attention operates only after an initial (pre-attentive) stage of visual perception by selecting a particular location in space so that the features present at that location can be bound, perceived as a perceptual whole and ultimately sent forward to higher-level processing (Hochstein & Ahissar, 2002; Lamme & Roelfsema, 2000; Zivony & Eimer, 2022). This suggests that this processing occurs along a solely feedforward pathway. However, the notion of top-down attention in GSM points to the importance of the feedback pathways in addition to feedforward pathways. Indeed, anatomical studies demonstrate that essentially all connections between successive pairs of areas within the visual cortex are reciprocally connected (Briggs, 2020; Felleman & Van Essen, 1991; Lamme et al., 1998; Markov et al., 2014). These reciprocal connections give rise to a re-entrant hierarchy, whereby iterative processing allows top-down influences to provide behavioural context to visual perception (Froudarakis et al., 2019; Singer, 2021). The re-entrant hierarchical model of perception aligns with theories that propose perception is constructed not only from a hierarchy of feedforward connections, but also from the processing that occurs in a reverse hierarchy of feedback connections (Hochstein & Ahissar, 2002).

1.1.2 Selective Visual Attention Across Space

The previous section highlights how some of the fundamental psychological theories in attention research aim to bridge behaviour and brain. For instance, instead of “attention” meaning some abstract process in higher-level cognition, the proposal put forth by FIT essentially gave attention a concrete computational role in the brain of binding features together (Nakayama & Martini, 2011). While much of what was proposed by FIT has since been revised (e.g., pre-attentive vs attentive stages, parallel vs serial search, etc.; Deco & Zihl, 2001; Gilbert & Li, 2013; Serences & Kastner, 2014), the notion of attention as a computation has been an important step in building this brain-behaviour bridge. At the neural level, however, attention is best understood as an emergent property arising from biased competition computations – a process best described by the biased competition theory (BCT; Desimone & Duncan, 1995).

A large body of evidence from neuroscientific studies using single-cell physiology and neuroimaging shows that multiple objects present in the visual field cannot be fully represented in the visual system at the same time, and therefore must compete for neural representation by mutually suppressing one another (Beck & Kastner, 2005, 2007; Kastner & Ungerleider, 2001; Kim et al., 2021; Luck et al., 1997; Miller et al., 1993; Recanzone et al., 1997; Reynolds et al., 1999; Rolls & Tovee, 1995). For example, Reynolds et al. (1999) performed single-cell recording of V2 and V4 neurons in the macaque monkey. They had the monkey attend to a location in space that was far outside the recorded neuron's receptive field. They recorded the neuron's response (i.e., its firing activity) when a reference stimulus was presented alone, and then again when a second, "probe" stimulus was also present in the field. When the reference was the neuron's preferred stimulus (i.e., it elicited a high response) and the probe was a non-preferred stimulus (i.e., it elicited a low response), firing was suppressed after adding the probe. On the other hand, when the reference was a non-preferred and the probe was a preferred stimulus, firing increased. Thus, the response of a V4 neuron to two simultaneously present objects in its receptive field is a weighted average of each response (Reynolds et al., 1999). These suppressive interactions have been identified in multiple areas of the monkey's visual cortex (Britten & Heuer, 1999; Luck et al., 1997; Miller et al., 1993; Recanzone et al., 1997; Reynolds et al., 1999; Rolls & Tovee, 1995) and have also been found in the human visual cortex (Beck & Kastner, 2005, 2007; Kastner et al., 1998; Kastner & Ungerleider, 2001; Kim et al., 2021).

According to BCT, top-down and bottom-up signals bias this sensory competition by facilitating processing of the behaviourally relevant stimulus and simultaneously suppressing distracting stimuli (Desimone & Duncan, 1995). Reynolds et al. (1999) also demonstrated the modulatory effects of top-down, spatially-directed attention on competition between multiple items simultaneously present within the visual field. They repeated the same experiment, but this time with the monkey trained to attend to the reference stimulus inside the recorded neuron's receptive field. They found that the effect of attention was to nearly restore the neuron's response prior to the addition of the probe. For example, if the addition of a (nonpreferred) probe suppressed firing when attention was outside the receptive field, then attending to the (preferred) reference stimulus re-instated firing activity to more closely resemble the higher response elicited by the (preferred) reference stimulus alone. On the other hand, if the addition of a (preferred) probe increased the neuron's firing activity, then attending to the (nonpreferred) reference stimulus lowered the neuron's firing activity to the level corresponding to the response of the neuron to the (nonpreferred) reference alone (see also Fernandes et al., 2021; Ni & Maunsell, 2019; Volotsky et al., 2019). These findings imply that attention can resolve ongoing competition by overcoming the suppressive influences of competing stimuli nearby, ultimately allowing the attended stimuli to "win" the competition at the expense of unattended stimuli. Attentional modulation of competitive interactions has been found across the visual hierarchy, including V1, V2, V4, MT and the inferior temporal (IT) cortex (Bichot et al., 2019; Chelazzi et al., 1993; Monosov et al., 2011; Moran & Desimone, 1985; Reynolds et al., 1999).

BCT proposes that top-down biases are first generated in areas outside of the visual cortex and then fed back to extrastriate areas. Initially, it was proposed that the prefrontal cortex (PFC) most likely serves as a primary source of these top-down biases (Desimone & Duncan, 1995). The PFC is a particularly attractive site for this due to its extensive feedback connections with the extrastriate cortex (Barbas et al., 2005). Furthermore, the PFC is an important site for visuospatial working memory due to the ability of PFC neurons to maintain internal representations in the absence of stimulation (Arnsten et al., 2010; Goldman-Rakic, 1995). Indeed, the PFC is thought to be included in a larger network involved in top-down attention control that includes both a dorsal attention network (DAN), comprised of the frontal eye fields (FEF), superior parietal lobule (SPL) and intraparietal sulcus (IPS), and a ventral attention network (VAN), including the inferior frontal gyrus (IFg), middle frontal gyrus (MFg) and temporo-parietal junction (TPJ; Alves et al., 2022; Corbetta et al., 2008; Corbetta & Shulman, 2002).

1.1.3 Selective Visual Attention Over Time

While single-feature and conjunction search explore the mechanisms of attention across space, preview search highlights how these mechanisms operate over time as well (Wolfe, 2021). In a typical preview search condition, the final display is identical to that of a standard conjunction search (e.g., a red letter “O” target among green letter “O” and red letter “Q” distractors). However, unlike a conjunction search, one set of distractor items (e.g., the group of green letter “O”s) is displayed for a short time (a minimum of about 450 msec; see Mavritsaki et al., 2006; Watson & Humphreys, 1997) before the second set of distractor items and target item appear alongside (see Figure 1.3). Although the final search display of a preview search is identical to that of a standard conjunction search, the "previewing" of half the distractors produces significantly more efficient search that can even be as efficient as if only new items were presented (e.g., a single-feature search; for reviews, see Olivers et al., 2006; Watson et al., 2003).

In an attempt to explain how this search benefit arises from time-based attention, Watson and Humphreys (1997) originally proposed that new items are prioritised by top-down attentional inhibition to old items, a process termed *visual marking*. The presence of this visual marking mechanism and its importance in eliciting the preview benefit is supported by dot-probe detection studies, which show detection of probes at preview locations is worse compared to detection of the same probes at locations of new stimuli, indicating the presence of inhibition at preview locations

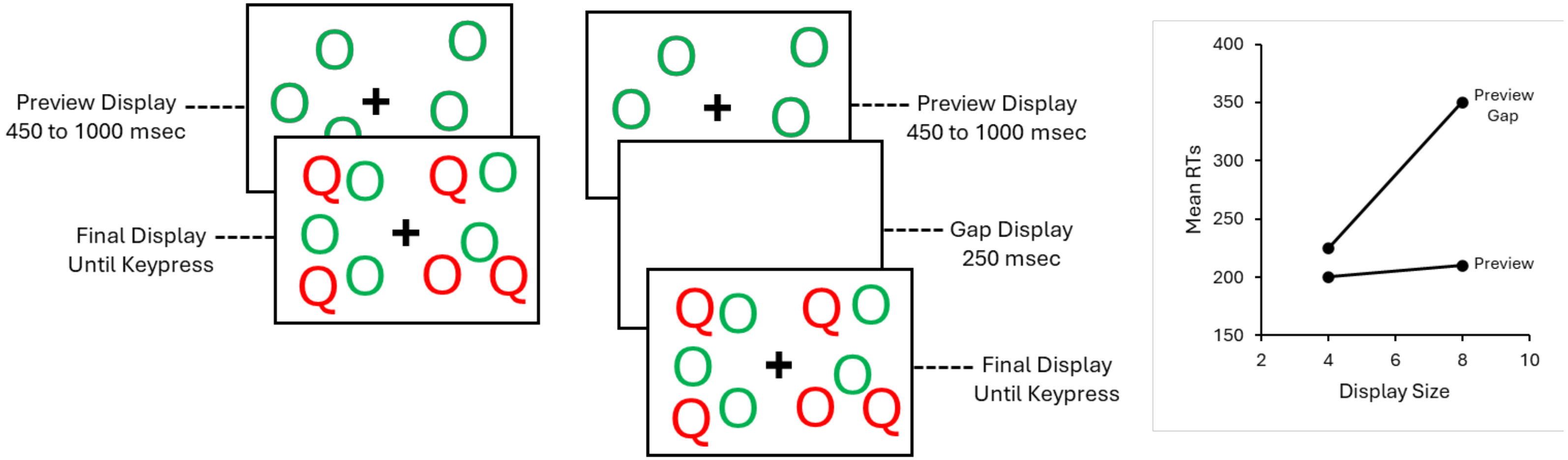
(Braithwaite et al., 2005; Osugi et al., 2009; Osugi & Murakami, 2014; Watson & Humphreys, 2000). Furthermore, this active inhibition has been shown to carry over, so that singleton distractors that carry preview feature values in the final display cause less interference that those with features not previously held by preview items (Andrews et al., 2011; Braithwaite et al., 2003; Mason et al., 2004; Olivers & Humphreys, 2003). More recently, Berggren & Eimer (2018) demonstrated that, during the preview period, the P_D is elicited - an event related potential (ERP) associated with the active suppression of distractor stimuli (Berggren & Eimer, 2018; Gaspelin & Luck, 2018). Finally, in addition to active inhibition, active expectancy for the target's features has also been shown contribute to the preview benefit (Braithwaite & Humphreys, 2003).

In addition to the significant top-down contribution in preview search, bottom-up factors – most notably temporal binding – also play an important role. *Temporal binding* refers to the binding of separable visual features according to their common temporal onset (Singer, 2015; Singer & Gray, 1995). Theories like FIT have primarily focused on the binding of separable features into objects when they occur in the same spatial location. However, temporal properties of features also provide important information as well. Indeed, when separable features appear at the same time, they become bound into a perceptual whole (Elliot & Müller, 2000; Makarov et al., 2024; Singer, 1999, 2021; Usher & Donnelly, 1998). Temporal binding is crucial to the preview benefit, and this is best demonstrated through preview gap search. Preview gap search is similar to preview search in that a first set of distractor items appear alone during the initial (750 msec) preview period. However, in the preview gap condition, these items then disappear, and a blank "gap" display is presented for 250 msec. After the gap display, both old and new items appear simultaneously (see Figure 1.3). Under these preview gap search conditions, the preview benefit is completely abolished, with search slopes becoming as inefficient as conjunction search again (Kunar et al., 2003; Mavritsaki & Humphreys, 2016; Watson & Humphreys, 1997). In an effort to understand why the preview benefit is lost under these search conditions, Kunar et al. (2003) found that the preview benefit can be restored if preview items are briefly presented alone again after the gap, thus suggesting the importance of distinct common onsets for distractor groups. How temporal binding modulates the preview benefit has been detailed by the binding spiking search over time and space (b-sSoTS) model (Mavritsaki & Humphreys, 2016), which is discussed in detail in section 1.3.

Within the conceptual framework of the priority map, it is easy to envision different points in space being represented by various levels of priority according to that point's combined contribution of bottom-up stimulus salience and top-down behavioural relevance. An additional, often overlooked, aspect of the priority map, however, is its temporal properties (Capizzi et al., 2023; Wolfe, 2021; Zivony & Eimer, 2022). These temporal properties yield a priority map whose landscape changes continuously; as such, an object's level of priority can evolve over time (Wolfe, 2021). Across behavioural, network and neural levels of observations, research has been able to piece together how bottom-up and top-down mechanisms work together to give rise to selection across space (Buschman & Kastner, 2015; Carrasco, 2011; Fiebelkorn & Kastner, 2020). However, how these dynamics change as time passes by still remains comparatively poorly understood. Therefore, it is of great theoretical interest to better understand time-based attention processes and how these might differ between different populations.

Figure 1.3

Preview and Preview Gap Search Displays and Slopes



Note. In the preview condition (left), one set of distractor items is presented alone for a "preview" period. Then a second set of distractors and the target item appear. This yields flat slopes (right) and is referred to as the "preview benefit" (Olivers et al., 2006). In the preview gap condition (middle), items are presented alone for a "preview" period. Then items are offset, leaving a "gap" display. Then, preview items re-appear in their original positions alongside the new items. This leads to the loss of the preview benefit, such that slopes becomes steep again (right; Watson & Humphreys, 1997). Adapted from "Visual Marking: Using Time in Visual Selection" by D. G. Watson, G. W. Humphreys and C. N. L. Olivers, 2003, *Trends in Cognitive Sciences, 7*(4), p. 181 (https://doi.org/10.1016/S1364-6613(03)00033-0). Copyright 2003 by Elsevier Science Ltd.

1.1.4 Development of Selective Visual Attention

Starting from an early age, the ability to selectively attend to visually salient stimuli allows us to effectively navigate the world around us (Johnson, 2019). This environmental interaction, in turn, contributes to the development of the brain's intricate structural and functional organisation that subserves the ability to regulate and maintain attention according to our internal goals (Amso & Scerif, 2015; Lynn & Amso, 2023). Ultimately, this complex growth and development of selective attention is particularly important to understand in order to deepen our understanding of cognition and behaviour in general.

The brain undergoes a caudal-to-rostral trajectory of development (Baum et al., 2020; Charvet & Finlay, 2014; Gogtay et al., 2004; Sydnor et al., 2021). Accordingly, the visual system first begins to develop inutero (Johnson, 2019), and these visual areas, as well as other primary sensorimotor areas, become adult-like well before higher-order association areas (Gogtay et al., 2004), which continue to develop across adolescence and even into young adulthood (Fuster, 2002; Preuss & Wise, 2022). During development, the brain undergoes substantial changes in its structure and connectivity, which ultimately contribute to more efficient functional activity (Soman et al., 2023a). Grey matter thins (Gogtay et al., 2004) and white matter volume increases with pruning of excessive synaptic connections (Petanjek et al., 2011) and continued myelination (Barnea-Goraly et al., 2005). Furthermore, short-range connections within areas are joined by more long-range connections between distributed regions (Cao et al., 2017; Fair et al., 2007, 2009; Supekar et al., 2009). These changes contribute to fast and efficient neural communication, which in turn supports age-related improvements in cognitive function (Luna et al., 2015). These changes are particularly relevant to the development of selective visual attention, which relies on efficient PFC networks to maintain representations of goals in working memory and on long-range connections that allows signals to be fed back to the visual cortex (Beck & Kastner, 2009; Clark et al., 2015; Desimone & Duncan, 1995;

Martinez-Trujillo, 2022). Accordingly, selective visual attention continues to improve across childhood and adolescence, and this is reflected in improved behavioural performance (Amso & Scerif, 2015; Oakes & Amso, 2018).

Improvements in behavioural performance during development mirror the caudal-to-rostral trajectory of development, so that easier, more bottom-up attention develops first, while higher-level top-down attention continues to develop across adolescence (Amso & Scerif, 2015; Oakes & Amso, 2018). This pattern of developmental improvements is also evident in visual search performance. For instance, within the first post-natal year, the basic architecture of the visual cortex develops, and this is reflected in improvements in the ability to detect basic visual features like orientation, colour, and motion (Atkinson & Braddick, 2020; Braddick & Atkinson, 2011; Braddick et al., 1986). Accordingly, these improvements are likely to contribute to the relatively early mastery of single-feature searches (Gerhardstein & Rovee-Collier, 2002; Quinn & Bhatt, 1998). Indeed, efficient single-feature search has been reported as early as 3-4 months for orientation pop-out (Quinn & Bhatt, 1998) and 1 year for colour pop-out (Gerhardstein & Rovee-Collier, 2002).

In contrast to the early development of single-feature search, improvements in the effortful process required for conjunction search have a more protracted trajectory (Lynn et al., 2020, 2023; Merrill & Conners, 2013; Merrill & Lookadoo, 2004). For instance, Merrill and Lookadoo (2004) compared three age groups on a conjunction search where the target was a black circle, and distractors were black squares and grey circles. They found that 7-year olds were significantly less efficient than both 10-year olds and young adults, and 10-year olds were less efficient than young adults. Importantly, by varying the ratio of black-to-grey items in the display in a second experiment, Merrill and Lookadoo (2004) showed that age-related differences in slope increased as the number of black items increased. When the number of black items was sufficiently small, all groups performed similarly; however, as the number of black items increased, efficiency decreased with age. Thus, the authors concluded age-related improvements are likely the result increased efficiency in the ability to effectively guide attention to the most likely target item (Merrill & Lookadoo, 2004). Indeed, a number of studies have similarly reported that search for conjunctive targets becomes more efficient with age (Donnelly et al., 2007; Lynn et al., 2023, 2023; Trick & Enns, 1998). These improvements are most often associated with the continuing development of higher-order regions of the cortex, such as the PFC, which subserve WM and other processes key to efficient search (Amso & Scerif, 2015; Kolk & Rakic, 2022; Luna et al., 2015; Lynn & Amso, 2023).

Much of the existing literature on the nature and mechanisms of attention applies to the fully developed state (Boshra & Kastner, 2022; Carrasco, 2011; Fiebelkorn & Kastner, 2020). However, in order to truly understand attention, there must be an understanding of how this stable adult state was achieved (Amso & Scerif, 2015; Kim et al., 2021; Lynn & Amso, 2023). Furthermore, identifying the mechanisms that give rise to selective attention in typical development will also provide insight into how these might contribute to attentional difficulties in atypical development, like those in ADHD.

1.2 Attention-Deficit/Hyperactivity Disorder (ADHD)

Attention-deficit/hyperactivity disorder (ADHD) is a common mental disorder characterised by developmentally inappropriate and impairing levels of inattention, hyperactivity and impulsivity (American Psychiatric Association, 2013). ADHD affects approximately 8.0% of children and adolescents (Ayano et al., 2023) and between 3.1-6.7% of adults (Ayano et al., 2023; Song et al., 2021; Yuan et al., 2024), making it one of the most prevalent mental health disorders worldwide (Cortese et al., 2023; Polanczyk et al., 2015; Vasileva et al., 2021). ADHD has been traditionally characterised as a neurodevelopmental disorder that begins in childhood and resolves by adulthood (Asherson & Agnew-Blais, 2019; Sonuga-Barke et al., 2023). However, the symptoms and impairments of ADHD continue to persist into adulthood for somewhere between 65% and 90% of cases (Faraone et al., 2006; Sibley et al., 2022). Furthermore, recent evidence supports the existence of late-onset ADHD, where symptoms first arise after the age of 12 (Moffitt et al., 2015; Rajagopal et al., 2022), thus challenging the characterisation of ADHD as a neurodevelopmental disorder (Sonuga-Barke et al., 2023).

Research demonstrates that individuals with ADHD are at a higher risk for functional impairments and adverse outcomes, including lower educational and occupational attainment (Gjervan et al., 2012; Voigt et al., 2017), problems with peer and romantic relationships (Harpin et al., 2016; Wozniak, 2022), and lower overall quality of life (Orm et al., 2023; Quintero et al., 2019). Furthermore, children and adults with ADHD are more likely to have comorbid mental and somatic (e.g., obesity) problems (Barkley, 2020; Cortese et al., 2016; Hanson et al., 2020) are at an increased risk for self-harm/suicidal ideation (Septier et al., 2019; Zhong et al., 2021) and criminality (Erskine et al., 2016). Accordingly, there exists a distinct need to develop a thorough understanding of what difficulties occur ADHD, how they arise, and how this translates to functioning in everyday life.

One of the early theories of ADHD proposed that symptoms associated with the disorder arise from reduced arousal (Satterfield et al., 1974). Specifically, Satterfield et al. (1974) found that children with ADHD who had low levels of central nervous system (CNS) arousal had the highest levels of disruptive behaviour in the classroom and were the best responders to stimulant medication (Satterfield et al. 1974). The authors went on to reference work that stimulant-treated children with ADHD show improved attention and performance on psychological tests - referring to Conners' Continuous Performance Task (CPT; Conners, 1968, 1971). Indeed, one of the more commonly used neurocognitive measures to assess for differences in ADHD is the CPT (Onandia-Hinchado et al., 2021; Pagán, Huizar, & Schmidt, 2023). There are several variants of the CPT, but for all, the goal is to consistently identify a particular target stimuli among distractors (where items are presented successively) over a prolonged period of time - usually 15 minutes or more. Indeed, compared to non-ADHD controls, children and adults with ADHD typically perform worse on the CPT, with more variable RTs and higher error rates (Bisch et al., 2016; Delisle & Braun, 2011). However, this is not always the case, as some studies have reported no significant differences between ADHD and non-ADHD individuals (Dobson-Patterson et al., 2016). Furthermore, while recent research also provides support for the idea that the CPT is able to effectively identify symptoms of inattention (Pagán, Huizar, Short, et al., 2023), there are still mixed findings as to the CPT's sensitivity (i.e., ability to correctly identify individuals with ADHD) and its overall diagnostic utility (Callan et al., 2024; Johnsen et al., 2024; Pagán, Huizar, & Schmidt, 2023).

Other ADHD research has focused on response inhibition as the primary issue of the disorder. Barkley (1997) proposed that the wide variety of impairments associated with ADHD arise from atypical behavioural inhibition, or the ability to stop an initiated behaviour in furtherance of a specific behavioural goal (Bari & Robbins, 2013; Nigg, 2017). This difficulty in response inhibition is often theoretically tied to hyperactive/impulsive symptoms (rather than inattentive symptoms), and in CPT and Go/No-Go tasks, differences are thought to be reflected behaviourally by increased commission errors (false alarms). In another popular measure, the Stop Signal Reaction Time (SSRT) task, response inhibition difficulties are reflected in longer RTs (Bari & Robbins, 2013; Nigg, 2005). Indeed, children, adolescents and adults with ADHD all perform worse on measures of response inhibition (Bonham et al., 2021; Kolodny et al., 2020; Mehren et al., 2019; Roberts et al., 2016; Wright et al., 2014). Barkley (1997) proposed that this reduced behavioural inhibition gives rise to the wide variety of difficulties in executive functioning. However, empirical evidence supporting this specific relationship is lacking. In a review of 34 meta-analyses that compared performance between ADHD and non-ADHD individuals on a wide variety of neurocognitive domains (e.g., set shifting, WM, RT variability, etc.), Pievsky and McGrath (2018) found that the size of response inhibition difficulties were moderate (.52) and, rather than being the domain with the largest effect (as would expect if it is indeed the core problem), was nearly identical in size to other domains (Pievsky & McGrath, 2018).

The notion that ADHD is characterised by difficulties in arousal and/or response inhibition seems intuitive. Indeed, the proposals put forth by Satterfield et al. (1974) and Barkley (1997) highlight a key challenge present in ADHD research: the vocabulary surrounding impairments appears to diverge, as the terms "arousal," "vigilance" and "sustained attention," are typically associated with the inattentive subtype, while "response inhibition" is associated with the hyperactive/impulsive subtype. For example, much of the research in ADHD expresses a difficulty in the ability to reconcile two symptoms dimensions that are viewed as paradoxical (Avisar, 2022; Castellanos et al., 2006; Sergeant et al., 2003; Sonuga-Barke, 2003; Sonuga-Barke et al., 2023), with the inattentive subtype reflected by a lack of responding (omission errors) and the hyperactive/impulsive subtype indicated by an inappropriate level of over-responding (commission errors; Albrecht et al., 2015; Pagán, Huizar, & Schmidt, 2023). Naturally, when individuals with ADHD demonstrate difficulty in sustained attention or vigilance tasks, this is interpreted within frameworks that support the idea of a core mechanism of low arousal/activation (e.g., Cognitive Energetic Model; Sergeant, 2000; Sergeant et al., 1999). Similarly, in tasks of response inhibition, difficulties are often interpreted in terms of Barkley's (1997) behavioural inhibition model (for some examples, see Huang-Pollock et al., 2012 and Pievsky & Mcrath, 2018).

However, it is important to return to the original text and review the authors' definitions of these terms and the context in which they were offered. For example, at the time of Satterfield's (1974) low arousal theory, children with ADHD were diagnosed as having "hyperactive child syndrome." Indeed, the participants in Satterfield et al.'s (1974) study were characterised as having, "[A] chronic symptom pattern of hyperactivity, distractibility, excitability and impulsivity" (Satterfield et al. 1974, p. 839). Thus, it is likely that, today, these children would be characterised as the hyperactive/impulsive subtype (APA, 2013). Importantly, in explaining the relationship between low levels of (CNS) arousal (as measured by skin conductance levels) and high levels of disruptive classroom behaviour in these children, Satterfield et al. (1974) offered the following explanation:

"Lack of inhibitory control over sensory function could be expected to result in easy distractibility, with the low aroused child responding to irrelevant stimuli as ready as to relevant stimuli." (Satterfield et al. 1974, p. 842). This relationship between low arousal and hyperactive/impulsive behaviour blurs the seemingly clear dichotomy between subtypes, impairments, and causal mechanisms – how could low arousal cause both difficulties in under-responding (inattentive) *and* over-responding (hyperactive impulsive)?

1.2.1 Selective Attention in ADHD

In the present thesis, it is argued that some of the apparently contradictory nature of ADHD can be lessened by understanding difficulties in terms of selective attention and by focusing on the nature of competitive interactions at the neural level. As discussed in the previous section (section 1.1), selective attention refers to the ability to selectively process relevant information while simultaneously ignoring information that is irrelevant and potentially distracting. Importantly, this definition of selective attention describes the behavioural result that arises from biased competition neural computations which occur within and across the cortical hierarchy (Beck & Kastner, 2009; Buschman & Kastner, 2015; Lynn & Amso, 2023). This selection occurs across the cortical hierarchy at multiple levels of abstraction – so whether it's low-level sensory information, or higher-order working memory representations or rule structure representations, competition occurs at every level of the cortical hierarchy (Amso & Scerif, 2015; Lynn & Amso, 2023). Thus, when there is a shared focus on the competitive interactions that occur at the neural level, it is easier to conceptualise how inefficient behaviour might arise from selection of the wrong stimuli, rule, or motor response.

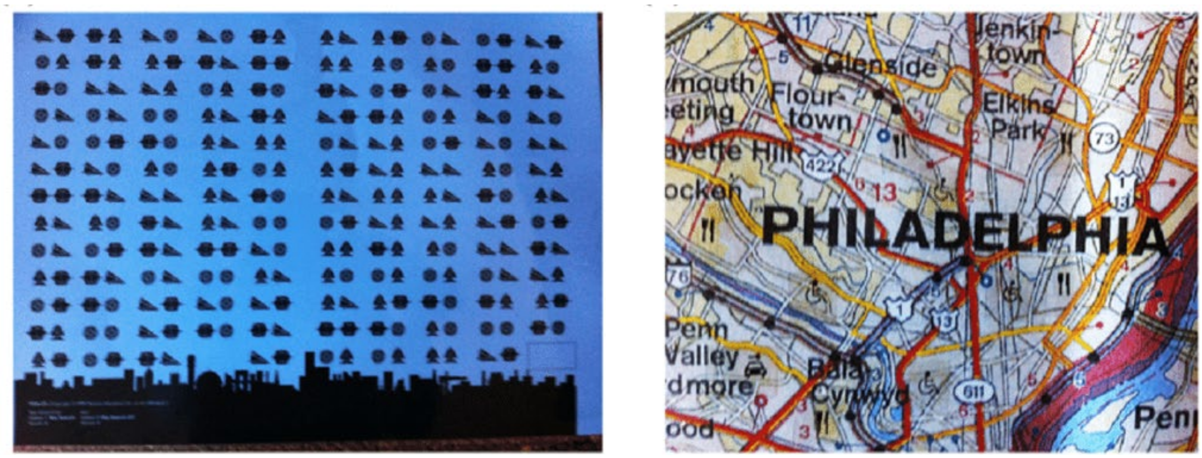
Furthermore, by understanding difficulties in ADHD through selective attention and the associated neural framework of biased competition, a more cohesive view of both inattentive and hyperactive/impulsive symptoms can be achieved. The PFC is a critical site in cognitive control and the regulation of attention (Friedman & Robbins, 2022; Martinez-Trujillo, 2022). Within the PFC, two key catecholamines - dopamine (DA) and norepinephrine (NE) - contribute to maintaining the region's extremely sensitive neurochemical environment (Cools & Arnsten, 2022). Specifically, these catecholamines are crucial to maintaining an optimal levels of arousal, which in turn support an optimal signal-to-noise ratio (SNR; Kroener et al., 2009). Optimal SNR supports the ability to maintain complex representations online in WM, and these representations serve as the source of top-down attention biases (Panichello & Buschman, 2021). Importantly, optimal SNR occurs at moderate levels of arousal. At low levels of arousal (e.g., during drowsiness or boredom), ADHD-like symptoms appear, such as impaired WM, increased distractibility, poor impulse control and motor hyperactivity (Arnsten et al., 1996). Similar symptoms - in particular, impaired WM - also appear at atypically high levels of arousal (e.g., during stress) as well (Brennan & Arnsten, 2008; Cools & Arnsten, 2022). Several of the genes associated with ADHD involve catecholamine neurotransmission, including NE and DA receptors and transporters (Bidwell et al., 2011; Bonvicini et al., 2020; Grünblatt et al., 2019; Yang et al., 2013), and dopamine beta-hydroxylase (DBH), the enzyme required for NE synthesis (Shalev et al., 2019; Tong et al., 2015). Furthermore, the gold-standard treatment for ADHD is psychostimulant medication (e.g., Ritalin, Adderall; Anbarasan et al., 2022). Non-stimulant medications are also available but are considered less efficacious (Cortese et al., 2018). Both stimulant and non-stimulant medications for ADHD act by raising the amount of catecholamine neurotransmission in the PFC (Spencer et al., 2015; Spencer & Berridge, 2019). Thus, the seemingly paradoxical symptoms could be explained by this “inverted U,” relationship in the PFC, where difficulties in ADHD may arise not from a definitive lack of attention, but problems in regulating levels of arousal, where too little or too much arousal reduces the ability to control interference and thus impairs competitive interactions.

So far, at the behavioural level, evidence for atypical selective attention in ADHD has been mixed. For example, a literature review of seven studies compared visual search performance between children with and without ADHD found that, although groups performed similarly under single-feature search conditions, children with ADHD were less efficient in conjunction search tasks, particularly in overly easy and overly complex search displays (Mullane & Klein, 2008). These findings suggest that children with ADHD have difficulty allocating effortful attention under both “boring” and stressful conditions, but difficulties disappear at optimal levels of stimulation (Brennan & Arnsten, 2008; Mullane & Klein, 2008). However, in a recent systematic review of twenty-two studies using visual search tasks, Hokken et al. (2023) found that children with ADHD were slower only 33% of the time and less accurate 56% of the time. The failure to find conclusive differences between groups in this review, however, could be due to the inclusion of studies that use continuous search tasks (such as TEA-Ch and cancellation tasks; see Figure 1.4), and using RT and accuracy but failing to examine search slope, which is critical to understanding the mechanisms of search (Wilding, 2005). Furthermore, while these reviews included only studies in which participants were off any ADHD medication during the time of testing, none contained a sample of medication-naïve participants. As the use of medication has been shown to normalise structural differences in ADHD (Schweren et al., 2013; Sobel et al., 2010; Spencer et al., 2013), this could affect the accuracy of results.

Despite inconsistencies at the behavioural level, though, neuroimaging methods have also demonstrated that, even in the absence of observable behavioural differences, children with ADHD show atypical neural activity that reflects differences in both in top-down functions, like the active suppression of distractors (Cross-Villasana et al., 2015; O’Conaill et al., 2015; Skalski et al., 2021; Wang et al., 2016) as well as bottom-up functions, like allocating attention to salient (pop-out) stimuli (Guo, Luo, Kong, Li, Si, Jensen, et al., 2023; Guo, Luo, Kong, Li, Si, Sun, et al., 2023; Wang et al., 2016, 2017). Thus, despite previous inconsistencies in research examining selective visual attention in ADHD, through focusing on the state of competitive interactions and their neural underpinnings, there is still much untapped potential here.

Figure 1.4

Commonly Used Measures of Selective Attention



Note. Two subtests on the Test of Everyday Attention for Children (TEA-Ch; Manly et al., 1999). In Sky Search (left), children are required to circle all twenty targets (pairs of identical spaceships) with a pencil while ignoring distractors. Time for completion and accuracy are recorded. In Map Mission (right), children are instructed to circle as many targets (knife-and-fork symbol) as possible within a period of 1 minute. The score is the number of targets correctly marked. From "Age Effects on the Development of Stimulus Over-Selectivity are Mediated by Cognitive Flexibility and Selective Attention" by M. P. Kelly and P. Reed, 2020, *International Journal of Behavioral Development, 45*(1), p. 91 (https://doi.org/10.1177/0165025420949702). Copyright 2020 by Sage Publications.

1.3 Computational Modelling of Visual Attention and Search

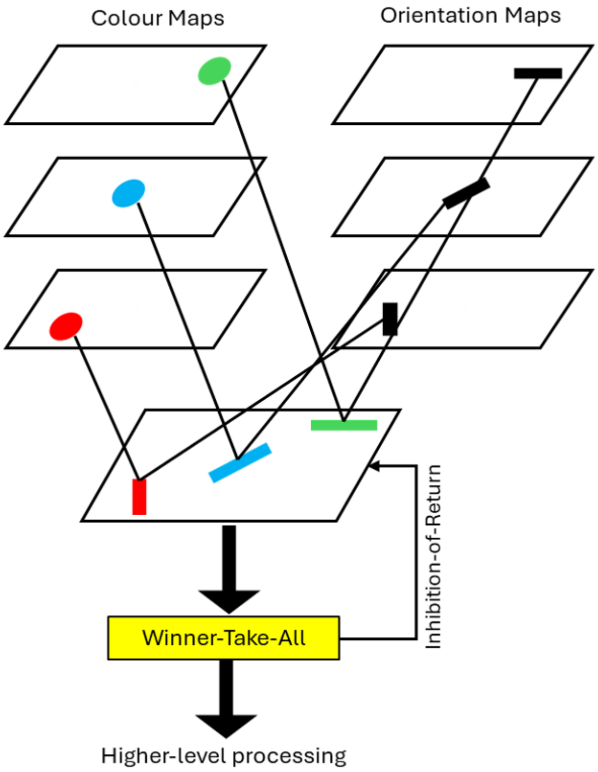
In section 1.1, some of the seminal theories and models of selective attention, such as FIT and GSM, were reviewed while being situated in the visual hierarchy. From this, it can be seen that researchers have aimed to understand selective attention and greater cognition by using behavioural data to break cognition into its component parts. Particularly over the past thirty years or so, there has been clear shift such that more classical behavioural measures of performance are now typically augmented by the inclusion of neuroimaging (e.g., EEG, fMRI, etc.). This shift has ultimately allowed researchers to map cognitive components onto the brain, thus illuminating its functional layout and giving rise to the discipline of cognitive neuroscience (Litwińczuk et al., 2023; Williams & Henson, 2018). While these advances are no doubt substantial, they ultimately fall short in their ability to answer the fundamental question of *how* complex cognition arises from the brain. In order to achieve this feat, we must incorporate biologically plausible computational models that are capable of performing tasks, thus allowing us peer inside the black box of cognition. The present section will first briefly review some of the key computational models in cognitive science to explain how selective attention arises the behavioural level and how certain fields of artificial intelligence (AI), such as machine-learning (ML), have contributed to this. This is followed by the use of models in computational neuroscience to explain how selective attention arises at the neural level. This short review will then be followed by the introduction of the biologically plausible computational model capable of performing visual search tasks used in the present thesis.

As reviewed in section 1.1.1, the concept of bottom-up attention is often associated with the “pop-out” effect seen in single-feature search (Wolfe, 2015a, 2020). An item appears to “pop-out” from a display when it is highly salient, and this saliency depends on a number of factors, including the particular features of a given stimuli, as well as its relationship to other, surrounding stimuli (Wolfe & Horowitz, 2017). One important aspect in understanding both visual attention and perception is, then, to understand how saliency is computed. Drawing on the “master map” idea proposed by FIT (see section 1.1.1), Koch and Ullman (1985) approached this problem of algorithmically computing saliency by putting forth their *saliency map* concept in their computational model of selective attention. In order to compute the saliency of a particular image, Koch and Ullman’s (1985) model first decomposed the given image into separate feature maps. A single topographic then map receives and sums all of the inputs from each feature map (see Figure 1.5).

Based on the information provided from this saliency map, as locations compete for selection in a winner-take-all (WTA) manner (Koch & Ullman, 1985). Thus, the most salient location (represented by the highest level of activity) wins the competition. Selection then moves on to the item with the next highest saliency, using an active inhibition-of-return (IOR; Klein, 2000; Posner et al., 1980) mechanism to suppress the location and allow attention to shift to the next item. Importantly, this computational model was biologically inspired and thus provides insight into how saliency might actually be computed by biological neurons in the brain.

Figure 1.5

Bottom-up Attention Computations in a Saliency Map



Note. Koch and Ullman's (1985) notion of how attention emerges from competitive computations within a saliency map. First, separable visual features are represented in distinct feature maps. Activations from these feature maps are summed in a single topographic map of space. Locations in space are thus represented as different activation levels of stimuli, and the location with the highest activation "wins" selection. If the selected position is indeed the target, it is passed on to higher-level processing. If the selected position is not the target, this position is suppressed through IOR, and the position with the next highest activation is then selected. Adapted from "Search Asymmetry: A Diagnostic for Preattentive Processing of Separable Features," by A. Treisman and J. Southern, 1985, *Journal of Experimental Psychology: General, 114*(3), p. 306 (https://doi.org/10.1037/0096-3445.114.3.285). Copyright 1985 by the American Psychological Association.

Since Koch and Ullman's (1985) seminal work, there has been an explosion of research in this area. These advances are due, in part, to the fast-growing computational power of technology and increasingly bigger datasets from which to learn (Itti & Borji, 2015). More recently, the use of convolutional neural networks (CNNs) have been applied to be very effective at detecting salient objects (Borji et al., 2019; Hou et al., 2017; Li et al., 2017). CNNs are deep neural networks that can learn to recognise objects in images by itself (Krizhevsky et al., 2012; LeCun et al., 2015; Li et al., 2017; Long et al., 2015). These types of models, and other complex neural network models, are used in the ML field to perform tasks (Kriegeskorte & Douglas, 2018). However, their complex architecture and millions of parameters can make it difficult to understand how a solution to a given task was achieved (Kriegeskorte & Douglas, 2018).

Computational neuroscience has also utilised computational models that are biologically plausible in order to explain neural activity. Spiking neural networks (SNNs) are comprised of neuron units that transmit information (i.e., they fire) only when it's membrane potential reaches a threshold (Ghosh-Dastidar & Adeli, 2011; Yamazaki et al., 2022). One model of the spiking neuron, the leaky integrate-and-fire model (LIF; Tuckwell, 1998), integrates inputs over time until the threshold is reached, while also taking into account the behaviour of ion channel behaviour

(Yamazaki et al., 2022). Importantly, biologically plausible computational models can provide critical insight into how the complex, dynamical interactions between real biological neurons can give rise to component functions. One example of this can be seen in Deco and Rolls (2005) model of biased competition computations with and without spatially directed attention. Using Reynolds et al.'s (1999) results from single-cell recordings of V2 and V4 neurons in the macaque monkey (see section 1.1.2), this model was comprised of integrate-and-fire neuron units that were organised into two layers: the first of these two layers was meant to reflect neurons in area V2, while the second layer was meant to reflect area V4. The neurodynamical nature of this model allowed them to successfully simulate the neural activity detailed in Reynold et al.'s (1999) results. When multiple items (oriented bars) were in the visual field (via the input parameter), the activity of the spiking neurons showed that items inhibited each other. When attention was applied (via an additional, "attention" input to neurons of the attended item), neural activity was restored, reflecting a bias to the processing of that item.

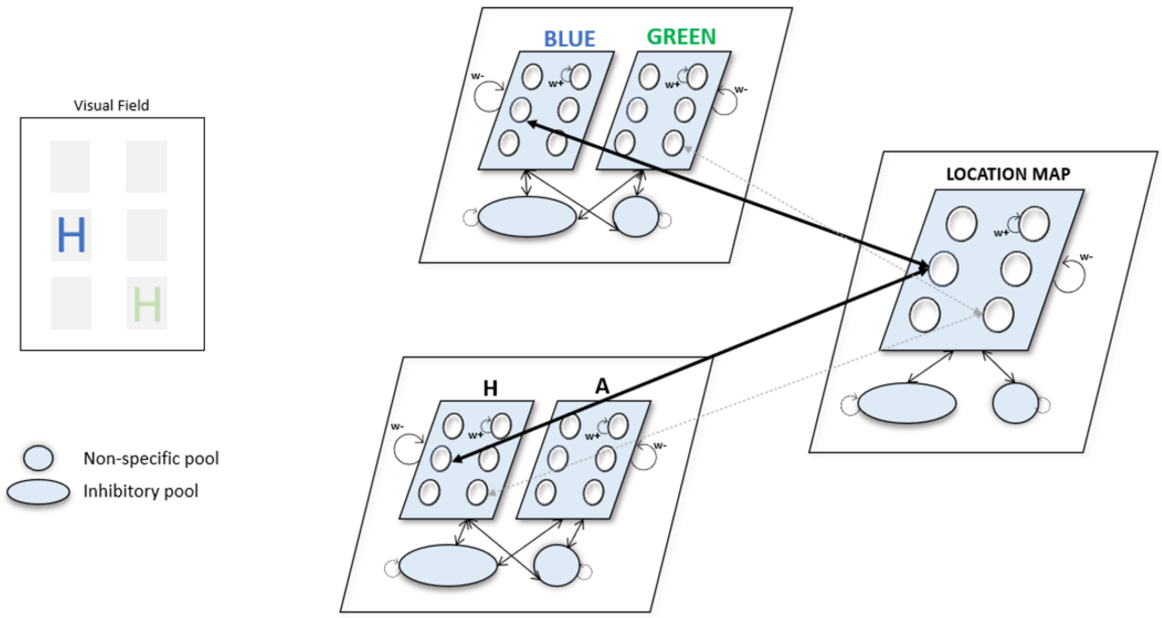
Deco and Rolls (2005) went on to explore in more detail how other elements contribute to this attentional modulation. For one, the authors examined how changes to the connection strengths between cortical areas affects biased competition. They found that, in order to achieve optimal competition within a cortical layer, feedback connections between cortical areas must be about weaker than feedforward (by a factor of 2.5). Furthermore, the authors also demonstrated how, differing levels of stimulus salience modulate the strength of attentional input. They found that attentional modulation is maximal when bottom-up input (salience) is at intermediate levels, and these attentional effects are minimal at both low and high levels of bottom-up input – an effect that occurs solely from the additive synaptic effects in the postsynaptic neuron (Deco & Rolls, 2005). Thus, this spiking neural network provides unique insight into the neural dynamics of attention, including how they neurons compete, how they cooperate, and how they interact with environmental factors.

1.3.1 Modelling of Visual Search

In the previous section it is discussed how computational modelling has aided the study of attention at both the cognitive level and at the neural level. Next, it is discussed how one model in particular – the spiking search over time and space (sSoTS) model – has effectively combined these approaches, and in doing so, has begun to bridge the gap between the high-level behaviours and the low-level neurobiological mechanisms of attention. The sSoTS model (Mavritsaki et al., 2006, 2011) is a neurodynamical computational model comprised of thousands of integrate-and-fire neuron units across three distinct layers (see Figure 1.6). The sSoTS model employs a similar architecture as Deco and Rolls' (2005) model; within each layer, there are pools (where a pool consists of some number of neurons with similar biophysical properties and inputs) of specific excitatory neurons, inhibitory neurons, and non-specific excitatory neurons. However, in the sSoTS model, two of the three layers contain feature maps, which are meant to reflect the visual cortex of the human brain, where visual features, such as colour and shape, are coded by distinct groups of neurons in the intermediate stages of visual processing (Conway, 2018; Grill-Spector & Malach, 2004; Grill-Spector & Weiner, 2014; Pasupathy et al., 2020). These two layers represent two particular feature dimensions (colour and shape), and within these there are two features each (blue and green; letter shapes "A" and "H"). In addition to the feature map layers, there is also a third layer that contains a saliency map (also sometimes referred to as a location map), where the activity of the feature maps is summed to represent the strength of a sensory signal at a particular location in space. With this architecture and processing dynamics, the sSoTS model was able to simulate the whole-system behaviour that arises from neural biased competition. Thus, even though we are limited in our ability to study human behaviour at the neuronal level, by using biologically plausible models like sSoTS, we can begin to direct our investigations to consider both physiology and psychology (Astle et al., 2023; Kriegeskorte & Douglas, 2018; Mavritsaki et al., 2011).

Figure 1.6

Architecture of the Binding-Spiking Over Time and Space (b-sSoTS) Model



Note. In the feature dimension *colour* (top) both feature maps (blue and green) are connected with inhibitory and non-specific pools. The layer organisation was identical for the feature dimension *letter shape* (bottom), but with these feature maps representing letters “H” and “A.” The location map layer (right) is connected with the inhibitory and non-specific pools in its layer with identical weights as in the feature dimension layers. The connections between the feature maps and the location map above are shown for two spatially and temporally distinct items. Adapted from “A Computational Model of Visual Marking Using an Inter-Connected Network of Spiking Neurons: The Spiking Search Over Time & Space Model (sSoTS)” by E. Mavritsaki, D. Heinke, G. W. Humphreys, and G. Deco, 2006, *Journal of Physiology – Paris*, *100*(1), p. 113 (https://doi.org/10.1016/j.jphysparis.2006.09.003). Copyright 2006 by Elsevier Ltd.

One example of how the sSoTS model has been used to explore how attention is allocated across space is through investigating the mechanisms that underlie the classic distinction between so-called parallel and serial search in single-feature and conjunction. As previously discussed in section 1.1.1, FIT proposed that single-feature and conjunction search's flat and steep slopes are a product of parallel and serial processing, respectively (Treisman & Gelade, 1980). While this parallel vs. serial dichotomy may hold (to a certain extent) in cognitive models of visual search (Wolfe, 2020), these models cannot examine whether the brain is capable of successfully searching for a conjunctive target with strictly parallel processing. It is with these sort of "black box" system problems that the sSoTS model and similar neurodynamical models of attention are particularly helpful (see also Deco & Zihl, 2001). Mavritsaki et al. (2006) used the sSoTS model to simulate single-feature and conjunction search. In both conditions, it was assumed that the observer had prior knowledge of the target item's features, and so the feature map "blue" and the feature map "letter shape H" were activated at all locations at baseline. At the start of each trial, neurons representing the stimuli for each condition were activated, and this activity was summed in the location map, where items competed for selection. The analysis of the spiking data for these conditions showed that, in both single-feature and conjunction, all items do indeed compete in parallel. The steep slopes associated with conjunction search arise from the increased competition between items, as the increased similarity between distractors and the target (i.e., from sharing one of the two target features) causes higher activation in distractor items compared to single-feature search (Mavritsaki et al., 2006).

The sSoTS model has also yielded important insights into the neural mechanisms underlying the allocation of attention to a particular moment in time. As previously discussed, time-based attention has been widely studied using preview search (see section 1.1.3; Olivers et al., 2006; Watson & Humphreys, 1997). Under preview conditions, search becomes as efficient as in a typical single-feature search, despite the final display being identical to that of a standard conjunction search (Watson et al., 2003; Watson & Humphreys, 1997). In order to provide a computational explanation for the preview benefit, this search condition was simulated with the sSoTS model. Simulations of this search condition highlighted some of the potential mechanisms at work in generating the preview benefit. One such mechanism is neuronal adaptation. Indeed, upon the initial presentation of stimuli within the visual field, certain physiological changes occur that allow the neuron sensitive to that stimuli to change its state from one of rest to one of active firing (Ibbotson & Meffin, 2020; Kandel et al., 2013). However, this initial rate of firing adapts, so that there is a decay of this original firing frequency to some steady state (Ahmed et al., 1998; Benda, 2021; Weber et al., 2019). During the first 300 msec of this adaptation process, it is believed that the decaying rate of firing arises from the slow [Ca^{2+}]-activated K^+ current (Madison & Nicoll, 1984). This frequency adaptation mechanism was included in the formulation of the integrate-and-fire neurons used in the sSoTS model, thus allowing the role of neuronal adaptation in the preview benefit to be investigated. Indeed, Mavritsaki et al. (2006) found that, after neurons coding for the preview items fire, there is a build-up of Ca^{2+} , which causes these neurons to reduce their firing as time goes on. Simulations showed that this process of adaptation of firing to the preview items takes about 300-400 msec to fully take effect, which can account for the relatively long time course of the preview benefit. During this period, the reduction in firing rate causes these preview items become less salient, so they compete less with new items by the time the final display appears (Mavritsaki et al., 2006, 2011).

In addition to neuronal adaptation, behavioural data indicates the contribution of a top-down process, referred to as visual marking, whereby old items are suppressed in order to prioritise the selection of new items (Olivers et al., 2006; Watson et al., 2003). Indeed, using behavioural techniques including dot-probe procedures and dual-task conditions, strong evidence has been generated to support this notion of a top-down attentional inhibition, which is applied to the location of old items (Osugi et al., 2009; Osugi & Murakami, 2014; Watson & Humphreys, 1997, 2000). Accordingly, the sSoTS model incorporates this top-down suppressive mechanism by the attentional inhibition input, which is applied to the locations of distractor items at the start of the preview display Indeed, with the summed contribution both the top-down attentional input and the firing adaptation mechanism sSoTS was able to simulate the preview benefit, where search was as efficient as when only the new items compete (i.e., a single-feature search), thus matching human search data in the preview condition (Mavritsaki et al., 2006, 2011).

One interesting property of spiking-level models like sSoTS is that, in addition to behavioural data, neuroimaging data can also be simulated. Indeed, by differentiating the excitatory and inhibitory synaptic outputs (reflecting top-down expectancy for target items and top-down inhibition of distractors) of the model and convolving this activity with an assumed hemodynamic response (HDR) function, Mavritsaki et al (2010) was able to determine which process occurred where within the brain. This was achieved by using the HDRs predicted by the model as regressors in the analysis of functional magnetic resonance imaging (fMRI) data that showed preview search to be associated with increased activation in the posterior parietal cortex (PPC). The authors found that, within this PPC, active inhibition and expectancy occurred in two distinct regions (these two active mechanisms work alongside the passive mechanism of neuronal adaptation, which occurs in visual cortex neurons). The activity from attentional inhibition significantly predicted the HDR function in the precuneus, while activity from target-feature expectation significantly predicted HDR function in the lateral parietal cortex (Mavritsaki et al., 2010). Furthermore, when the activity within the location map was summed and convolved with the assumed HDR, the authors found that a reliable correlation with the blood oxygen level dependent (BOLD) signal in the right TPJ (Mavritsaki et al., 2010). These findings suggest that this region is involved in the computation of saliency, with decreased activation reflecting less contrast between target and distractors (and thus increased competition). This notion is further supported by later fMRI work showing reduced activation in the right TPJ when working memory load is increased during the preview period (Allen et al., 2008).

Finally, more recently the sSoTS model has also been used to investigate the role of temporal binding in the preview benefit, which has been demonstrated by the loss of the benefit in the preview gap condition (see section 1.1.3). The sSoTS model was unable to simulate the loss of the preview benefit under preview gap conditions. Instead of slopes becoming highly inefficient again (similar to conjunction slopes), some benefit to search was still elicited, thus failing to match human behaviour. Therefore, Mavritsaki and Humphreys (2016) added a binding parameter to the model in a revised version of the sSoTS model, called the binding spiking search over space and time (b-sSoTS) model. In the b-sSoTS model, when two distinct visual features (e.g., blue and H) activate simultaneously at the same location in the visual field, this further excites the location map, thus making the temporally bound object (e.g., a blue H) more salient. This increase in saliency arises as a result of the increased feed-backward weight between the location map and feature maps – similar to the binding by synchrony (BBS) mechanism (Singer, 2015; Singer & Gray, 1995). With this additional binding parameter, b-sSoTS was able to simulate human visual search data. In the standard preview condition, the extra activation provided by temporal binding is applied to each set - old preview items and new items, as these have distinct onsets. For the preview items, this activation is not enough to combat any of the suppressive effects of marking or adaptation. For new items, this extra activation only further segments new items from old, thus contributing to the prioritisation of these items. The model was also able to simulate the loss of the benefit in the preview gap condition, and further show that this loss occurs because when all items share a common onset after the gap display, the additional activation that occurs from the temporal binding of the extra distractors (preview items re-appearing) work against the suppressive effects of marking and adaptation, so that all items compete fully again (Mavritsaki & Humphreys, 2016).

1.4 Summary and Aims of Thesis

To summarise, selective attention - the ability to selectively prioritise relevant information while suppressing irrelevant, distracting information - relies on both bottom-up (stimulus-driven) and top-down (goal-driven) functions that operate not only across space, but over time as well. In the visual domain, selective attention has been extensively explored across multiple levels of observation - behavioural, network and neural (Buschman & Kastner, 2015; Carrasco, 2011). At the behavioural level, influential theories, including FIT, GSM and similarity theory, have been successful in breaking down attention into its component parts. At the neural level, single-cell recordings have demonstrated that selective attention emerges as a result of biased competition computations. While these two levels of observation are not mutually exclusive, there are still major gaps in our understanding - particularly, how do the biased competition computations of at the neural level give rise to components, influence their dynamics and ultimately achieve the "attention" we observe at the behavioural level? In order to start to answer this critical question, the use of task-performing biologically plausible computational models will be a key element of future research.

Although the name implies an obvious attention difficulty, this has been particularly difficult to identify in the ADHD research (Avisar, 2022; Huang-Pollock & Nigg, 2003; Wilding, 2005). Inconsistent and non-significant findings early on selective attention in this field may have dissuaded researchers from replicating or extending these early studies (Nigg, 2005). Unsurprisingly, much of the more recent work in this field has moved on to other, related functions like arousal or executive functioning – at times, conflating these concepts (Hokken et al., 2023). Finally, when selective attention is investigated in ADHD, measures are often potentially confounding (Wilding, 2005). Accordingly, it is critical that future research needs to collectively agree upon a definition of selective attention and identify an accurate way to measure it (Hommel et al., 2019; Shomstein et al., 2023). Accordingly, it is important to use tasks that hypothesis-driven and are easily to create, manipulate and replicate. Furthermore, tasks should be easy to translate across a variety of settings to collect both behavioural and neuroimaging. Finally, tasks must be replicable by a task-performing neurocomputational model so we can see how ADHD gives rise to behavioural differences. This will enable ADHD research to move toward a more complete understanding of differences in ADHD at both the behavioural and neural levels.

In order to progress in our understanding of attention and attention differences in ADHD, research in this domain must address some existing limitations. First, there is some inconsistency around how selective attention is defined in the ADHD literature. Definitions that only consider the abstract meaning makes it more difficult to link to neurobiological mechanism. Accordingly, it's critical that selective visual attention is defined as an emergent property arising from biased competition computations in which relevant information is selected at the expense of the irrelevant (Buschman & Kastner, 2015; Desimone & Duncan, 1995). Second, although there are a lot of variations of effortful search, these task conditions can fail to isolate selective attention mechanisms from higher executive functioning. As such, it’s crucial to use traditional visual search tasks (Wolfe, 2020) to examine component mechanisms. Third, we must also approach atypical attention by examining how cognitive components arise from the dynamic interactions between biological neurons. Therefore, the use of task-performing neurocomputational models to examine the interaction of biologically plausible component mechanisms is important (Kriegeskorte & Douglas, 2018). Taken together, difficulty in defining selective attention, measuring selective attention difficulties at the behavioural level, and explaining how these difficulties arise from the neurobiological mechanisms of ADHD warrants further research using both behavioural and computational modelling methods. Specifically, this will be crucial for examining how space- and time-based attention in ADHD differs behaviourally and mechanistically. The limited research in this domain presents an opportunity to examine how ADHD symptoms impact the visual marking and temporal binding component mechanisms that give rise to time-based attention.

1.4.1 Overarching Aim

The overarching aim of the present thesis is to examine age- and ADHD-related differences in selective visual attention. Specifically, an interdisciplinary approach using both behavioural and computational modelling methods will be used to examine time-based attention. At the behavioural level, the efficiency with which attention is allocated to a particular moment in time will be analysed through visual search performance. Conclusions drawn from this performance will then be tested using a neurocomputational model with biologically plausible activation functions. Together, these methods will create a fuller picture of attention in both typical development (i.e., those with low levels of ADHD symptoms) and in those with high levels of ADHD symptoms.

The ability to selectively prioritise relevant information relies on both top-down (goal-driven) and bottom-up (stimulus-driven) attentional mechanisms and their dynamic interactions both across space and over time (Capizzi et al., 2023; Fiebelkorn & Kastner, 2020; Zivony & Eimer, 2022). In the present thesis, two attentional functions that operate in the temporal domain are focused on specifically. Visual marking, a top-down mechanism, and temporal binding, a bottom-up mechanism are examined by analysing a relative benefit to search efficiency (Mavritsaki & Humphreys, 2016; Olivers et al., 2006; Osugi et al., 2016; Watson et al., 2003). Differences in search benefits will thus provide evidence that one or both of these mechanisms is affected.

Behavioural measures of performance often lead to a black-box problem, in that we see the brain has completed a given task, but the way in which this solution was achieved remains a mystery. Furthermore, we often overlook the influence of physiological mechanisms, and how these contribute dynamically to observable behaviour (e.g., neuronal adaptation to stimuli). This lack of transparency can lead researchers to come to erroneous conclusions with regard to the mechanisms underlying performance. The present thesis thus aims to demonstrate how these limitations can be overcome by using computational modelling methods alongside behavioural. Here, the binding spiking-search over time and space (b-sSoTS) model, a biologically plausible model of visual search, is used to test and explore how mechanisms implicated by behavioural results might differ in ADHD. The architecture and neuronal characteristics of this model will be detailed in Chapter 2.

As a general format, the three subsequent chapters will first introduce key literature that supports the chapter's aims and objectives. Each of the three empirical chapters will present two studies. In the first two chapters, a behavioural study will be presented first, followed by a computational modelling study based on those results. In the last study, two behavioural studies will be presented. Each chapter will begin with an introductory literature review followed by the methods, results and discussion of the first study. Following this, a second literature review, methods, results and discussion will be presented for the second study. Finally, a discussion of the findings of both studies will be presented at the end of the chapter. The present thesis will begin by characterising visual search performance in late childhood compared to adults in order to draw a distinction between age-related and ADHD-related differences. Both group's visual search performance will be simulated and compared, and it will be shown how the model can constrain assumptions at the behavioural level (Chapter 2). Following this, children will be grouped according to their level of ADHD symptoms based on parent responses on the Conners 3 ADHD Index, and visual search performance in preview and preview gap will be compared. The computational modelling study in this chapter examines the possibility of temporal binding difficulties in children with high levels of ADHD symptoms (Chapter 3). The final empirical chapter examines these time-based functions in adults with low, borderline and high levels of ADHD symptoms and will then expand this investigation to determine whether differences arise based on the presence of a co-morbid impulse disorder (Chapter 4). The subsequent chapter will present a summary of the experimental findings, as well as discuss limitations and future directions.

1.4.2 Importance of Research

ADHD is a highly prevalent mental disorder (Fayyad et al., 2017; Song et al., 2021; Vasileva et al., 2021) that significantly impacts the ability to function in everyday life (Holst & Thorell, 2020; Orm et al., 2023). ADHD associated with a wide variety of adverse outcomes, including lower educational and occupational attainment (Gjervan et al., 2012; Voigt et al., 2017), substance abuse disorders (Groenman et al., 2017; Luderer et al., 2021), criminality (Mannuzza et al., 2008), and death (Barkley, 2020). While it can be easy to recognise the behaviours associated with the disorder, it has been much more difficult to identify a specific neurocognitive performance that confirms the diagnosis and distinguishes it from other conditions and mental disorders (Callan et al., 2024; Lovett & Harrison, 2021). Although issues in selective visual attention seems logical, findings have been inconclusive or non-significant, leading some to move away from the topic (Hokken et al., 2023; Huang-Pollock & Nigg, 2003; Nigg, 2005). However, there has a lot of untapped potential in this area in ADHD research. This is particularly true for the study of time-based attention, or how selectivity evolves over time. Using a combination of behavioural and computational methods is an important step in uncovering the mechanisms of this disorder, as it will allow us to consider the role of different attentional functions and parse out ones that may be overlooked (Hauser et al., 2016a; Kriegeskorte & Douglas, 2018). This may one day allow us to identify and intervene earlier in this disorder, possibly before adverse outcomes and improve the quality of life for affected individuals. Moreover, accurate identification may help us with mis- and over-diagnosis, as treatment could possibly make symptoms worse in individuals with other disorders (O’Connor et al., 2024).

Chapter 2: Age-Related Differences in Time-Based Attention

The present chapter presents the first combined behavioural and computational modelling study. Specifically, this chapter aims to examine age-related differences in time-based selective attention as a prerequisite for studying ADHD-related differences (Amso & Scerif, 2015; Kim & Kastner, 2019; Lynn & Amso, 2023). Chapter 2 begins with a review of the how attention improves across development, particularly in late childhood and adolescence. It will focus on how time-based attentional mechanisms differ as a function of age. Then, the chapter will then be divided into two sections. In the first half of chapter 2, preview and preview gap search are used to assess whether children's performance differs compared to adults. As mentioned previously, search efficiency in these conditions is linked to two functions of temporal attention - top-down visual marking and bottom-up temporal binding (Kunar et al., 2003; Mavritsaki & Humphreys, 2016; Osugi et al., 2016). The results from this behavioural study are reported. From these results, hypotheses about age-related differences are then generated, and these then are tested with the computational model in the second half of Chapter 2. Specifically, parameter changes are applied to the b-sSoTS model to determine the biological plausibility of the mechanisms proposed. The outcome of the study makes a compelling case for the utility in combining these two methods. Furthermore, it provides a baseline "child" version of the model (the b-sSoTS-c). This version of the model can be used for more accurate comparisons with children with ADHD in the next chapter.

2.1 Behavioural Study

2.1.1 Behavioural Background

As discussed in section 1.1, selective attention refers to the ability to prioritise behaviourally relevant information while simultaneously ignoring information that is distracting (Buschman & Kastner, 2015; Desimone & Duncan, 1995; Moore & Zirnsak, 2017). In the visual domain, selective attention allows us to effectively allocate our limited-capacity cognitive resources to stimuli based on particular spatial, featural or even temporal properties (Buschman & Kastner, 2015; Fiebelkorn & Kastner, 2020). A wide body of research has been dedicated to understanding the nature and mechanisms of attention in its stable adult state (Beck & Kastner, 2009; Carrasco, 2011). However, much less is known about selective attention functions develop in childhood and adolescence (Kim & Kastner, 2019; Lynn & Amso, 2023). The ability to allocate attention according to internally held goals plays a crucial role in development, as what is attended guides the development of neural connections, and these connections, in turn, allow for more efficient behaviour (Amso & Scerif, 2015; Luna et al., 2015; Lynn & Amso, 2023). Indeed, selective attention is intricately linked with complex processes such as memory and learning (King & Markant, 2020; Markant et al., 2015; Markant & Amso, 2014) and contributes to success in academic settings (Bouzabou et al., 2021; Bull & Scerif, 2001; St Clair-Thompson & Gathercole, 2006). As such, examining how visual attention changes with age could ultimately contribute to a better understanding of how complex cognition arises in typical development and how differences may arise in atypical development.

While the ability to orient attention toward a visually salient stimulus becomes efficient early on in life, optimisation of this attentional capacity to navigate the world efficiently is a complex skill that continues to develop across childhood and adolescence (Amso & Scerif, 2015; Johnson, 2019; Oakes & Amso, 2018). Indeed, the brain undergoes a caudal-to-rostral trajectory of development, so lower-level visual areas become adult-like before higher-level areas (Baum et al., 2020; Charvet & Finlay, 2014; Gogtay et al., 2004; Sydnor et al., 2021). This pattern of development is mirrored in improvements in behavioural performance (Oakes & Amso, 2018). For example, as discussed in section 1.1.4, mastery of single-feature search tasks, where targets appear to "pop-out" from the display due to their high level of contrast, occurs within the first year of life (Gerhardstein & Rovee-Collier, 2002; Quinn & Bhatt, 1998). In contrast, mastery of conjunction search, which requires effortful control in the allocation of attention, continues to develop into adolescence and adulthood (Lynn et al., 2020, 2023; Merrill & Conners, 2013; Merrill & Lookadoo, 2004). Taken together, it is likely that continued development of attention-related brain regions and networks constrain capacity at the behavioural level, particularly in tasks that require top-down control.

Previous research demonstrating worse performance in conjunction search in children suggests that age-related differences in top-down attention occur specifically in the spatial realm (see section 1.1.4; Donnelly et al., 2007; Merrill & Conners, 2013; Trick & Enns, 1998). However, top-down attention also operates in the temporal realm, such that attention can be allocated to a particular moment in time (Nobre & van Ede, 2018; Zivony & Eimer, 2022). Time-based attention has been widely studied in adults using preview search (see section 1.1.3). However, this has been far less studied in children. In preview search, top-down attentional inhibition is applied to old distractor items to prioritise the selection of new items – a process known as visual marking (for reviews, see Olivers et al., 2006; Watson et al., 2003). Considering that top-down mechanisms are still undergoing development, and that this likely contributes to the lesser efficiency in conjunction search, it follows that children could demonstrate similar difficulties in allocating top-down attention in time. However, the limited reports of preview search in children paint a less straightforward picture. For example, when Zupan et al. (2018) compared 6-, 8- and 12-year-olds as well as adults on a standard preview search task, they found that all age groups were able to visually mark old items to generate a preview benefit. Despite this, 6-year-olds inhibited fewer preview items and were unable to maintain this suppression for as long as older children and adults, suggesting weaker visual marking at this age. Interestingly, while the size of the preview benefit in adults was significantly correlated with switching and response inhibition, there was no relationship between executive functions and preview benefit in children. These findings suggested that the connection between top-down suppression of old items in preview search and executive function is something that is formed over the course of development with experience (Zupan et al., 2018).

Even when children are able to generate highly efficient, adult-like search in the preview condition, the mechanisms underlying this performance may differ or operate differently than adults. For example, Mason et al. (2004) found that 7- and 8-year-old children were able to generate a preview benefit in which slopes were as efficient as those in single-feature - a pattern of results more commonly associated with adults than children (Mason et al., 2003; Zupan et al., 2018). However, when Mason et al. (2004) more specifically examined the visual marking mechanism in these children using a singleton distractor paradigm, performance pointed to certain age-related differences. Specifically, the authors found that, for children, interference increased (RTs became longer) when final displays carried a singleton distractor that shared its features with preview items. Interestingly, the opposite has been shown to occur in adults (Olivers & Humphreys, 2003). The authors proposed that this increased interference may have stemmed from a loss of cognitive control during the final search display after maximum cognitive resources were recruited to actively suppress items during the preview display (Mason et al., 2004). Taken together, the existing previous reports of preview search in children show that, while the capacity to suppress old items is indeed present by age six (Zupan et al., 2018), the refinement of this top-down skill is likely to continue developing from ages seven to twelve. Accordingly, there is great theoretical interest in characterising how preview search differs in 7- to 12-year-old children and adults, as this could ultimately yield insight into how this time-based attention develops into the stable adult state.

This notion of children differing in the how attentional selection and suppression is further supported by electroencephalogram (EEG) studies. For example, Sun et al. (2018) compared 9- to 15-year-old children and adults in visual search where there was singleton distractor item. In addition to behavioural measures (i.e., RTs and accuracy), Sun et al. (2018) also recorded the P_D, an ERP component associated with active suppression of distractor items (Gaspelin & Luck, 2018). They found that children often elicited larger P_Ds than adults, particularly when performance was worse. The authors suggested that this pattern reflects a sort of compensatory mechanism in children to produce adult-like performance despite their still-developing abilities in general attentional allocation (Sun et al., 2018). Interestingly, this P_D component has also been shown to be present during the initial preview period (Berggren & Eimer, 2018). Taken together then, these findings indicate that, despite yielding adult-like behavioural performance, the mechanisms that underlie efficient selection and suppression of targets and distractors in children may be different than those in adults.

In addition to top-down visual marking, a second mechanism that contributes to time-based attention is temporal binding – the binding of features by common onset (see section 1.1.3). Indeed, both temporal binding and visual marking contribute to generating efficient search under preview conditions (Kunar et al., 2003; Mavritsaki & Humphreys, 2016). Temporal binding distinguishes features by time of onset, thus allowing newer items to be better prioritised over the old (Kunar et al., 2003; Mavritsaki & Humphreys, 2016). While temporal binding has been investigated in adults using preview gap search, it has yet to be examined in children. The ability to bind by common onset relies on fast and efficient communication between the distributed neurons encoding separable features (Singer, 2015, 2021). Over the course of development, improvements in neural efficiency arise as connections are either pruned or stabilised, resulting in effective communication both within- and between-networks (Luna et al., 2015; Marek et al., 2015; Soman et al., 2023a). Accordingly, in addition to difficulty in visual marking, children may be susceptible to problems in temporal binding as well.

Aims of Study. The present study aims to investigate age-related differences in visual marking and temporal binding comparing 7- to 12-year-old children and adults on preview and preview gap search. Over the course of childhood and adolescence, the brain undergoes substantial changes, particularly in its structural and functional connectivity (Cao et al., 2017; Luna et al., 2015; Soman et al., 2023a). This ultimately gives rise to continued behavioural improvements in tasks that elicit attention, which require effective communication between fronto-parietal networks and visual cortex (Amso & Scerif, 2015; Lynn & Amso, 2023). In preview search, the selection of new items is prioritised through the top-down suppression of old distractor items (Watson & Humphreys, 1997). This visual marking of old items typically yields search slopes that are more efficient than conjunction and can even be as efficient as single-feature. Therefore, it is hypothesized that children will struggle with this top-down mechanism and thus have a smaller preview benefit compared to adults.

Furthermore, although some bottom-up attentional functions reach adult-like levels at an early age (Atkinson & Braddick, 2020; Gerhardstein & Rovee-Collier, 2002; Trick & Enns, 1998), other bottom-up functions, like temporal binding, could have a longer developmental course (Uhlhaas et al., 2010). Previous research shows that, in addition to visual marking, temporal binding also contributes to the search benefit under preview search conditions (Mavritsaki & Humphreys, 2016). In order to parse out these two functions, preview gap search is used to investigate temporal binding. In preview gap search, a blank "gap" display is included after the initial preview display. When old items re-appear and new items appear alongside after this gap display, the increase in temporal binding activity modulates the suppressive effects of visual marking (Mavritsaki & Humphreys, 2016). Accordingly, the presence of intact temporal binding in the preview gap condition yields slopes that are significantly less efficient than preview and can even be as inefficient as conjunction. Therefore, it is hypothesized that children will show a larger benefit in the preview gap condition, indicative of reduced temporal binding.

2.1.2 Behavioural Method

Participants. ***Children***. A total of 61 children aged 7- to 12-years-old were recruited through six primary and secondary schools in Birmingham, UK. Thirty (49.2%) were male and 31 (50.8%) were female; the mean age was 9.53 years (*SD* = 1.04). Schools were contacted through either letter, email, or phone to the school's head teacher. Prior to any contact with students, the head teacher's written informed consent was obtained (see Appendix B). Upon consent from the head teacher, all students in Years 4, 5, and 6 were offered a participant information sheet (see Appendix A) and consent form for their parents or guardians (see Appendix B). Prior to the experiment, each child also provided their written consent to participate in the study (see Appendix B). Exclusionary criteria included a history of a serious mental or physical health condition, such as epilepsy. All participants reported having normal or corrected-to-normal vision. In exchange for their participation, students received a Certificate of Completion (see Appendix C). Ethical approval for this study was granted by the Business, Law, and Social Sciences Ethics Committee at Birmingham City University.

Adults. A total of 76 participants were recruited for the study. Seventeen (22.4%) were male and 59 (77.6%) were female; the mean age was 21.83 years (*SD* = 5.03). All participants were recruited through Birmingham City University's Research Participation Scheme (RPS). Those interested in participating in the study were required to read the participant information sheet (see Appendix A) and provide written informed consent online (see Appendix B). Exclusionary criteria included a history of serious mental or physical health condition, such as epilepsy. All participants reported having normal or corrected-to-normal vision. Individuals received course credit in exchange for their participation. Every experiment took place at the Department of Psychology, Birmingham City University and received ethical approval by the Business, Law, and Social Sciences Faculty Academic Ethics Committee (reference: Klein /3199 /R(A) /2019 /Mar /BLSS FAEC; see Appendix D). Please note that the participants included in the present study (both children and adults) are the same samples used in the following chapters (section 3.1 for children; section 4.1 for adults; see COVID-19 Impact Statement).

Materials. Intelligence testing was conducted for both children and adults, and both were also required to complete questionnaires. These are detailed in section 3.1.2 for children, and section 4.1.2 for adults.

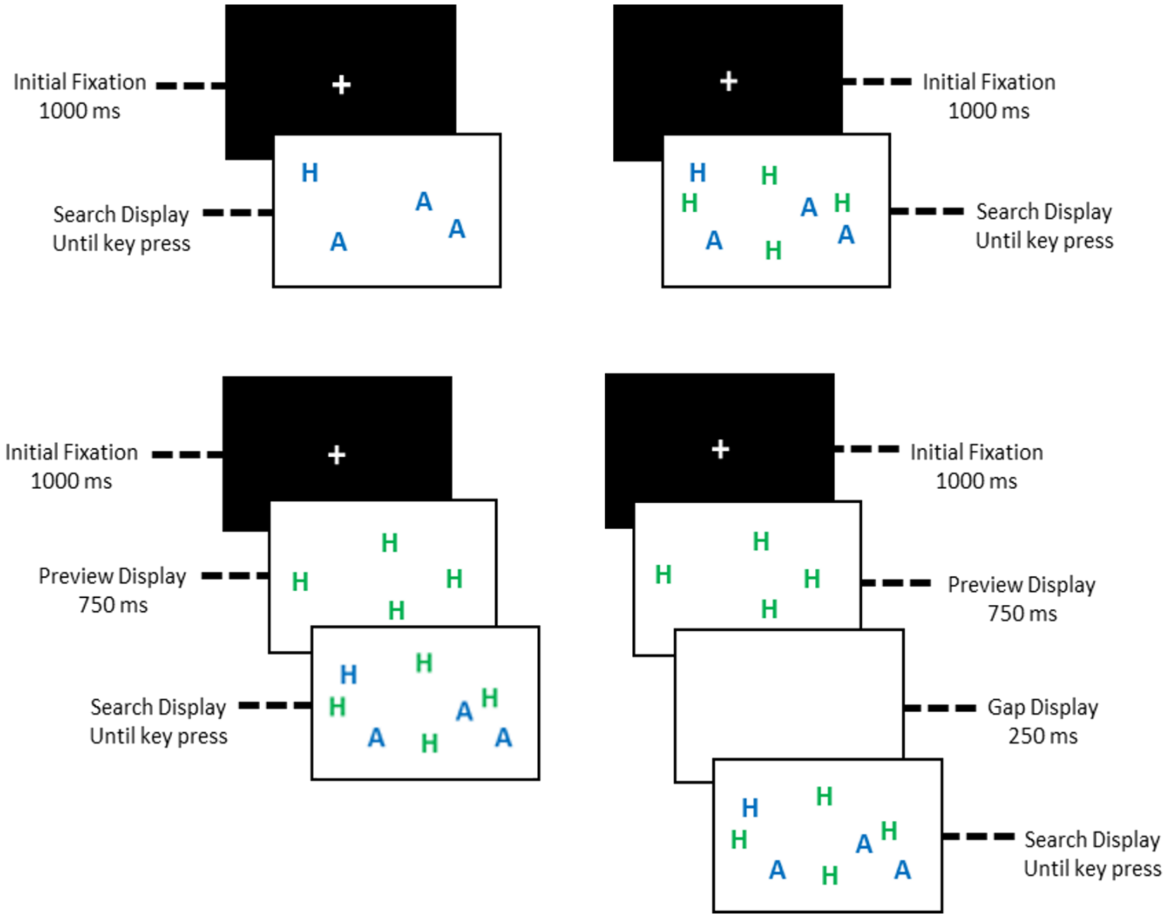
Stimuli and Equipment. The experiments were run using custom software written OpenSesame version 3.3 (Mathôt et al., 2012), which recorded each participant's scores. Experimental software ran on a Lenovo ThinkPad Yoga 12 laptop computer with an Intel Core i5 graphics card. Stimuli were displayed on a 12.5" digitized LCD screen 1920 x 1080 pixels, running at 60 Hz. Stimuli were viewed from approximately 50 cm. In all conditions, the target items were always a blue [RGB = 0, 0, 225] letter H. Distractor items were green [RGB = 0, 128, 0] letter Hs and blue letter As**.**

Design. The present study compared two groups that differed in age. Children between 7- and 12-years-old comprised one group, while adults comprised the other. These two groups were compared on four visual search tasks, each with three display sizes. The first condition, single-feature, had display sizes of 2, 4, and 8. The three other conditions, conjunction, preview and preview gap, had display sizes of 4, 8 and 16. As such, there were three independent variables: group, condition and display size. Group had two levels (children and adults), condition had four levels (single-feature, conjunction, preview, preview gap) and display size had three levels (2, 4, 8 for single-feature, 4, 8 and 16 for the others). The dependent variables, RTs and accuracy, were recorded for each participant, condition, and display size, and then these RTs and accuracies were compared between the two groups.

Procedure. Participants performed a search task to find a blue letter "H" (target) among distractors and were required to indicate whether the target was to the left or right of a white fixation cross that was presented in the middle of the screen prior to the search displays. If the target was to the left of the fixation cross, participants were instructed to press the "q" key on a standard keyboard. If the target was to the right of the fixation cross, participants were instructed to press the "p" key. The target was present in all trials.Participants completed four separate conditions: single-feature, conjunction, standard preview, and preview gap (see Figure 2.1). In the single-feature condition, participants were asked to locate the target amid either 1, 3, or 7 blue distractor letter "A"s. In the conjunction baseline condition, participants had to locate the target item among 1, 3 or 7 blue letter "A" distractors and 2, 4 or 8 green letter "H" distractors, giving the total set sizes of 4, 8 or 16 items. In the standard preview condition, an initial preview of either 2, 4 or 8 green letter "H"s appeared for 750 msec before 1, 3, or 7 blue distractor letter "A"s and the target (giving an overall display of 4, 8 or 16 items). In the preview gap condition, again, an initial preview of either 2, 4, or 8 green letter "H"s appeared for 750 msec, after which, a blank white "gap" screen was briefly displayed for 250 msec. After the "gap" screen, the preview distractor items reappeared in their original location alongside the new 1, 3, or 7 blue letter "A" distractors and target item (again giving an overall display of 4, 8 or 16 items). Participants were encouraged to fixate on the white cross in the middle of the screen during the 1000 msec fixation period but were free to move their eyes once the search items appeared.

Figure 2.1

Search Displays and Sequence of Events



Note. The displays for the four search conditions: single-feature (top left), conjunction (top right), preview (bottom left) and preview gap (bottom right).

The duration of the visual search task was approximately twenty minutes. Participants completed 240 trials each, split evenly across the conditions to give 60 trials in each condition. Within each condition, trials were again evenly split to give 20 trials for each display size. Each condition began with 5 practice trials. Conditions were blocked and followed the same sequence of single-feature, conjunction, preview, and preview gap for each participant. Participants were told to respond as quickly and accurately as possible. No feedback was given for either correct or incorrect responses.

Children were tested at their school's campus during a typical school day. Each school was asked to provide a quiet room with a table and chairs for children to be tested individually by the researcher. In addition to the search task, children underwent intelligence and achievement testing, which is detailed in chapter 3. Thus, the full experimental procedure took approximately 60 to 90 minutes. To provide minimal interruption to student's daily class schedule, the experiment was divided into two sessions that lasted thirty to forty-five minutes each. The visual search task was completed in the first of these sessions.

All adult participants used the RPS system to schedule a date and time to meet the experimenter. Testing took place in a quiet room with a table and chairs, located at Birmingham City University's City Centre campus. Adults also underwent intelligence testing, which is detailed in chapter 4. The search task and intelligence testing were administered in a single session, typically lasting 60 to 75 minutes. The visual search task was always completed first.

Data Analysis. The RTs for all conditions and display sizes was non-normal in children (all Shapiro-Wilk tests at $p < .05$). In adults, only the RTs for conjunction display size 4 and preview gap display size 16 were normal (all other Shapiro Wilk tests at $p < .05$). Levene's test indicated that the assumption of homogeneity of variance had been violated for each of the twelve condition-display size variations. The data was transformed (log, square root, reciprocal); however, this did not rectify the issue. Therefore, *F* tests are reported. In cases where Mauchley's test had indicated that the assumption of sphericity was violated, the Greenhouse-Geisser correction was used when estimates of sphericity were less than 0.75. When estimates of sphericity were greater than 0.75, the Huynh-Feldt correction was used. RTs were sorted for each participant, condition, and display size (see Table 2.1). Responses were excluded from analysis if they were (1) incorrect, (2) below 200 msec, or (3) more than 3 standard deviations above or below the individual's overall mean for a given condition and display size (see Mason et al., 2003). The RT-display size functions were calculated to provide a measure of search efficiency using the display sizes 4, 8 and 16 for all conditions (see Table 2.3; see Watson & Humphreys, 1997).

In order to make comparisons with the computational model's simulated visual search performance in the next study of this chapter, an efficiency index (mean RT/accuracy) is also calculated. This efficiency index allows for the accuracy of responses to be taken into account alongside their latency (Townsend & Ashby, 1983). Here, since accuracy rates are already quite high (overall accuracy was 96.27% for adults and 93.59% for children; see Table 2.2), the pattern of results using the efficiency index does not differ from the mean RTs.

Table 2.1

Mean RTs for Children and Adults in Each Condition and Display Size

Condition	Children		Adults	
	Mean	*SD*	Mean	*SD*
Single-feature 2	895.65	263.10	538.26	101.39
Single-feature 4	965.08	285.35	595.76	124.13
Single-feature 8	1061.53	302.80	650.99	110.05
Conjunction 4	1177.97	380.88	643.07	105.76
Conjunction 8	1376.32	381.82	765.87	153.51
Conjunction 16	1763.41	524.10	1014.39	239.83
Preview 4	986.88	309.63	578.82	130.33
Preview 8	1098.26	353.16	639.71	144.16
Preview 16	1274.15	462.48	763.65	171.87
Preview gap 4	1074.67	369.86	587.09	97.43
Preview gap 8	1210.11	357.97	708.91	129.68
Preview gap 16	1498.24	450.55	900.72	189.73

Table 2.2

Mean Accuracy Rates for Children and Adults in Each Condition and Display Size

Condition	Children		Adults	
	Mean	*SD*	Mean	*SD*
Single-feature 2	94.18	*6.07*	96.38	*3.97*
Single-feature 4	93.28	*5.54*	95.92	*4.22*
Single-feature 8	93.61	*5.64*	96.18	*4.15*
Conjunction 4	93.52	*6.01*	96.25	*4.48*
Conjunction 8	93.77	*6.75*	97.30	*3.78*
Conjunction 16	93.03	*7.32*	95.92	*5.34*
Preview 4	93.28	*5.77*	96.18	*4.31*
Preview 8	93.11	*5.41*	95.72	*4.74*
Preview 16	94.43	*5.71*	96.71	*4.51*
Preview gap 4	94.67	*5.07*	96.84	*3.73*
Preview gap 8	93.77	*5.30*	95.39	*5.21*
Preview gap 16	92.38	*8.14*	96.38	*4.87*

Note. Percentages are shown.

Table 2.3

Slope Statistics for Children and Adults

Group/Statistic	SF	CJ	PV	PVG
Children				
Slope	13.57	48.73	23.66	35.40
Intercept	847.43	984.43	898.93	930.60
Linearity (%)	99.54	99.99	99.81	99.99
Adults				
Slope	9.04	30.96	15.42	25.83
Intercept	510.65	518.81	516.85	491.19
Linearity (%)	97.97	99.99	99.99	99.81

Note. SF = single-feature; CJ = conjunction; PV = preview; PVG = preview gap.

2.1.3 Behavioural Results

Omnibus 2 x 4 x 3 ANOVAs. ***2 x 4 x 3 ANOVA: Mean RTs.*** Mean RTs were analysed using a 2 (group) x 4 (condition) x 3 (display size) mixed ANOVA. Group (adults x children) was a between-subjects factor. Condition (single-feature x conjunction x preview x preview gap) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction, preview and preview gap) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 23.59$, $p < .001$, and for the Condition x Display interaction, $\chi^2(20) = 91.69$, $p < .001$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .878$ and $\varepsilon = .827$, respectively). All of the main effects were significant. Children were slower than adults, $F(1, 135) = 155.46$, $p < .001$, partial $\eta^2 = .54$. RTs differed between conditions, $F(3, 405) = 188.65$, $p < .001$, partial $\eta^2 = .58$, and increased significantly with display size, $F(1.76, 236.95) = 536.30$, $p < .001$, partial $\eta^2 = .80$. The Group x Condition interaction was significant, $F(3, 405) = 25.67$, *p* < .001, partial η^2 = .16, as was the Group x Display interaction, *F*(2, 270) = 21.02, *p* < .001, partial η^2 = .14. The RT-increase with display size differed significantly between conditions, resulting in a significant Condition x Display interaction, *F*(4.97, 670.24) = 69.87, *p* < .001, partial η^2 = .34. Finally, there was a significant Group x Condition x Display interaction, *F*(6, 810) = 3.74, *p* < .01, partial η^2 = .03. In the next section, further analysis was undertaken to explore these significant interactions.

2 x 4 x 3 ANOVA: Accuracy. Accuracy rates were analysed using a 2 (group) x 4 (condition) x 3 (display) ANOVA. Group (adults x children) was a between-subjects factor, while condition (single-feature x conjunction x preview x preview gap) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction, preview and preview gap) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been met for condition, display, and their interaction. Overall, adults were significantly more accurate than children, *F*(1, 135) = 29.69, *p* < .001, partial η^2 = 0.18. None of the other main effects nor interactions reached significance, except for the Condition x Display interaction, *F*(6, 810) = 2.62, *p* = .016, partial η^2 = 0.02. Since accuracy rates were high (above 90% for both groups in all conditions and display sizes) and there was no significant three-way interaction between group, condition and display, no further analysis examining accuracy rates was undertaken.

2 x 4 x 3 ANOVA: Efficiencies. Efficiencies were also analysed using a 2 (group) x 4 (condition) x 3 (display size) mixed ANOVA. Group (adults x children) was a between-subjects factor. Condition (single-feature x conjunction x preview x preview gap) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction, preview and preview gap) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2)$ = 19.47, *p* < .001, and for the Condition x Display interaction, $\chi^2(20)$ = 104.59, *p* < .001. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity (ε = .898 and ε = .836, respectively). Children were less efficient than adults, *F*(1, 135) = 161.00, *p* < .001, partial η^2 = .54.

Efficiency differed between conditions, *F*(3, 405) = 166.75, *p* < .001, partial η^2 = .55. Efficiency also decreased significantly as display size increased, *F*(1.80, 242.53) = 489.77, *p* < .001, partial η^2 = .78. The Group x Condition interaction was significant, *F*(3, 405) = 25.29, *p* < .001, partial η^2 = .16, as was the Group x Display interaction, *F*(2, 270) = 25.45, *p* < .001, partial η^2 = .16. The RT-increase with display size differed significantly between conditions, resulting in a significant Condition x Display interaction, *F*(5.01, 676.85) = 57.26, *p* < .001, partial η^2 = .30. Finally, there was a significant Group x Condition x Display interaction, *F*(6, 810) = 3.90, *p* < .01, partial η^2 = .03. Like above, further analysis was undertaken in the next section to explore these significant interactions. Complete statistics for all omnibus ANOVAs are detailed in Appendix Table F.1.

Follow Up 2 x 2 x 3 ANOVAs. The results for the follow-up three-way ANOVAs are shown in Appendix Table F.2 and Appendix Table F.3. In this initial chapter, the process for determining whether there are preview and/or preview gap benefits is presented step by step with explanatory text. In the subsequent chapters, only the statistics are presented.

To determine whether a preview benefit (or loss of the preview benefit) has occurred, an initial comparison of single-feature and conjunction is required. In the single-feature condition, the target blue letter “H” is surrounded by either 1, 3, or 7 blue letter “A” distractor items. Under single-feature conditions, search of the items is considered automatic and parallel, with the target item appearing to “pop out” from the background (Treisman & Gelade, 1980). This parallel search strategy is reflected in fast RTs that are not affected by increases in display size. In the conjunction condition, the blue target and distractor items are joined by either 2, 4 or 8 green letter “H” distractor items (thereby doubling the overall display sizes). The addition of these distractor items transforms search from an automatic, parallel process to one that is effortful and serial, and this is reflected in both longer RTs that increase with display size (Treisman & Gelade, 1980). Thus, in this initial comparison, slopes of the RT – display size function in the single-feature should be flatter compared to the steep conjunction slopes.

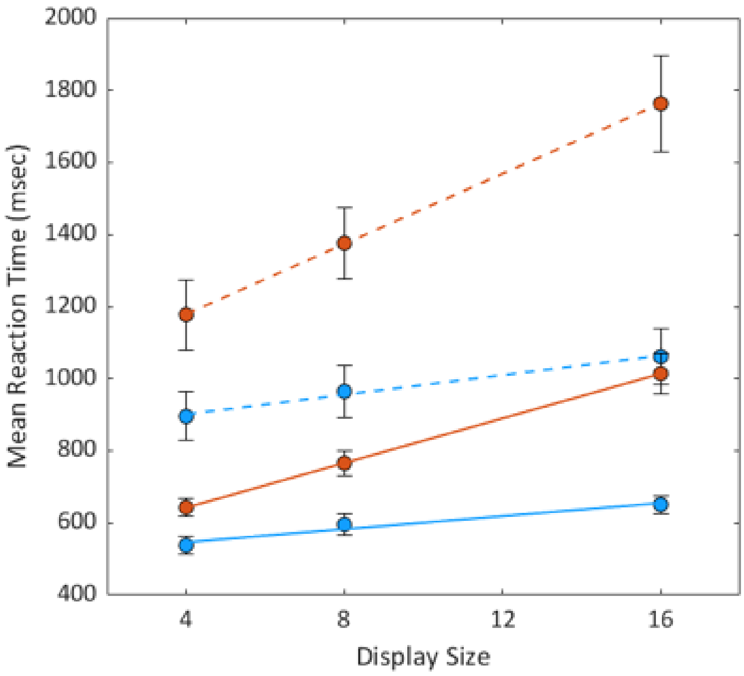
Single-feature vs. Conjunction: Mean RTs. Mean RTs were analysed using a 2 x 2 x 3 mixed ANOVA. Group (adults x children) was a between-subjects factor, while condition (single-feature x conjunction) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 29.81$, $p < .001$, and for the Condition x Display interaction, $\chi^2(2) = 25.55$, $p < .001$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity (ε = .849 and ε = .868, respectively). Children were significantly slower compared to adults, $F(1, 135) = 156.31$, $p < .001$, partial $\eta^2 = .54$. RTs were significantly slower in the conjunction condition, $F(1, 135) = 517.29$, $p < .001$, partial $\eta^2 = .79$. There was a significant Group x Condition interaction, $F(1, 135) = 71.69$, $p < .001$, partial $\eta^2 = .35$. Post-hoc pairwise comparisons using the Bonferroni correction showed that, for children, single-feature search was faster than conjunction (at $p < .001$), and this was also the case for adults (at $p < .001$). Compared to adults ($M = 212.77$, $SD = 98.54$), children ($M = 465.15$, $SD = 235.60$) had a significantly larger mean difference between conjunction and single-feature, $t(76.82) = -7.84$, $p < .001$. RTs increased significantly with display size, $F(1.70, 229.27) = 447.73$, $p < .001$, partial $\eta^2 = .77$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences ($p < .001$) at each of the three display sizes. There was a significant Group x Display interaction, $F(2, 270) = 21.26$, $p < .001$, partial $\eta^2 = .14$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for adults (all $p < .001$s) and for children (all $p < .001$s). For children ($M = 133.89$, $SD = 117.87$) there was a significantly larger mean difference between the two lower display sizes compared to adults ($M = 90.15$, $SD = 61.21$), $t(85.58) = -2.63$, $p = .01$. Between the larger two display sizes, children ($M = 241.77$, $SD = 22.18$) also had a significantly larger mean difference compared to adults ($M = 151.87$, $SD = 83.11$), $t(81.99) = -3.72$, $p < .001$. There was also a significant

Condition x Display interaction, *F*(1.74, 234.06) = 164.85, $p < .001$, partial $\eta^2 = .55$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for single-feature (all $p < .001$s) and for conjunction (all $p < .001$s). Compared to single-feature (*M* = 62.81, *SD* = 104.83), the conjunction condition (*M* = 156.44, *SD* = 149.72) had a significantly larger mean difference between the two lower display sizes, *t*(136) = -6.11, $p < .001$. Between the larger two display sizes, the conjunction condition (*M* = 310.22, *SD* = 232.42) also had a significantly larger mean difference compared to single-feature (*M* = 73.58, *SD* = 103.99), *t*(136) = -11.98, $p < .001$. Finally, there was a significant Group x Condition x Display interaction, *F*(2, 270) = 8.88, $p < .001$, partial $\eta^2 = .06$. Within-subjects contrasts showed that conjunction slopes were significantly steeper in children both at lower display sizes ($p < .05$) and at higher display sizes ($p < .05$). RTs increased with display size in conjunction more so in children. These slopes for both groups are shown in Figure 2.2.

Single-feature vs. Conjunction: Efficiency. Efficiencies were also analysed using a 2 x 2 x 3 mixed ANOVA with group (adults x children) as a between-subjects factor and condition (single-feature x conjunction) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction) as within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 17.77$, $p < .001$, and for the Condition x Display interaction, $\chi^2(2) = 14.15$, $p < .001$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .907$ and $\varepsilon = .927$, respectively). Children were significantly less efficient than adults, *F*(1, 135) = 159.34, $p < .001$, partial $\eta^2 = .54$. Search was significantly less efficient in the conjunction, *F*(1, 135) = 459.24, $p < .001$, partial $\eta^2 = .77$. There was a significant Group x Condition interaction, *F*(1, 135) = 70.40, $p < .001$, partial $\eta^2 = .34$. Post-hoc pairwise comparisons using the Bonferroni correction showed that, for children, single-feature search was more efficient than conjunction (at $p < .001$), and this was also the case for adults (at $p < .001$). Compared to adults (*M* = 218.56, *SD* = 103.42), children (*M* = 499.82, *SD* = 268.68) had a significantly larger mean difference between conjunction and single-feature, *t*(74.28) = -7.73, *p* < .001. Search became significantly less efficient as display size increased, *F*(1.82, 244.96) = 371.66, *p* < .001, partial η^2 = .73. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences (*p* < .001) at each of the three display sizes. There was a significant Group x Display interaction, *F*(2, 270) = 21.77, *p* < .001, partial η^2 = .14. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for adults (all *p* < .001s) and for children (all *p* < .001s). For children (*M* = 152.15, *SD* = 158.19) there was a significantly larger mean difference between the two lower display sizes compared to adults (*M* = 89.89, *SD* = 67.74), *t*(77.61) = -2.87, *p* = .005. Between the larger two display sizes, children (*M* = 264.63, *SD* = 215.44) also had a significantly larger mean difference compared to adults (*M* = 164.06, *SD* = 93.95), *t*(78.26) = -3.40, *p* < .001. There was a significant Condition x Display interaction, *F*(1.86, 250.42) = 119.58, *p* < .001, partial η^2 = .47. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for single-feature (all *p* < .001s) and for conjunction (all *p* < .001s). Compared to single-feature (*M* = 70.98, *SD* = 125.81), the conjunction condition (*M* = 164.27, *SD* = 209.07) had a significantly larger mean difference between the two lower display sizes, *t*(136) = -4.42, *p* < .001. Between the larger two display sizes, the conjunction condition (*M* = 337.99, *SD* = 275.60) also had a significantly larger mean difference compared to single-feature (*M* = 79.63, *SD* = 136.07), *t*(136) = -10.86, *p* < .001. Finally, there was a significant three-way interaction between group, condition and display, *F*(2, 270) = 7.27, *p* < .001, partial η^2 = .05. Within-subjects contrasts showed that conjunction efficiency slopes were significantly steeper in children both at lower display sizes (*p* < .05) and at higher display sizes (*p* < .05). Efficiencies decreased as display size increased in conjunction more so in children.

Figure 2.2

Mean RTs for Children and Adults in Single-feature and Conjunction



Note. Single-feature = blue; conjunction = orange; children = dotted lines; adults = solid lines. Error bars represent ±2 *SE*s.

Next, single-feature and conjunction slopes are used to determine whether a preview benefit has occurred. In the preview condition, the final search display is identical to that of conjunction. However, in the preview condition, the green letter “H” distractors appear alone first for 750 msec before blue items (both blue letter “A” distractors and the blue letter “H” target) appear alongside. The added temporal element here typically results in a benefit to performance, with slopes being significantly flatter than those of conjunction (Olivers et al., 2006; Watson & Humphreys, 1997). This benefit to performance is thought to arise (in part) from active suppression of the green letter “H” distractors – a process referred to as visual marking (Watson et al., 2003; Watson & Humphreys, 1997). Previous work also shows that this visual marking of old items can be so effective that slopes that are as flat as those in single-feature (Watson et al., 2003; Watson & Humphreys, 1997). Thus, single-feature and preview are also compared to determine whether either group's preview slopes have become this flat.

Conjunction vs. Preview: Mean RTs. In order to determine whether a preview benefit occurred, mean RTs for correct trials were analysed using a 2 (group) x 2 (condition) x 3 (display) mixed ANOVA. Group (adults x children) was a between-subjects factor, and condition (conjunction x preview) and display (4 x 8 x 16) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 41.19$, $p < .001$, and for the Condition x Display interaction, $\chi^2(2) = 45.38$, $p < .001$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .794$ and $\varepsilon = .790$, respectively). Children were significantly slower than adults, $F(1, 135) = 146.16$, $p < .001$, partial $\eta^2 = .52$. RTs became significantly faster in the preview condition compared to conjunction, $F(1, 135) = 236.46$, $p < .001$, partial $\eta^2 = .64$. There was a significant Group x Condition interaction, $F(1, 135) = 32.30$, $p < .001$, partial $\eta^2 = .19$. Post-hoc pairwise comparisons using the Bonferroni correction showed that, for children, preview search was faster than conjunction (at $p < .001$), and this was also the case for adults (at $p < .001$). Compared to adults ($M = 147.05$, $SD = 88.60$), children ($M = 319.47$, $SD = 245.50$) had a significantly larger mean difference between conjunction and preview, $t(72.57) = -5.22$, $p < .001$. RTs increased with display size, $F(1.59, 214.39) = 392.87$, $p < .001$, partial $\eta^2 = .74$. There was a significant Group x Display interaction, $F(2, 270) = 18.95$, $p < .001$, partial $\eta^2 = .12$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for adults (all $p < .001$s) and for children (all $p < .001$s). For children ($M = 154.87$, $SD = 142.56$), there was a significantly larger mean difference between the two lower display sizes compared to adults ($M = 91.84$, $SD = 59.74$), $t(76.88) = -3.23$, $p = .002$. Between the larger two display sizes, children ($M = 281.49$, $SD = 217.98$) also had a significantly larger mean difference compared to adults ($M = 186.23$, $SD = 93.83$), $t(77.80) = -3.19$, $p = .002$. There was also a significant

Condition x Display interaction, $F(1.58, 213.31) = 74.36$, $p < .001$, partial $\eta^2 = .36$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for preview (all $p < .001$s) and for conjunction (all $p < .001$s). Compared to preview (M = 83.37, SD = 121.11), the conjunction condition (M = 164.27, SD = 209.07) had a significantly larger mean difference between the two lower display sizes, $t(136) = -4.63$, $p < .001$. Between the larger two display sizes, the conjunction condition (M = 337.99, SD = 275.60) also had a significantly larger mean difference compared to preview (M =147.07, SD = 189.56), $t(136) = -7.43$, $p < .001$. Finally, there was a significant Group x Condition x Display interaction, $F(2, 270) = 4.14$, $p < .05$, partial η^2 = .03. Within-subjects contrasts showed that conjunction slopes were steeper than preview slopes for children at higher display sizes ($p = .05$), but there was no significant differences in slopes between lower display sizes ($p = .37$). Slopes for both groups are shown in Figure 2.3. Both groups were able to generate a preview benefit, and this benefit was larger for children at higher display sizes. The magnitude of this preview benefit is further analysed using the Preview Benefit (PB) index.

Conjunction vs. Preview: Efficiency. Efficiency was analysed in the same way as mean RTs using a 2 x 2 x 3 mixed ANOVA with group (adults x children) as a between-subjects factor, and condition (conjunction x preview) and display size (4 x 8 x 16) as within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of display, $\chi^2(2) = 19.10$, $p < .001$, and for the Condition x Display interaction, $\chi^2(2) = 31.78$, $p < .001$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .900$ and $\varepsilon = .841$, respectively). Children were significantly less efficient than adults, $F(1, 135) = 160.89$, $p < .001$, partial $\eta^2 = .54$. Search became more efficient in the preview condition compared to conjunction, $F(1, 135) = 223.80$, $p < .001$, partial $\eta^2 = .62$. There was a significant Group x Condition interaction, $F(1,135) = 35.69$, $p < .001$, partial $\eta^2 = .21$. Post-hoc pairwise comparisons using the Bonferroni correction showed that, for children, preview search was faster than conjunction (at $p < .001$), and this was also the case for adults (at $p < .001$). Compared to adults (M = 150.97, SD =

94.85), children (*M* = 351.74, *SD* = 273.37) had a significantly larger mean difference between conjunction and preview, *t*(71.62) = -5.48, *p* < .001. Efficiency decreased as display size increased, *F*(1.80, 243.05) = 330.46, *p* < .001, partial η^2 = .71. There was a significant Group x Display interaction, *F*(2, 270) = 18.60, *p* < .001, partial η^2 = .12. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for adults (all *p* < .001s) and for children (all *p* < .001s). For children (*M* = 170.28, *SD* = 196.43) there was a significantly larger mean difference between the two lower display sizes compared to adults (*M* = 92.68, *SD* = 66.27), *t*(70.99) = -2.95, *p* = .004. Between the larger two display sizes, children (*M* = 296.52, *SD* = 247.14) also had a significantly larger mean difference compared to adults (*M* = 195.46, *SD* = 98.70), *t*(75.36) = -3.01, *p* = .004. There was also a significant Condition x Display interaction, *F*(1.68, 227.01) = 69.92, *p* < .001, partial η^2 = .34. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for preview (all *p* < .001s) and for conjunction (all *p* < .001s). Compared to preview (*M* = 90.20, *SD* = 140.89), the conjunction condition (*M* = 164.27, *SD* = 209.07) had a significantly larger mean difference between the two lower display sizes, *t*(136) = -4.16, *p* < .001. Between the larger two display sizes, the conjunction condition (*M* = 337.99, *SD* = 275.60) also had a significantly larger mean difference compared to preview (*M* =142.92, *SD* = 206.91), *t*(136) = -7.29, *p* < .001. Finally, there was a significant Group x Condition x Display interaction, *F*(2, 270) = 5.13, *p* < .01, partial η^2 = .04. Within-subjects contrasts showed that groups did not differ in slopes at lower display sizes (*p* = .15) or at higher display sizes (*p* = .06). Efficiency slopes were steeper in the conjunction condition compared to preview, and this occurred similarly for both groups.

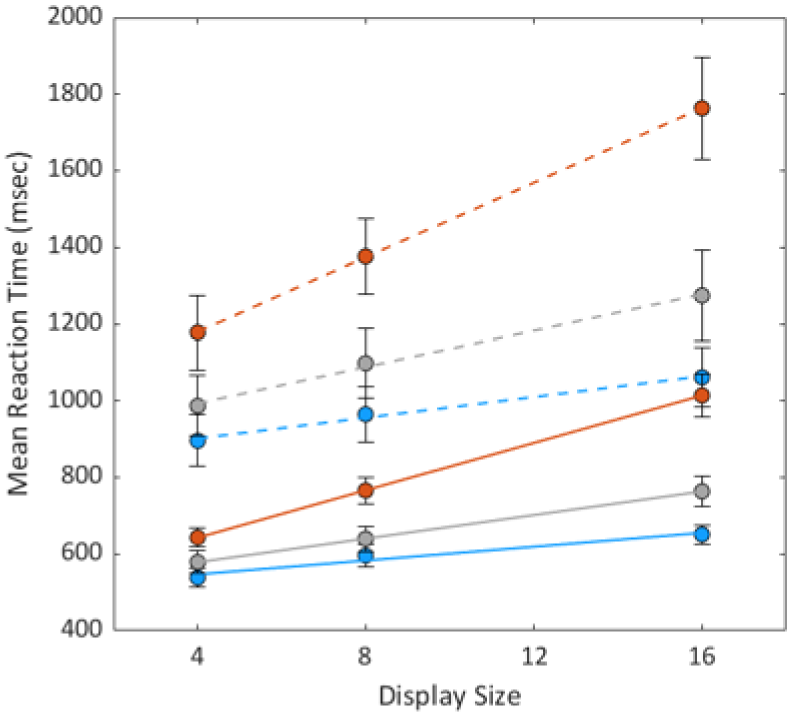
Single-feature vs. Preview: Mean RTs. Mean RTs for correct trials were analysed using a 2 (group) x 2 (condition) x 3 (display) mixed ANOVA. Group (adults x children) was a between-subjects factor, while condition (single-feature x preview) and display (2 x 4 x 8 for single-feature; 4 x 8 x 16 for preview) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 22.10$, $p < .001$, and for the Condition x Display interaction, $\chi^2(2) = 17.19$, $p < .001$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .885$ and $\varepsilon = .910$, respectively). Children were significantly slower compared to adults, $F(1, 135) = 129.93$, $p < .001$, partial $\eta^2 = .49$. RTs also became significantly slower in the preview condition, $F(1, 135) = 49.87$, $p < .001$, partial $\eta^2 = .27$. There was a significant Group x Condition interaction, $F(1, 135) = 7.13$, $p < .01$, partial $\eta^2 = .05$. Post-hoc pairwise comparisons using the Bonferroni correction showed that, for children, single-feature search was faster than preview (at $p < .001$), and this was also the case for adults (at $p = .001$). Compared to adults ($M = 65.73$, $SD = 93.99$), children ($M = 145.68$, $SD = 239.14$) had a significantly larger mean difference between preview and single-feature, $t(74.88) = -2.46$, $p < .016$. RTs also increased with display size, $F(1.77, 238.91) = 227.57$, $p < .001$, partial $\eta^2 = .63$. There was a significant Group x Display interaction, $F(2, 270) = 9.77$, $p < .001$, partial $\eta^2 = .07$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for adults (all $p < .001$s) and for children (all $p < .001$s). For children ($M = 90.41$, $SD = 105.41$) there was a significantly larger mean difference between the two lower display sizes compared to adults ($M = 59.20$, $SD = 54.61$), $t(85.47) = -2.10$, $p = .039$. Between the larger two display sizes, children ($M = 136.17$, $SD = 150.47$) also had a significantly larger mean difference compared to adults ($M = 89.58$, $SD = 55.63$), $t(73.18) = -2.30$, $p = .025$. There was also a significant Condition x Display interaction, $F(1.82, 245.81) = 19.20$, $p < .001$, partial $\eta^2 = .13$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for single-feature (all $p < .001$s) and for preview (all $p < .001$s). The mean difference between single-feature ($M = 62.81$, $SD = 104.83$) and the preview condition ($M = 83.37$, $SD = 121.11$) at the two lower display sizes did not reach significance, $t(136) = -1.55$, $p = .124$. Between the larger two display sizes, the preview condition ($M = 147.07$, $SD = 189.56$) had a significantly larger mean difference compared to single-feature ($M =73.58$, $SD = 103.99$), $t(136) = -4.08$, $p < .001$. The Group x

Condition x Display interaction, however, failed to reach significance, *F*(2, 270) = 1.26, *p* = .29, partial η^2 = .01. Preview slopes were steeper than single-feature, and the pattern of these slopes was similar between groups.

Single-feature vs. Preview: Efficiency. Efficiencies were analysed in the same way as mean RTs using a 2 x 2 x 3 ANOVA with group (adults x children) as a between-subject factor, and condition (single-feature x preview) and display (2 x 4 x 8 for single-feature; 4 x 8 x 16 for preview) as within-subject factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2)$ = 21.68, *p* < .001, and for the Condition x Display interaction, $\chi^2(2)$ = 14.82, *p* < .001. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity (ε = .887 and ε = .905, respectively). Overall, children were significantly less efficient compared to adults, *F*(1, 135) = 133.91, *p* < .001, partial η^2 = .50. Search became less efficient in the preview condition compared to single-feature, *F*(1, 135) = 49.75, *p* < .001, partial η^2 = .27. There was a significant Group x Condition interaction, *F*(1, 135) = 6.93, *p* < .01, partial η^2 = .05. Post-hoc pairwise comparisons using the Bonferroni correction showed that, for children, single-feature search was more efficient than preview (at *p* < .001), and this was also the case for adults (at *p* = .001). Compared to adults (*M* = 67.58, *SD* = 89.95), children (*M* = 148.08, *SD* = 247.12) had a significantly larger mean difference between preview and single-feature, *t*(72.78) = -2.42, *p* < .018.Efficiency decreased significantly as display size increased, *F*(1.77, 239.48) = 179.93, *p* < .001, partial η^2 = .57. There was a significant Group x Display interaction, *F*(2, 270) = 8.72, *p* < .001, partial η^2 = .06. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for adults (all *p* < .001s) and for children (all *p* < .001s). For children (*M* = 100.77, *SD* = 127.53) there was a significantly larger mean difference between the two lower display sizes compared to adults (*M* = 64.39, *SD* = 60.10), *t*(81.24) = -2.05, *p* = .05. Between the larger two display sizes, children (*M* = 139.13, *SD* = 177.13) also had a significantly larger mean difference compared to adults (*M* = 88.92, *SD* = 60.36), *t*(71.21) = -2.12, *p* = .038.There was also a significant Condition x Display interaction, *F*(1.85, 244.40) = 10.55, *p* < .001, partial η^2 = .07. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for single-feature (all *p* < .001s) and for preview (all *p* < .001s). The mean difference between single-feature (*M* = 70.98, *SD* = 125.81) and the preview condition (*M* = 90.20, *SD* = 140.86) at the two lower display sizes did not reach significance, *t*(136) = -1.23, *p* = .220. Between the larger two display sizes, the preview condition (*M* = 142.92, *SD* = 79.63) had a significantly larger mean difference compared to single-feature (*M* = 79.63, *SD* = 136.08), *t*(136) = -3.11, *p* = .002.The three way interaction did not reach significance, *F*(2, 270) = 0.43, *p* = .62, partial η^2 = .00. Preview efficiency slopes were steeper than single-feature, and this occurred similarly between groups.

Figure 2.3

Mean RTs Across Conditions and Display Sizes to Identify Preview Benefit



Note. Single-feature = blue; conjunction = orange; preview = grey; children = dotted lines; adults = solid lines. Error bars represent ±2 *SE*s.

Previous work indicates that temporal binding also contributes to the preview benefit (Mavritsaki & Humphreys, 2016). The mechanism of temporal binding can be examined using preview gap search. In preview gap search, green letter "H" distractors are again previewed for 750 msec, similar to the preview condition. However, after this period, preview items are offset, leaving a blank "gap" display for a short 250 msec period. After the gap display, preview items re-appear in their original positions and new blue items appear alongside (see Figure 2.1). Under preview gap conditions, the preview benefit is lost, and slopes can become as inefficient as those in conjunction (Watson & Humphreys, 1997). This loss of the preview benefit is due to the additional temporal binding activity that occurs when all items share a common onset (Mavritsaki & Humphreys, 2016). First, search in preview gap is compared with single-feature and conjunction conditions to determine whether any benefit to search arises or the loss of the benefit is complete.

Conjunction vs. Preview Gap: Mean RTs. Mean RTs for correct trials were analysed using a 2 x 2 x 3 mixed ANOVA. Group (adults x children) was a between-subjects factor, and condition (conjunction x preview gap) and display (4 x 8 x 16) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 20.18$, $p < .001$, and for the Condition x Display interaction, $\chi^2(2) = 14.72$, $p < .001$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .895$ and $\varepsilon = .924$, respectively). Children were significantly slower compared to adults, $F(1, 135) = 162.94$, $p < .001$, partial $\eta^2 = .55$. RTs became significantly faster in the preview gap condition relative to conjunction, $F(1, 135) = 67.04$, $p < .001$, partial $\eta^2 = .33$. There was a significant Group x Condition interaction, $F(1, 135) = 10.98$, $p = .001$, partial $\eta^2 = .08$. Post-hoc pairwise comparisons using the Bonferroni correction showed that, for children, preview gap search was faster than conjunction (at $p < .001$), and this was also the case for adults (at $p < .001$). Compared to adults ($M = 75.53$, $SD = 94.74$), children ($M = 178.23$, $SD = 248.84$) had a significantly larger mean difference between conjunction and preview gap, $t(73.97) = -3.05$, $p = .003$. RTs increased with display size, $F(1.79, 241.53) = 464.87$, $p < .001$, partial $\eta^2 = .78$. There was a significant Group x Display interaction $F(2, 270) = 17.57$, $p < .001$, partial $\eta^2 = .78$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for adults (all $p < .001$s) and for children (all $p < .001$s). Children ($M = 166.90$, $SD = 194.76$) and adults ($M = 122.31$, $SD = 194.76$) did not significantly differ from each other at the lower display sizes, $t(69.86) = -1.72$, $p = .090$. Between the larger two display sizes, children ($M = 337.61$, $SD = 207.28$) also had a significantly larger mean difference compared to adults ($M = 220.16$, $SD = 108.44$), $t(85.94) = -4.01$, $p < .001$. There was a significant Condition x Display interaction, $F(1.85, 249.54) = 18.67$, $p < .001$, partial $\eta^2 = .12$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for preview gap (all p < .001s) and for conjunction (all p < .001s). At the two lower display sizes, the preview gap (*M* = 127.89, *SD* = 180.23) and conjunction (*M* = 156.44, *SD* = 149.72) conditions did not differ significantly, $t(136) = 1.86$, $p = .065$. Between the larger two display sizes, the conjunction condition (*M* = 310.22, *SD* = 232.42) also had a significantly larger mean difference compared to preview (*M* = 234.70, *SD* = 170.94), $t(136) = 3.91$, $p < .001$. Finally, there was a significant three-way interaction between group, condition and display, $F(2, 270) = 4.02$, $p < .05$, partial $\eta^2 = .03$. Further within-subjects contrasts showed that slopes did not differ between groups at low display sizes ($p = .05$) or high display sizes ($p = .28$). RTs increased with display size more so in conjunction compared to preview gap, and this occurred similarly for both groups. Figure 2.4 shows these slopes for both groups.

***Conjunction vs. Preview Gap: Efficiency*.** Efficiency was analysed in the same way as mean RTs using a 2 x 2 x 3 mixed ANOVA with group (adults x children) as a between-subjects factor and condition (conjunction x preview gap) and display size (4 x 8 x 16) as within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 18.68$, $p < .001$, and for the Condition x Display interaction, $\chi^2(2) = 18.74$, $p < .001$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .902$ and $\varepsilon = .902$, respectively). Children were significantly less efficient compared to adults, $F(1, 135) = 166.01$, $p < .001$, partial $\eta^2 = .55$. Search became more efficient in the preview gap condition, $F(1, 135) = 54.77$, $p < .001$, partial $\eta^2 = .29$. There was a significant Group x Condition interaction, $F(1, 135) = 10.38$, $p < .01$, partial $\eta^2 = .07$. Post-hoc pairwise comparisons using the Bonferroni correction showed that, for children, preview gap search was more efficient than conjunction (at $p < .001$), and this was also the case for adults (at $p < .001$). Compared to adults (*M* = 75.18, *SD* = 97.96), children (*M* = 191.11, *SD* = 294.24) had a significantly larger mean difference between conjunction and preview gap, $t(70.70) = -2.95$, $p = .004$. Efficiency decreased as display size increased, $F(1.81, 243.64)$

= 403.77, *p* < .001, partial η^2 = .75. There was a significant Group x Display interaction, *F*(2, 270) = 21.68, *p* < .001, partial η^2 = .14. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for adults (all *p* < .001s) and for children (all *p* < .001s). Children (*M* = 187.92, *SD* = 231.74) and adults (*M* = 128.04, *SD* = 69.05) did not significantly differ from each other at the lower display sizes, *t*(68.58) = -1.95, *p* = .055. Between the larger two display sizes, children (*M* = 384.18, *SD* = 253.15) had a significantly larger mean difference compared to adults (*M* = 231.24, *SD* = 119.21), *t*(81.20) = -4.35, *p* < .001. There was also a significant Condition x Display interaction, *F*(1.80, 243.56) = 10.74, *p* < .001, partial η^2 = .07. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for preview gap (all *p* < .001s) and for conjunction (all *p* < .001s). At the two lower display sizes, the preview gap (*M* = 145.13, *SD* = 184.78) and conjunction (*M* = 164.27, *SD* = 209.07) conditions did not differ significantly, *t*(136) = 1.04, *p* = .302. Between the larger two display sizes, the conjunction condition (*M* = 337.99, *SD* = 275.60) also had a significantly larger mean difference compared to preview gap (*M* = 260.68, *SD* = 225.62), *t*(136) = 3.09, *p* < .001. The three-way interaction between group, condition and display, however, did not reach significance *F*(2, 270) = 2.36, *p* = .10, partial η^2 = .02. Conjunction efficiency slopes were significantly steeper than preview gap, and this occurred similarly for both groups.

***Single-feature vs. Preview Gap: Mean RTs*.** Mean RTs for correct trials were analysed using a 2 x 2 x 3 mixed ANOVA. Group (adults x children) was a between-subjects factor, and condition (single-feature x preview gap) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for preview gap) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been met for Condition, Display and Condition x Display. Children were significantly slower compared to adults, *F*(1, 135) = 150.17, *p* < .001, partial η^2 = .53. RTs became slower in the preview gap condition compared to single-feature, *F*(1, 135) = 183.62, *p* < .001, partial η^2 = .57. There was a significant Group x Condition interaction, *F*(1, 135) = 22.87, *p* < .001, partial η^2 = .15. Post-hoc pairwise comparisons using the Bonferroni correction showed that, for children, single-feature was faster than preview gap (at $p < .001$), and this was also the case for adults (at $p < .001$). Compared to adults (M = 137.24, SD = 95.65), children (M = 286.92, SD = 251.32) had a significantly larger mean difference between preview gap and single-feature, $t(73.96) = -4.40$, $p < .001$. RTs increased with display size, $F(2, 270) = 381.34$, $p < .001$, partial $\eta^2 = .74$. There was a significant Group x Display interaction, $F(2, 270) = 11.16$, $p < .001$, partial $\eta^2 = .08$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for adults (all $p < .001$s) and for children (all $p < .001$s). There was no significant difference between children (M = 102.44, SD = 152.38) and adults (M = 89.66, SD = 56.60) at the two lower display sizes, $t(73.31) = -0.62$, $p = .536$. Between the larger two display sizes, however, children (M = 192.29, SD = 128.64) had a significantly larger mean difference compared to adults (M = 123.51, SD = 62.82), $t(82.74) = -3.83$, $p < .001$. There was also a significant Condition x Display interaction, $F(2, 270) = 96.31$, $p < .001$, partial $\eta^2 = .42$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for preview gap (all $p < .001$s) and for single-feature (all $p < .001$s). Compared to single-feature (M = 70.98, SD = 125.81), the preview gap condition (M = 145.13, SD = 184.78) had a significantly larger mean difference between the two lower display sizes, $t(136) = -3.93$, $p < .001$. Between the larger two display sizes, the preview gap condition (M = 260.68, SD = 225.62) also had a significantly larger mean difference compared to preview (M = 79.63, SD = 136.08), $t(136) = -8.67$, $p < .001$. The Group x Condition x Display interaction, however, failed to reach significance, $F(2, 270) = 1.80$, $p = .17$, partial $\eta^2 = .01$. Preview gap slopes were significantly steeper than single-feature slopes, and the difference between these slopes was similar between groups.

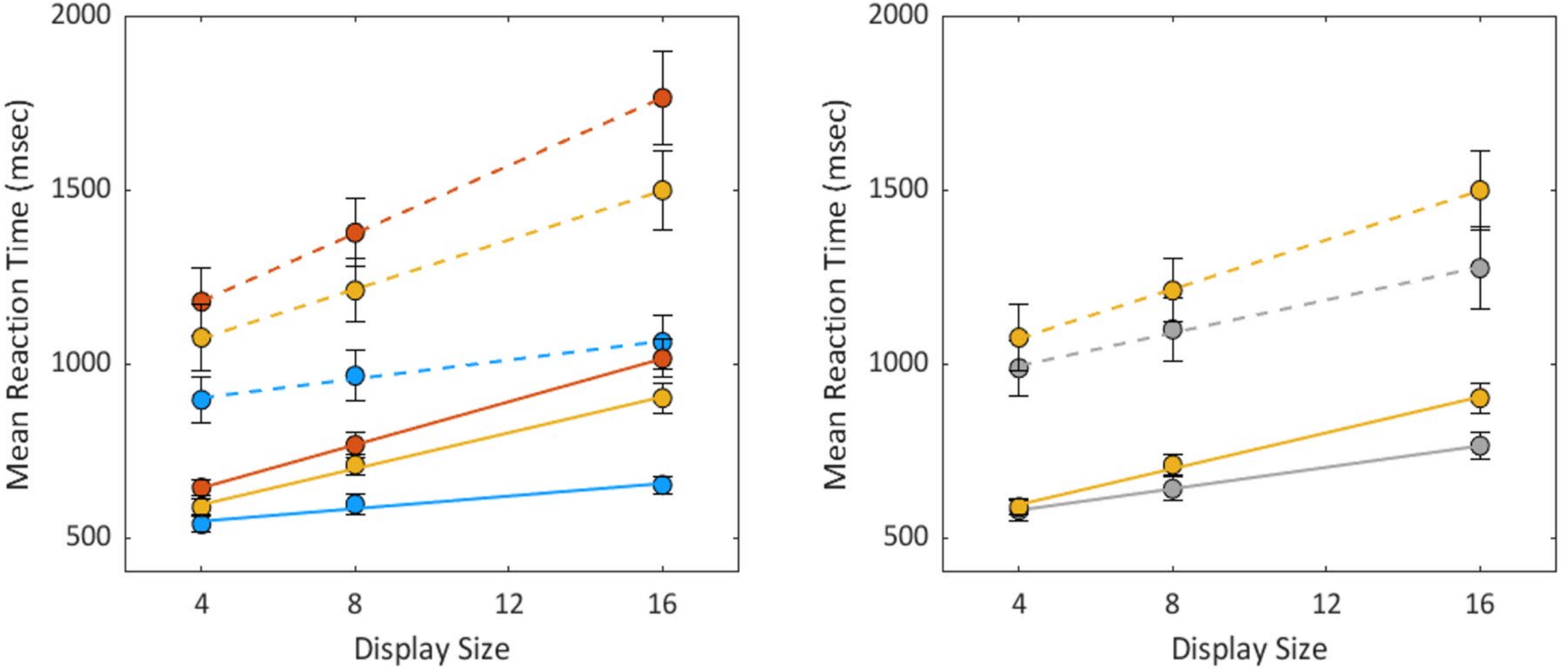
Single-feature vs. Preview Gap: Efficiency. Efficiency was analysed in the same way as mean RTs using a 2 x 2 x 3 mixed ANOVA where group (adult x children) was a between-subjects factor and condition (single-feature x preview gap) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for preview gap) were within-subject factors. Mauchley's test indicated that the assumption of sphericity had been violated only for the main effect of Display, $\chi^2(2) = 14.29$, $p < .001$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .927$). Children were significantly less efficient, $F(1, 135) = 143.23$, $p < .001$, partial $\eta^2 = .52$. Search became significantly less efficient in the preview gap condition compared to single-feature, $F(1, 135) = 149.05$, $p < .001$, partial $\eta^2 = .53$. There was a significant Group x Condition interaction, $F(2, 270) = 19.93$, $p < .001$, partial $\eta^2 = .13$. Post-hoc pairwise comparisons using the Bonferroni correction showed that, for children, single-feature search was more efficient than preview gap (at $p < .001$), and this was also the case for adults (at $p < .001$). Compared to adults ($M = 143.38$, $SD = 102.23$), children ($M = 308.71$, $SD = 302.24$) had a significantly larger mean difference between preview gap and single-feature, $t(71.05) = -4.09$, $p < .001$. Efficiency decreased as display size increased, $F(1.85, 250.20) = 318.86$, $p < .001$, partial $\eta^2 = .70$. There was a significant Group x Display interaction, $F(2, 270) = 19.93$, $p < .001$, partial $\eta^2 = .13$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for adults (all $p < .001$s) and for children (all $p < .001$s). For lower display sizes, there was no significant difference between children ($M = 118.40$, $SD = 155.53$) and adults ($M = 99.75$, $SD = 61.08$), $t(74.87) = -0.884$, $p = .380$. Between the larger two display sizes, however, children ($M = 226.79$, $SD = 176.93$) had a significantly larger mean difference compared to adults ($M = 124.70$, $SD = 78.08$), $t(78.69) = -4.19$, $p < .001$. There was also a significant Condition x Display interaction, $F(2, 270) = 83.11$, $p < .001$, partial $\eta^2 = .38$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for preview gap (all $p < .001$s) and for single-feature (all $p < .001$s). Compared to single-feature ($M = 62.81$, $SD = 104.83$), the preview gap condition ($M = 127.89$, $SD = 180.23$) had a significantly larger mean difference between the two lower display sizes, $t(136) = -3.87$, $p < .001$. Between the larger two display sizes, the preview gap condition ($M = 234.70$, $SD = 170.94$) also had a significantly larger mean difference compared to single-feature ($M = 73.58$, $SD = 103.99$), $t(136) = -9.75$, $p < .001$. Finally, there was a significant Group x Condition x Display interaction, $F(2, 270) =$

4.02, $p < .05$, partial $\eta^2 = .03$. Within-subjects contrasts showed that efficiency decreased with display size more so in preview gap particularly in children at between higher display sizes ($p < .05$), slopes were similar between groups at lower display sizes ($p = .90$).

Comparisons with the baselines indicate that, for both groups, there is some benefit to search in the preview gap condition, as search is more efficient than conjunction (see Figure 2.4). However, in order to determine whether the preview benefit has been lost in the preview gap condition, these two conditions are compared.

Figure 2.4

Mean RTs Across Conditions and Display Sizes to Identify Preview Gap Benefit



Note. On the left, preview gap slopes (yellow lines) are compared first with conjunction (orange lines) and single-feature (blue lines) to determine whether any benefit has occurred. On the right, preview gap slopes are compared with preview slopes (grey lines) to determine whether the preview gap benefit (if present) is similar to the standard preview benefit. Children = dotted lines; adults = solid lines. Error bars represent ±2 SEs.

Preview vs. Preview Gap: RTs. Mean RTs for correct trials were analysed using a 2 x 2 x 3 mixed ANOVA. Group (adults x children) was a between-subjects factor, and condition (preview x preview gap) and display (4 x 8 x 16) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated only for the main effect of Display, $\chi^2(2) = 16.89$, $p < .001$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .912$). Children were significantly slower than adults, $F(1, 135) = 132.10$, $p < .001$, partial $\eta^2 = .50$. RTs became significantly slower in the preview gap condition compared to the preview, $F(1, 135) = 63.20$, $p < .001$, partial $\eta^2 = .32$. There was a significant Group x Condition interaction, $F(1, 135) = 6.79$, $p = .01$, partial $\eta^2 = .05$. Post-hoc pairwise comparisons using the Bonferroni correction showed that, for children, preview search was faster than preview gap (at $p < .001$), and this was also the case for adults (at $p < .001$). Compared to adults (*M* = 71.51, *SD* = 98.72), children (*M* = 141.24, *SD* = 205.79) had a significantly larger mean difference between preview and preview gap, $t(81.97) = -2.43$, $p = .017$. RTs increased significantly with display size, $F(1.82, 246.25) = 320.52$, $p < .001$, partial $\eta^2 = .70$. There was a significant Group x Display interaction, $F(2, 270) = 10.12$, $p < .001$, partial $\eta^2 = .07$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for adults (all $p < .001$s) and for children (all $p < .001$s). Children (*M* = 123.41, *SD* = 159.04) and adults (*M* = 91.35, *SD* = 62.99) did not differ significantly at the lower display sizes, $t(75.10) = -1.48$, $p = .142$. However, between the larger two display sizes, children (*M* = 232.01, *SD* = 193.40) had a significantly larger mean difference compared to adults (*M* = 157.88, *SD* = 88.34), $t(79.99) = -2.77$, $p = .003$. There was also a significant Condition x Display interaction, $F(2, 270) = 28.05$, $p < .001$, partial $\eta^2 = .17$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for preview (all $p < .001$s) and for preview gap (all $p < .001$s). Compared to preview (*M* = 83.37, *SD* = 121.11), the preview gap condition (*M* = 127.89.27, *SD* = 121.11) had a significantly larger mean difference between the two lower display sizes, $t(136) = -2.61$, $p = .010$. Between the larger two display sizes, the preview gap condition (*M* =

234.70, *SD* = 170.94) also had a significantly larger mean difference compared to preview (*M* =147.07, *SD* = 189.56), *t*(136) = -7.43, *p* < .00. The Group x Condition x Display interaction, however, failed to reach significance, *F*(2, 270) = 0.86, *p* = .42, partial η^2 = .01. Preview gap slopes were significantly steeper than preview, and this occurred similarly for both groups.

***Preview vs. Preview Gap: Efficiency*.** Efficiency was analysed in the same way as mean RTs using a 2 x 2 x 3 mixed ANOVA with group (adults x children) as a between-subjects factor and condition (preview x preview gap) and display size (4 x 8 x 16) within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2)$ = 21.99, *p* < .001, and for the Condition x Display interaction, $\chi^2(2)$ = 22.62, *p* < .001. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity (ε = .885 and ε = .882, respectively). Children were significantly less efficient compared to adults, *F*(1, 135) = 138.98, *p* < .001, partial η^2 = .51. Search became less efficient in the preview gap condition compared to the preview condition, *F*(1, 135) = 54.71, *p* < .001, partial η^2 = .29. There was a significant Group x Condition interaction, *F*(1, 135) = 7.04, *p* < .01, partial η^2 = .05. Post-hoc pairwise comparisons using the Bonferroni correction showed that, for children, preview search was more efficient than preview gap (at *p* < .001), and this was also the case for adults (at *p* < .001). Compared to adults (*M* = 75.79, *SD* = 100.08), children (*M* = 160.63, *SD* = 255.49) had a significantly larger mean difference between preview gap and preview, *t*(72.57) = -5.22, *p* < .001. Efficiency decreased as display size increased, *F*(1.77, 239.06) = 316.36, *p* < .001, partial η^2 = .70. There was a significant Group x Display interaction, *F*(2, 270) = 14.60, *p* < .001, partial η^2 = .10. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for adults (all *p* < .001s) and for children (all *p* < .001s). Children (*M* = 136.51, *SD* = 172.79) and adults (*M* = 102.54, *SD* = 69.57) did not differ significantly at the lower display sizes, *t*(75.61) = -1.44, *p* = .153. Between the larger two display sizes, however, children (*M* = 258.69, *SD* = 198.25) had a significantly larger mean difference compared to adults (*M* = 156.15, *SD* = 96.30), *t*(82.51) = -3.70, $p < .001$. There was also a significant Condition x Display interaction, *F*(1.77, 238.22) = 30.93, $p < .001$, partial $\eta^2 = .19$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for preview (all $p < .001$s) and for preview gap (all $p < .001$s). Compared to preview (*M* = 90.17, *SD* = 140.89), the preview gap condition (*M* = 145.13, *SD* = 184.78) had a significantly larger mean difference between the two lower display sizes, *t*(136) = -3.08, $p = .002$. Between the larger two display sizes, the preview gap condition (*M* = 260.68, *SD* = 225.62) also had a significantly larger mean difference compared to preview (*M* =142.92, *SD* = 206.91), *t*(136) = -4.67, $p < .001$.The Group x Condition x Display interaction, however, failed to reach significance, *F*(2, 270) = 2.63, $p = .07$, partial $\eta^2 = .02$. Preview gap efficiency slopes were significantly steeper than preview, and this occurred similarly for both groups.

Preview Benefit and Preview Gap Benefit Indices. To compare the magnitude of the benefit to search in both the preview and preview gap conditions between groups, an index of search benefit was computed (see e.g., Blagrove & Watson, 2010; Zupan et al., 2018). These preview and preview gap benefit (PB and PGB, respectively) indices are independent of single-feature and conjunction baseline slope values and thus provides a nonbiased measure that illustrates the behavioural benefit elicited from previewing old items, and the behavioural cost derived from the inclusion of the gap display after the preview. These indices were determined by calculating the difference between the conjunction (CJ) and preview/preview gap (PV/PVG) slopes, divided by the difference between the CJ and single-feature (SF) slopes (see Equations 1 and 2) for each individual participant.

$$PB = \frac{CJ\ slope - PV\ slope}{CJ\ slope - SF\ slope} \tag{1}$$

$$PGB = \frac{CJ\ slope - PVG\ slope}{CJ\ slope - SF\ slope} \tag{2}$$

Index values fall between 0 and 1: values tending toward 1 reflect a larger benefit in preview/preview gap search, while values more toward 0 reflect a smaller search benefit in these conditions. For children, the mean PB index value was 0.780 (*SE* = 0.134) and for adults the mean PB index value was 0.624 (*SE* = 0.075). An independent samples t-test was conducted to determine whether PB index values differed significantly between groups. Levene's test indicated that the assumption of homogeneity of variance had been met. There was no significant difference between groups, *t*(135) = -1.07, *p* = 0.29 (two-sided p), Cohen's *d* = -0.183. PB index values for children were non-normal, *W* = 0.768, *p* < .001; there were 4 outliers at the lower end of the scale with values less than or equal to -1.0 and 3 outliers at the higher end of the scale with values greater than or equal to 2.6. PB values for adults were also non-normal, *W* = 0.786, *p* < .001. For adults, there were 6 outliers at the lower end of the scale with values less than or equal to -0.5 and 2 outliers at the upper end of the scale with values greater than or equal to 2.1.

For the PGB index, children had a mean value of 0.172 (*SE* = 0.143) while adults had a mean value of 0.038 (*SE* = 0.103). Again, an independent samples t-test was conducted to determine whether these values differed significantly. Levene's test indicated that the assumption of homogeneity of variance had been met. Children and adults PGB index values were not significantly different, *t*(135) = -0.77, *p* = .44 (two-sided p), Cohen's *d* = -0.133. For children, PGB index values were non-normal, *W* = 0.787, *p* < .001. There were 6 outliers at the lower end of the scale with values less than or equal to -1.6 and 2 values at the upper end of the scale with values greater than or equal to 2.0. Adults also had non-normal PGB index values, *W* = 0.847, *p* < .001. Adults had 8 outliers at the lower end of the scale with values less than or equal to -1.1 and 1 outlier at the upper end of scale with a value of 1.9. PB and PGB values for each group are listed in Table 2.4 and shown in Figure 2.5.

Table 2.4

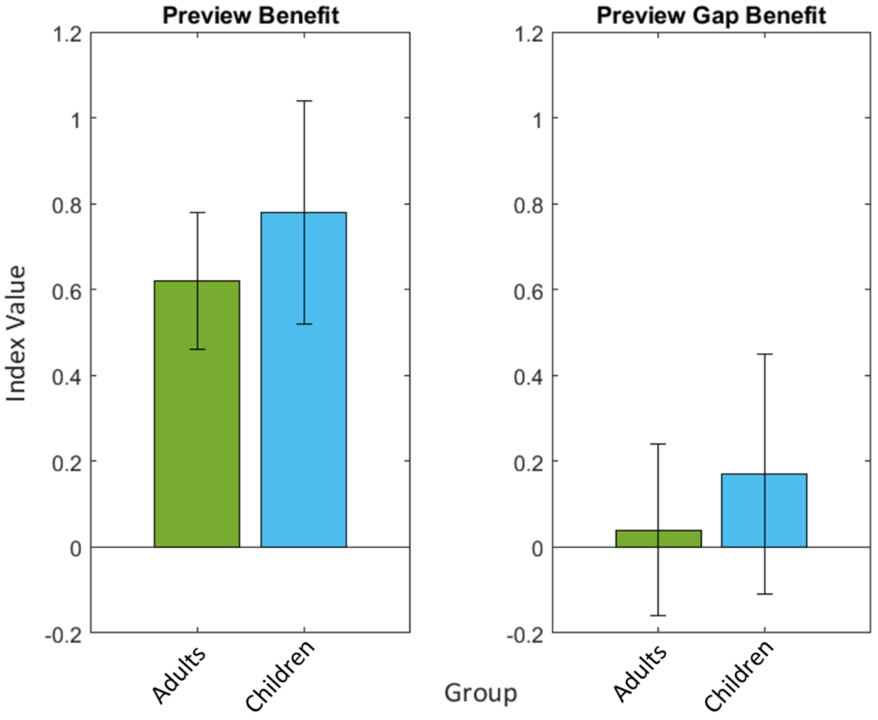
Mean Index Values, Standard Deviations, and T-test Statistics for Children and Adults

Index	Children		Adults		t(135)	p^b	Cohen's *d*
	M	*SD*	*M*	*SD*			
PB	0.780	1.050	0.624	0.656	-1.07	0.289	-0.183
PGB	0.172	1.12	0.038	0.896	-0.771	0.442	-0.133

Note. PB = preview benefit; PGB = preview gap benefit; ^{b} Two-sided.

Figure 2.5

Preview and Preview Gap Benefit Index Values for the Children and Adults



Note. Values of 0 indicate no benefit – none of the old items could be sufficiently suppressed in the competition for selection, and therefore search was as inefficient as if all items had been presented simultaneously. Values of 1 indicate the maximum benefit – all old items were sufficiently suppressed, and therefore competition for selection occurred amongst only the new items. While PB values typically trend more toward 1, PGB values tend more toward 0. Error bars represent ± 2 SEs.

2.1.4 Behavioural Discussion

The aim of the present study was to investigate age-related differences in visual marking and temporal binding. This was achieved by comparing search performance between children and adults in the preview and preview gap conditions. Previous research has shown that top-down attentional control and maintenance has a relatively long developmental trajectory, as children often perform worse than adolescents and adults on measures of this function (Amso & Scerif, 2015; Luna et al., 2015). Accordingly, it was hypothesized that children would have a reduced preview benefit. This, however, was not the case: children's preview benefit was not significantly different than adults. These results are consistent with the limited previous reports that show by 7- to 8-years-old, children are able to generate a robust preview benefit (Mason et al., 2004), that can be similar in magnitude to those elicited by adults (Zupan et al., 2018).

A second mechanism that contributes to the preview benefit is temporal binding (Kunar et al., 2003; Mavritsaki & Humphreys, 2016). Neurophysiological research on temporal binding suggests that efficient communication between areas coding for features is crucial to binding (Singer, 2015). In late childhood, the brain is still developing long-range connection between regions (Cao et al., 2017; Fair et al., 2009; Sporns et al., 2004), as well as increasing the quality of signal transfer by myelinating the white matter tracts and reducing noise by eliminating unnecessary grey matter (Lebel & Deoni, 2018; Luna et al., 2015). Accordingly, temporal binding may be reduced in children. Therefore, it was hypothesized that children would have more of a benefit in the preview gap condition compared to adults. However, contrary to this hypothesis, children and adults both experienced a loss of the preview benefit in the preview gap condition. These findings are similar to the studies in adults that show the preview benefit is lost under preview gap conditions (Mavritsaki & Humphreys, 2016; Olivers & Humphreys, 2004; Watson & Humphreys, 1997).

Across all conditions, children demonstrated overall significantly longer RTs and lower accuracy compared to adults. This could possibly be indicative of a more general issue with the ability to encode information as efficiently as adults. Indeed, although children have the capacity to perform complex cognitive functions, these functions become increasingly refined over the course of development (Ferguson et al., 2021; Tervo-Clemmens et al., 2023). RTs become faster and less variable, and responses become more accurate (Luna et al., 2015; Scantlebury et al., 2014). These behavioural improvements are thought to arise as a result DA-dependent Hebbian plasticity, which increases SNR, and ultimately refines the within-region connectivity (Luna et al., 2015; Perica et al., 2022; Uhlhaas et al., 2010).

Another interesting aspect of the present results is the difference in children and adult's conjunction slopes. For children, search in the conjunction condition was significantly more inefficient relative to adults (slopes in adults were roughly 31 msec/item; for children, they were about 49 msec/item). Conjunction search is considered to reflect more top-down attention functioning relative to single-feature (Wolfe, 2021). This is due, in part, to the fact that the observer must adopt an attentional template - a WM representation of the target's features (Wolfe, 2015b, 2020). Accordingly, the target representation needs to be sufficiently maintained online, presumably in the PFC, and must then be fed back to the visual cortex in order to effectively guide selection (Beck & Kastner, 2009; Desimone & Duncan, 1995; Martinez-Trujillo, 2022). As both the PFC and its extensive long-range connections continue to develop across adolescence (Preuss & Wise, 2022), this could contribute to difficulty in this particular condition. Indeed, these results are consistent with previous reports of less efficient conjunction search in children compared to adults (Merrill & Conners, 2013; Merrill & Lookadoo, 2004; Trick & Enns, 1998).

Interestingly, children's difficulty in conjunction (and thus presumably with the top-down functioning it requires) did not extend into the preview and/or preview gap conditions. Indeed, the attentional template is also used in preview search to guide search in the final display (Braithwaite et al., 2005; Braithwaite & Humphreys, 2003). Therefore, it seems that difficulties should also occur in the preview condition. However, in contrast, children were able still able to ignore old preview items in a similar manner as adults. One possible reason for this pattern of results may be that, because children are already dealing with reduced top-down attention (as seen by the steeper conjunction slopes), when faced with a task that requires additional top-down control (e.g., over time as well as across space) they may compensate by applying more top-down control than adults in order to ensure success. As mentioned in section 2.1.1, previous work has shown that this compensatory effort in applying active suppression to salient-but-irrelevant distractor items is present in children, as measured by larger P_D amplitudes compared to adults (Sun et al., 2018). Thus, a similar compensatory response may be used by children here.

Finally, previous research demonstrates that, after the gap display in the preview gap condition (given that temporal binding is intact), competition between items is reset so that all items compete fully again, similar to a conjunction search (Mavritsaki & Humphreys, 2016). Considering that children's conjunction search slopes are significantly more inefficient than adults, it seems logical that this pattern would arise again, so that children's preview gap slopes would also be significantly more inefficient than adults' slopes in the preview gap condition. However, this is not the case, as children's performance in the preview gap condition was not significantly different. Thus, temporal binding could be reduced, as this would allow old preview items to compete less at the final display. In the next section, these age-related differences proposed from the behavioural performances observed here are explored further using a neurocomputational model.

2.2 Computational Modelling Study

2.2.1 Computational Modelling Background

In the previous section, high-level behaviour is observed and interpreted as component mechanisms of attention. Single-feature reflects the most basic of functions: the ability to direct attention to the most salient item within the space across the visual space. In conjunction search, performance relies on this initial attentional component as well as a second factor of directing attention across space according to internal behavioural goals (Treisman & Gelade, 1980; Wolfe, 2021). In preview and preview gap, there's an added temporal aspect. Thus, in addition to the components at work in the first two conditions, bottom-up temporal binding and top-down visual marking are considered (Olivers et al., 2006; Watson et al., 2003). When studying cognition in this way, it can be easy to mistakenly assume that, because a given component may produce efficient behaviour when it's isolated, this component will remain efficient in varying conditions (e.g., top-down attention in conjunction and top-down attention in preview). However, this overlooks the dynamical interaction of components in any given task. Indeed, in order to reveal how mechanisms interact to give rise to complex cognition, we need to be able to open the "black-box" of human information processing. To do this, we can use computational models that are capable of performing the same tasks as humans (Kriegeskorte & Douglas, 2018; Mareschal et al., 2007).

One neurocomputational model, the b-sSoTS model, is able to perform visual search tasks, and thus can provide a biologically plausible detailed account of search across space and time. As discussed in section 1.3.1, the b-sSoTS model is a SNN model that allows for high-level behaviours to be investigated more deeply at the neural level. Accordingly, the b-sSoTS model is able to provide invaluable insights into the neurobiologically plausible dynamic components that give rise to psychological phenomena like the preview benefit (Mavritsaki et al., 2011). Indeed, as discussed in section 1.3.1, the b-sSoTS model has been previously used to demonstrate how frequency adaptation acts as a passive inhibition mechanism alongside visual marking (i.e., active inhibition) to suppress old preview items from biased competition computations (Mavritsaki et al., 2006). The model has also been used to investigate how cognition operates in lesion patients and has further been used to simulate neuroimaging (fMRI) data (Mavritsaki et al., 2009, 2010; Mavritsaki & Humphreys, 2016). However, the b-sSoTS model was initially built to simulate these attentional mechanisms in the stable adult state and therefore needs to be adjusted to consider the neural differences in the developing brain.

There have been substantial advancements in developmental cognitive neuroscience with regards to the use of computational models, particularly through frameworks like neuroconstructivism (Astle et al., 2023; Mareschal et al., 2007). These are often artificial neural networks (ANNs), which abstract from biological details but are inspired by real biological neural networks (Khaligh-Razavi & Kriegeskorte, 2014; Mareschal & Thomas, 2007; Shultz, 2017; Shultz & Nobandegani, 2021; Thomas & Karmiloff-Smith, 2002; Westermann & Ruh, 2012). These have provided critical insights into development (Shultz, 2017). Comparatively, there are far fewer models of the developing brain that are biologically detailed, despite their ability to provide crucial insight into maturation. For example, Edin et al. (2007) took a neurocomputational model originally designed according to the adult brain and implemented several structural developmental changes, such as increased synaptic strength, synaptic pruning, and myelination to simulate children's performance and fMRI activation in a working memory task. This bottom-up approach to understanding developmental ultimately showed that synaptic strengthening gives rise to improvements in WM (Edin et al. 2007). Here, a more top-down approach is taken, as the proposed mechanisms for differences in children derived from the behavioural study in the previous part of this study are used to guide parameter changes in the b-sSoTS model.

Aims of Study. Over the course of childhood and adolescence, the brain undergoes substantial changes at both the cellular and network levels (Cao et al., 2017; Flores-Barrera et al., 2014; Perica et al., 2022; Raja et al., 2022). These changes, in turn, give rise to more efficient behaviour and increased cognitive control (Edin et al., 2007; Kolk & Rakic, 2022; Luna et al., 2004; Scantlebury et al., 2014). In the previous section, four visual search tasks were used to examine how selective visual attention differs in 7- to 12-year-old children compared to adults. From these results, four hypotheses were then generated to account for differences at the behavioural level. (1) weaker encoding of relevant information in children gives rise to slower RTs and lower accuracy; (2) effortful conjunction search is worse in children due to reduced top-down expectancy for the target’s features; (3) an adult-like preview benefit in children is achieved through a compensatory increase in the active inhibition of old items; and (4) adult-like performance in the preview gap condition is due to reduced temporal binding, allowing old items to compete less. In the present study, changes to the parameters of the original b-sSoTS model will be undertaken to test the biological plausibility of hypotheses.

2.2.2 Computational Modelling Method

Description of the b-sSoTS Model. The b-sSoTS model is comprised of 5000 spiking neuron units that are organised into pools, where each pool contains some number of neurons with similar biophysical properties and inputs. A certain number of pools are then grouped into distinct layers to reflect the neural encoding of objects in visual space during search. The simulations here reflect a simplified scenario in which the maximum display size in the final search screen is six items.

Overall, b-sSoTS has a total of three layers (see Figure 1.7). There are two separate layers that each code for a particular visual feature dimension, which are colour and letter shape. Within, for instance, the colour feature dimension layer, there are two distinct feature maps that encode the colour of stimuli (blue or green) present among the six possible locations in the visual field. There is identical organisation of the letter-shape feature dimension, with the two feature maps encoding the letters "H" and "A." The third layer, referred to as the location map, sums outputs that originate at the same location in each of the separate feature maps, thus representing the presence of a perceptually bound object (e.g., a blue letter H) at a particular location in the visual field. Each layer also contains two additional pools: one inhibitory pool and one non-specific pool (see also Deco & Zihl, 2001). Inhibitory pools are included to reflect that a neuron is either excitatory or inhibitory in all of its connections (i.e., Dale's hypothesis; Tuckwell, 1998). The non-specific pools are meant to reflect that, in the real brain, neurons encoding for specific stimuli (here, represented in the four feature maps and the location map), are also surrounded by other neurons present in the same area, but that are not involved in the encoding of that visual stimuli. In the model, the neurons in these non-specific pools activate spontaneously and have connections with each of the maps within its layer. For each layer, the number of excitatory (pyramidal) and inhibitory (interneuron) cells is 80:20, as this is the ratio typically found in the human brain (Abeles, 1991; Rolls & Deco, 2002).

Within each of the layers, both the inhibitory and non-specific pools are connected with the pools that comprise the feature maps. Within each feature map, pools are mutually excitatory, as each pool represents a mutually exclusive location in the visual field. Furthermore, feature map pools are inter-connected with pools in the location map that represent the same position in visual space.

Finally, the b-sSoTS model also considers that external activity (outside the system) can affect the system. This noise is simulated by neurons also receiving a background level of spontaneous activity (λ_{ext}), with a Poisson noise distribution with a value of 3 Hz, which is consistent with activity levels reported in the cerebellar cortex (Rolls & Treves, 1998; Wilson et al., 1994).

Neuronal Characteristics. Unlike the model neurons of ANNs, which only model rate of firing, model neurons of SNNs are also able to model changes in membrane potential and the precise timing of spikes. These models are thus better able to capture the behaviour of a real biological neuron. Accordingly, neural networks comprised of these spiking neurons operate more similarly to the brain than ANNs (Kriegeskorte & Douglas, 2018; Yamazaki et al., 2022). The LIF neuron model (Tuckwell, 1998) is a popular spiking neuron model due to its high computational efficiency while still maintaining biological plausibility (Yamazaki et al., 2022). Each of the 5000 neuron model units in the b-sSoTS model are LIF neurons. When the LIF neuron's sub-threshold membrane potential reaches a threshold, it “fires” (i.e., becomes active). After firing, this membrane potential is then reset to a fixed value. This sub-threshold potential follows Equation 3,

$$\frac{\mathrm{d}V(t)}{\mathrm{d}t} = \frac{1}{C_m}\left(-g_m(V(t) - V_L) - I_{syn}(t)\right) \tag{3}$$

where C_{m} is the membrane capacitance, g_{m} is the membrane leak conductance, V_{L} is the resting potential, and $I_{\mathrm{syn}}$is the synaptic currents.

For the synaptic currents, each neuron contains excitatory currents with two components: (1) a fast excitatory component mediated by AMPA-like dynamics ($I_{\mathrm{AMPA,rec}}$) and (2) a slow excitatory component mediated like NMDA-like dynamics ($I_{\mathrm{NMDA,rec}}$). There is also an external AMPA current ($I_{\mathrm{AMPA,ext}}$) to model external neurons, and an inhibitory GABAergic current ($I_{\mathrm{GABA,}}$) to model the inhibition to inhibitory and excitatory neurons. Finally, there is also a frequency adaptation current based on [Ca^{2+}]-activated K^{+} current (I_{AHP}). Thus, the synaptic currents in the b-sSoTS model are given in Equation 4,

$$I_{syn}(t) = I_{\mathrm{AMPA,ext}}(t) + I_{\mathrm{AMPA,rec}}(t) + I_{\mathrm{NMDA,rec}}(t) + I_{\mathrm{GABA}}(t) + I_{\mathrm{AHP}}(t) \qquad (4)$$

Additional details regarding the current are provided in Appendix G.

Mean Field Approximation for Model Parameters. As mentioned above, neuron units within the model are organised into pools, where each pool is comprised of many similar (statistically) model neurons. Thus, rather than solving the differential equations for each of the neurons (which would become very computationally expensive and time-consuming), the mean-field approach can be applied to describe the activity of these pools as a whole. Pools of neurons are described by a probability density function, which reflects the distribution of membrane potentials across the group. A population transfer function is applied when the system is in a steady state to yield the common time-dependent population activity, or the ensemble average. Here, the temporally averaged spiking rate of a single neuron is replaced by an equivalent average rate of all neurons within a pool at a given time (see Appendix H). This way, pools of neurons are represented by a single equation rather than the numerous differential equations of the individual neurons. The mean-field approximation ultimately allows for the identification of the model's parameters – specifically, the values of the connection weights within and between the layers. These parameters can be identified when the model reaches a stable state (i.e., when activity of pools converge) after being presented with a given input. Once the parameter values of the stable state are ascertained, these values can then be applied to the spiking model to investigate transient states. In sum, the mean field approach allows for the identification of the model's parameters without the need for excessive computational power as the number of equations that must be solved is drastically reduced. The connectivity weights were identified using the mean-field approach, and remaining parameters were set by hand in the spiking level by Mavritsaki et al. (2006). All of the parameters used are listed in Table 2.5.

Search Conditions. The model was set to simulate four search tasks: single-feature, conjunction, preview and preview gap. The onset of a stimulus at a given position was simulated by the pools encoding for that stimulus' features (i.e., pools in the feature maps) receiving input (the λ_{in} parameter, see Table 2.5). For example, to simulate the presence of a green letter “H” in the visual field at the bottom right corner (i.e., position 6, see Figure 1.6), the corresponding pools in the “green” and “letter H” map would receive input, so neurons in those pools would increase their firing rates. In all conditions, the target was a blue letter "H." In the single-feature condition, the target blue letter "H" was surrounded blue letter "A"s. In the conjunction condition, the target blue letter "H" was surrounded by green letter "H" and blue letter "A"s. In the preview condition, green letter "H" distractors appeared for a period of 450 msec before blue letter "A" distractors and the blue letter "H" target appeared alongside. In the preview gap condition, green letter "H" distractors appeared for a period of 450 msec, then a blank gap screen appeared for 450 msec. After this gap display, old green "H" distractor items appeared in their original positions alongside new blue letter "A" distractors and the target blue letter "H." Display sizes all conditions were 4 and 6.

Data Analysis. There were 300 runs of each simulation. From this, 20 runs were grouped per condition per display size to create data for one “participant.” Overall, this yielded a total of 15 participants, and these 15 participants made up the data set used in the analysis. To match the data analysis procedure used in the behavioural study, mean RTs were then calculated for each "participant", condition, and display size. A run (similar to a single trial in behavioural data) was excluded if it was (1) incorrect or (2) more than 2 standard deviations above or below the "participant's" mean. In line with previous computational modelling work (Mavritsaki & Humphreys, 2016), the mean RT and accuracy were then used to create an efficiency index (mean RT/accuracy) in order to consider the accuracy of responses in addition to latency. The mean efficiency index values for each condition and display size are shown in Table 2.6.

Table 2.5

Parameters Used in the b-sSoTS Model

Parameter	Values	Description
$g_{AMPA,\,rec} excitatory$	0.0208 nS	AMPA recurrent synaptic conductance for excitatory neurons
$g_{AMPA,\,rec} inhibitory$	0.0162 nS	AMPA recurrent synaptic conductance for inhibitory neurons
$g_{NMDA} excitatory$	0.22 nS	NMDA recurrent synaptic conductance for excitatory neurons
α	0.18 μM	[Ca^{2+}] influx when a spike occurs
N_E	1600 (800)	Number of excitatory neurons in each layer for the feature maps (for the location map)
N_I	400 (200)	Number of inhibitory neurons in each layer for the feature maps (for the location map)
N_{ext}	800	Number of external neurons
w^+	2.4	Coupling for the pools in the feature maps
w_{i1}	1.0	Inhibition for the two feature map dimensions
w_{i2}	0.9	Inhibition for the location map
w_{i3}	1.0	Connection weight from the feature maps to location map
w_{i4}	0.25	Connection weight from the location map to the to the feature maps
λ_{in}	150 Hz	The total input that each pool receives from the external neurons to show that there is an item in the visual field.
λ_{att}	190 Hz	The total top-down that the target pools receive to signify the target's characteristics.
$maxAc$	0.18	The maximum top-down Inhibition that can be applied to the previewed distractors' maps.
$wbind$	0.2	Binding parameter, increase in the feed-backward weight from LMs to FMs due to grouping
thrAC	5 Hz	Threshold for the pool in feature map being active

Note. b-sSoTS = binding-spiking search over time and space; AMPA = α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid; NMDA = N-methyl-D-aspartic acid or N-methyl-D-aspartate; Ca^{2+} = calcium; LM = location map; FM = feature map.

Table 2.6

Mean Efficiencies for Simulated Adults

Condition	Mean	*SD*
Single-feature 4	274.86	16.11
Single-feature 6	315.76	13.98
Conjunction 4	401.77	45.89
Conjunction 6	534.28	82.30
Preview 4	348.32	36.62
Preview 6	368.26	33.71
Preview Gap 4	345.97	54.74

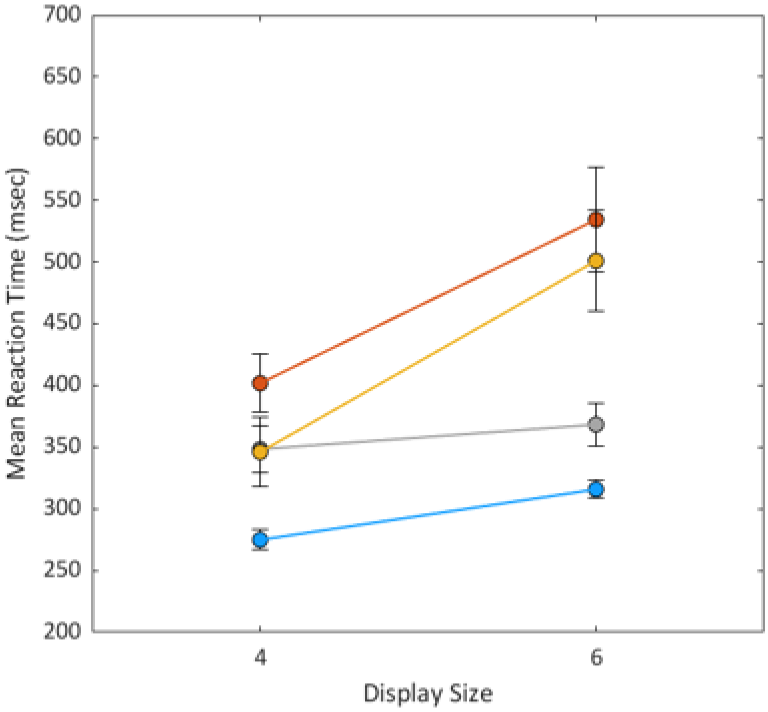
Note. The efficiency index values are calculated by dividing mean RTs by the accuracy (Townsend & Ashby, 1983).

2.2.3 Computational Modelling Results

Prior to conducting simulations of visual search in children, the b-sSoTS model was first run using its baseline parameter values (listed in Table 2.5) in order to confirm that the model matches human search data for adults. The results are organised in a similar way as the behavioural results in section 2.1.3. First, single-feature and conjunction are compared, then preview is compared with each to determine whether a preview benefit has occurred. Finally, the preview gap is compared with each. Baseline b-sSoTS simulations should match the pattern of adult visual search data so that: (1) conjunction search is significantly less efficient than single-feature; (2) preview search is significantly more efficient than conjunction and possibly as efficient as single-feature; (3) preview gap search is less efficient than single-feature/preview and possibly as inefficient as conjunction. Efficiency slopes for each condition are shown in Figure 2.6.

Figure 2.6

Mean Efficiencies for Conditions and Display Sizes for Simulated Adults



Note. Single-feature = blue; conjunction = orange; preview = grey; preview gap = yellow. Error bars represent ±2 SEs.

Baseline b-sSoTS: Simulated Adults. ***4 (Condition) x 2 (Display) ANOVA.*** Efficiencies were analysed using a 4 (condition) x 2 (display size) repeated-measures ANOVA. Both condition (single-feature x conjunction x preview x preview gap) and display size (4 x 6) were within-subject factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Condition, $\chi^2(5) = 18.75$, $p < .001$, and for the Condition x Display interaction, $\chi^2(5) = 13.49$, $p < .001$. Accordingly, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .684$ and $\varepsilon = .630$, respectively). Efficiencies were significantly different between conditions, $F(2.05, 28.72) = 65.17$, $p < .001$, $\eta^2 = 0.82$, and efficiency also decreased significantly as a display size increased, *F*(1,14) = 178.92, $p < .001$, $\eta^2 = 0.93$. Finally, the efficiency slopes differed between conditions, resulting in a significant Condition x Display interaction, *F*(1.89, 26.48) = 11.02, $p < .001$, $\eta^2 = 0.44$. Further analysis was conducted to explore this interaction.

Single-feature vs. Conjunction. Efficiencies were analysed using a 2 (condition) x 2 (display size) repeated-measures ANOVA. Both condition (single-feature x conjunction) and display size (4 x 6) were within-subjects factors. Search was significantly more efficient in the single-feature condition, *F*(1,14) = 210.57, $p < .001$, $\eta^2 = 0.94$, and efficiency decreased as display size increased, *F*(1,14) = 56.34, $p < .001$, $\eta^2 = 0.80$. There was a significant Condition x Display interaction, *F*(1,14) = 10.38, $p < .01$, $\eta^2 = 0.43$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences between the two display sizes for both single-feature (at $p < .001$) and conjunction (at $p < .001$). Compared to single-feature (*M* = 40.90, *SD* = 22.10), the conjunction condition (*M* =132.51, *SD* = 97.87) had a significantly larger mean difference between display sizes, *t*(14) = 3.22, *p* = .006. The search slopes were 20.45 msec/item and 66.25 msec/item, respectively.

Preview vs. Conjunction. Efficiencies were analysed using a 2 (condition) x 2 (display size) repeated-measures ANOVA. Both condition (preview x conjunction) and display size (4 x 6) were within-subjects factors. Search was significantly more efficient in the preview condition, *F*(1,14) = 55.76, $p < .001$, $\eta^2 = 0.79$. Efficiency also decreased as display size increased, *F*(1,14) = 30.65, $p < .001$, $\eta^2 = 0.69$. There was a significant Condition x Display interaction, *F*(1,14) = 14.41, $p < .01$, $\eta^2 = 0.51$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences between the two display sizes for both preview (at $p < .001$) and conjunction (at $p < .001$). Compared to preview (*M* = 19.94, *SD* = 51.99), the conjunction condition (*M* =132.51, *SD* = 97.87) had a significantly larger mean difference between display sizes, *t*(14) = -3.80, *p* = .002. The search slope for the preview condition was 9.97 msec/item.

Preview vs. Single-feature. Efficiencies were analysed using a 2 (condition) x 2 (display size) repeated-measures ANOVA. Condition (preview x single-feature) and display size (4 x 6) were within-subjects factors. Search was significantly more efficient in the single-feature condition, $F(1,14) = 121.90$, $p < .001$, $\eta^2 = 0.90$. Efficiency decreased as display size increased, $F(1,14) = 16.39$, $p < .001$, $\eta^2 = 0.54$. The interaction between condition and display size did not reach significance, $F(1,14) = 2.20$, $p = .16$, $\eta^2 = 0.14$, indicating that slopes did not differ significantly between conditions.

Preview gap vs. Conjunction. Efficiencies were analysed using a 2 (condition) x 2 (display size) repeated-measures ANOVA, with condition (preview gap x conjunction) and display size (4 x 6) as within-subjects factors. Search was significantly more efficient in the preview gap condition, $F(1,14) = 6.46$, $p < .05$, $\eta^2 = 0.90$, and efficiency decreased as display size increased, $F(1,14) = 118.37$, $p < .001$, $\eta^2 = 0.89$. Search slopes did not differ significantly between conditions, as reflected by the lack of a significant Condition x Display interaction, $F(1,14) = 0.31$, $p = .586$, $\eta^2 = 0.02$. The search slope for preview gap was 77.50 msec/item.

Preview gap vs. Single-feature**.** Efficiencies were analysed using a 2 (condition) x 2 (display size) repeated-measures ANOVA. Condition (preview gap x single-feature) and display size (4 x 6) were both within-subjects factors. Search was significantly more efficient in the single-feature condition, $F(1,14) =106.17$, $p < .001$, $\eta^2 = 0.88$, and efficiency decreased as display size increased, $F(1,14) = 75.18$, $p < .001$, $\eta^2 = 0.84$. There was also a significant Condition x Display interaction, $F(1,14) = 21.44$, $p < .001$, $\eta^2 = 0.61$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences between the two display sizes for both single-feature (at $p < .001$) and preview gap (at $p < .001$). Compared to single-feature ($M = 40.90$, $SD = 22.10$), the preview gap condition ($M = 154.99$, $SD = 88.84$) had a significantly larger mean difference between display sizes, $t(14) = 4.63$, $p < .001$.

Preview gap vs. Preview. Efficiencies were analysed using a 2 (condition) x 2 (display size) repeated-measures ANOVA with condition (preview gap x preview) and display size (4 x 6) as within-subjects factors. Search was more efficient in the preview condition, $F(1,14) = 22.26$, $p < .001$, $\eta^2 = 0.61$, and efficiency decreased as display size increased, $F(1,14) = 43.29$, $p < .001$, $\eta^2 = 0.76$. There was a significant two-way interaction between condition and display, $F(1,14) = 25.83$, $p < .001$, $\eta^2 = 0.65$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences between the two display sizes for both preview gap (at $p < .001$) and preview (at $p < .001$). Compared to preview ($M = 19.94$, $SD = 51.99$), the preview gap condition ($M = 154.99$, $SD = 88.84$) had a significantly larger mean difference between display sizes, $t(14) = 5.08$, $p < .001$.

The baseline b-sSoTS does indeed match the pattern of slopes of adults. Search in single-feature and preview are highly efficient while conjunction and preview gap are significantly less efficient. This is clearly demonstrated in Figure 2.9, with single-feature and preview's relatively flat slopes compared to the steep slopes of conjunction and preview gap. Next, several parameter changes were applied to the b-sSoTS model in order to simulate children's visual search data.

Parameter Search and Changes. The results of the behavioural study (see section 2.1.3) showed that children are: (1) overall slower and less accurate across conditions; (2) less efficient under conjunction search conditions; (3) able to generate a preview benefit of similar magnitude than adults; and (4) lose the preview benefit in the preview gap condition. Several mechanisms for these observed differences were subsequently proposed. First, overall reductions in RT and accuracy could be indicative of reduced synaptic strength between neurons encoding similar stimuli. Second, less efficient conjunction search could be due to weaker top-down expectancy for the target's features. Third, an adult-like preview benefit could arise as a result of a compensatory increase in active suppression applied to old items. Finally, in order to account for adult-like performance in preview gap, it was suggested that children may also have problems in temporally binding items.

While at least some of the proposed mechanisms might occur generally in children, it is unclear whether these components together can actually account for the behaviour observed in this particular neurocognitive performance (Kriegeskorte & Douglas, 2018). Furthermore, the neurobiological plausibility of these components and of how they interact dynamically also needs to be considered. Accordingly, these hypotheses were tested by matching them with a proposed parameter and applying an increase or decrease to their value according to the proposals and then simulating search with these changes to determine whether it produced a sufficient match for the children's actual performance. Once a match is determined, spiking level data can then be analysed to examine how these mechanisms affect the neural activity that gives rise to the observed behaviour. Table 2.7 shows the parameter and changes expected to produce a given element of the search behaviour observed in children's performance.

Table 2.7

Proposed Parameter Changes to Account for Children's Visual Search Performance

Finding	Hypothesis	Parameter	Description	Change
Overall slower RTs and reduced accuracy	Weaker encoding relevant information generally	w_+	Coupling for the pools in the feature maps	Reduce
Less efficient conjunction search	Difficulty using WM template to guide attention across space	λ_{att}	The total top-down that the target pools receive to signify the target's characteristics.	Reduce
Adult-like preview benefit	Compensatory increase in active inhibition of old items	*maxAc*	The maximum top-down inhibition that can be applied to the previewed distractors' maps.	Increase
Adult-like preview gap benefit	Weaker temporal binding	*wbind*	Binding parameter, increase in the feed-backward weight from LM to FMs due to grouping	Reduce

Note. Findings from the behavioural study (see section 2.1) first serve to generate hypotheses regarding the mechanisms involved in children's visual search performance. These hypothesised mechanisms are then matched to certain parameters in the b-sSoTS model (see Table 2.5) and changes in these parameters are implemented in order to test the hypotheses. RTs = reaction times; WM = working memory; LM = location map; FM = feature maps.

Reduced Self-Coupling. Simulations began with changes to the w_+ parameter, which is the coupling weight between neuron units within specific excitatory pools. This parameter reflects the causal relationship between presynaptic neurons that consistently fire post-synaptic neurons. This relationship is described by Hebb's rule, which posits that when neurons fire in a correlated way, the strength of the connection between them will increase, while the connection between neurons that fire in an uncorrelated way remains weak (Hebb, 1949). Hebb originally postulated that the strong connections between neurons whose firing is correlated would allow for the creation of cell assemblies, whose connected firing is able to store representations (Hebb, 1949; Huyck & Passmore, 2013; Lansner, 2009). Since all neurons within a particular specific excitatory pool fire at approximately the same time (i.e., when a stimulus is presented), they are strongly coupled and are thus representative of a cell assembly. In the human brain, these kinds of associations between neurons become stronger with experience over the course of development (Luna et al., 2015). In visual search performance, children showed less efficient behaviour overall in terms of slower reaction times and lower accuracy. Therefore, the possibility that that this might reflect weaker connections between neurons within specific excitatory pools was first explored.

Guided by this hypothesis, the w_+ parameter was reduced by 0.1 (4.17%), from a value of 2.4 to 2.3 in all four conditions, keeping all other parameters constant. This was the same for all the specific excitatory pools in all four of the feature maps, as well as in the location map. Efficiency (mean RT in msec/accuracy) was first analysed when all 300 trials were calculated for a single "participant" to gauge how well the parameter change produced results that would match children's data. When simulations were run with w_+ at 2.3, mean RTs were particularly higher in the single-feature and conjunction condition. The efficiency slope for conjunction increased to 85.28 msec/item (see Table 2.8). Preview was also slightly more efficient with a slope at 10.16 msec/item. Finally, the accuracy in the preview gap condition increased, causing search to become more efficient in this condition, with a slope of 45.34 msec/item.

Table 2.8

Efficiency Slopes for Conditions at Each Step of Parameter Search

Condition	Reduced SC 1	Reduced SC 2	Reduced TD	Reduced SC1 and TD
Single-feature	25.48	49.44	22.91	28.06
Conjunction	85.28	586.40	73.30	279.24
Preview	10.16	20.75	13.64	14.84
Preview Gap	45.34	380.50	45.58	31.59

Note. SC = self-coupling; TD = top-down guidance. Reduced SC 1 refers to the first reduction in the w_+ parameter (-4.17%). Reduced SC 2 refers to the second reduction in the w_+ parameter (-8.34%). Reduced TD refers to the reduction in the λ_{att} parameter (-10.52%). Reduced SC1 and TD refers to the combined reduction in the w_+ parameter (-4.17%) and the λ_{att} parameter (-10.52%).

Although the performance of the model with this 0.1 reduction in w_+ matched children's visual search performance fairly well, there were much larger increases in reaction times and reductions in accuracy in the real children's data. Therefore, the w_+ parameter was reduced by another step value of 4.17% to equal a value of 2.2 (-8.34%) to determine whether this would slow RTs even more. While RTs did increase, conjunction slopes became excessively steep at 586.40 msec/item. Thus, a value of 2.3 was accepted.

***Reduced Top-Down Guidance*.** The next changes were reductions applied to the λ_{att} parameter, which is the additional input that target pools receive to reflect the top-down expectancy of the target items features. The b-sSoTS model was originally extended from Deco and Roll's (2005) neurodynamical model of biased competition (see section 1.3). This model simulated the neural data reported by Reynold's (1999) that showed top-down spatial attention can bias the neural competition between items, thus allowing an attended item to "win" selection. Deco and Rolls (2005) were able to simulate this by adding this attentional input to the pools representing a particular location in space. However, observations at both the neural and behavioural levels demonstrate that top-down attention can also be non-spatial, i.e., can be applied to features across the visual field. For b-sSoTS, this means that this additional attention input is applied to all six pools within the feature map "blue" and the feature map "letter H;" thus, the item that is both blue and letter H will have the highest firing rate and win competition. In conjunction search, since all items have at least one of these two features, there is more competition between items (i.e., less contrast between target and distractors), and this leads to the longer RTs that increase with display size that is typically observed in this condition (Mavritsaki et al., 2006; Rolls & Deco, 2002).

In the human brain, this sort of feature-based attention is thought to arise when the target's features are held in WM as an attentional template in the PFC, and these top-down signals are then fed back to areas in the temporal and visual cortex. The PFC, as well as its long-range connections that allow for effective communication with lower areas, continue to develop across childhood and adolescence (Kolk & Rakic, 2022; Soman et al., 2023a). This development is thought to give rise to efficient performance in tasks that require top-down control of attention, like conjunction search (Luna et al., 2004; Oakes & Amso, 2018). Although the previous w_+ reductions resulted in less efficient conjunction search, reductions in the λ_{att} parameter were examined alone, and then alongside w_+ reductions, to determine whether these could also account for children's visual search performance in the behavioural study.

First, keeping all other parameters constant, the λ_{att} parameter was reduced by a value of 0.02 (10.52%) to equal 0.17, so that the total additional input received by target pools was 170 Hz. The reduction value here, which is in line with previous research (Mavritsaki et al., 2011), results in increased competition for targets that results from increased activation in feature maps excited by distractors (Mavritsaki et al., 2011). Accordingly, there were some increases in RTs, and efficiency slopes became steeper, with single-feature at 22.91 msec/item, conjunction at 73.30 msec/item, preview at 13.64 msec/item and preview gap at 45.58 msec/item. Although the increased RTs and reduced efficiency in conjunction search was achieved, these were better simulated by the w_+ reductions. Furthermore, in the real visual search data of children, the preview benefit is increased compared to adults (represented here by baseline b-sSoTS simulations). However, in the λ_{att} parameter reductions, the preview benefit has decreased compared to baseline.

Finally, w_+ and λ_{att} parameter reductions were reduced together, so that, while all other parameters were constant, simulations were conducted while w_+ was at a value of 2.3 and λ_{att} was at a value of 0.17. Here, RTs and slopes were indeed elevated; however, conjunction slopes became too high again at 279.24 msec/item. As λ_{att} parameter reductions alone failed to produce a better match to children's data than w_+ reductions, and combined w_+ and λ_{att} reductions failed to simulate children's conjunction search, the hypothesis of reduced top-down expectancy as a contributing factor to differences in children's visual search performance was ultimately rejected.

***Increase in Active Inhibition and Reduced Temporal Binding*.** Originally, it was hypothesized that, compared to adults, children may have a compensatory increase in active inhibition since the behavioural results showed children had a decrease in conjunction search efficiency that surprisingly failed to extend to preview and preview gap conditions. From the cognitive model solely, it's difficult to understand how difficulty in encoding and/or top-down expectancy could contribute to *more* efficient search behaviour in these conditions. However, in the simulations with reductions of the self-coupling weight, although search became slower and less efficient in single-feature and (particularly) in conjunction search, there was actually an increase in search efficiency in both preview and (particularly) preview gap. This seemingly contradictory results can then be analysed further by investigating spiking level behaviour to determine *how* this result arose in the first place (discussed in the next section). Since parameter changes in the w_+ weight were able to produce the children's preview/preview gap benefits alone, increased active inhibition and reduced temporal binding were rejected as a hypothesis, and w_+ reductions was accepted as a best match for the real children's data. Thus, the parameter change implemented here yields a new version of the b-sSoTS model, the b-sSoTS-c model (where "c" stands for "child") that accounts for the developmental differences present in the brain at late childhood.

Comparison of Simulated Adults and Simulated Children. With the b-sSoTS-c model, 300 runs were then split into 20 runs for 15 "participants" and the efficiencies of this dataset were compared with the dataset generated by the baseline b-sSoTS. Table 2.9 and Figure 2.7 show the mean efficiencies for both groups, while Table 2.10 shows the efficiency slopes. Note that the statistics for the dataset differ slightly from those calculated for all 300 runs (in the previous section), as the data analysis procedure for calculating means was applied to each and every "participant."

Table 2.9

Mean Efficiencies for Simulated Adults and Children

Condition	Simulated Adults		Simulated Children	
	Mean	*SD*	Mean	*SD*
Single-feature 4	274.86	16.11	300.02	15.41
Single-feature 6	315.76	13.98	350.60	19.57
Conjunction 4	401.77	45.89	409.24	34.55
Conjunction 6	534.28	82.30	609.53	136.88
Preview 4	348.32	36.62	338.19	25.93
Preview 6	368.26	33.71	344.14	18.21
Preview gap 4	345.97	54.74	307.22	26.34
Preview gap 6	500.96	79.38	413.73	73.95

Table 2.10

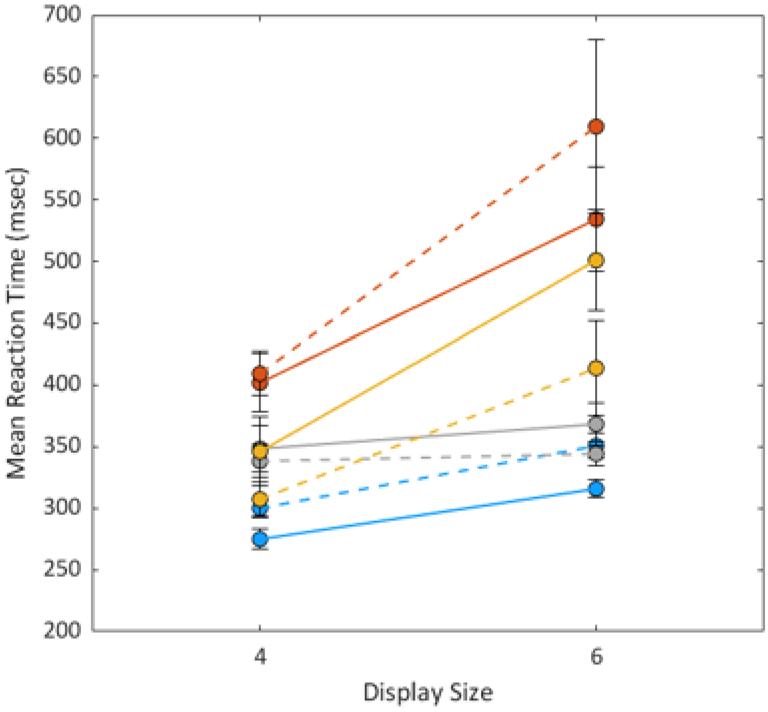
Efficiency Slope Statistics for Simulated Adults and Children

Condition	Simulated Adults	Simulated Children
Single-feature	20.45	25.29
Conjunction	66.26	100.14
Preview	9.97	2.98
Preview Gap	77.50	53.26

2 (Group) x 4 (Condition) x 2 (Display) ANOVA. Efficiencies were analysed using a 2 (group) x 4 (condition) x 2 (display size) mixed ANOVA. Group (simulated adults x simulated children) was a between-subjects factor. Condition (single-feature x conjunction x preview x preview gap) and display size (4 x 6) were within-subjects factors. There was no main effect of group. Levene's test was significant for efficiencies in preview at display size 6, F(1, 28) = 4.77, *p* < .05, indicating unequal variances at this level. For all other condition/display sizes, there was no significant differences between variances. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of condition, $\chi^2(5) = 44.25$, *p* < .001, and for the condition x display interaction, $\chi^2(5) = 42.14$, *p* < .001. Accordingly, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = .569 and ε = .548, respectively). Efficiency differed significantly between the conditions, *F*(1.71, 47.83) = 111.14, *p* < .001, $\eta^2 = 0.80$. Post-hoc pairwise comparisons using the Bonferroni correction showed that each of the conditions was significantly different from the others (at *p* < .001 for all). Single-feature was the most efficient (*M* = 310.31, *SE* = 2.11), followed by preview (*M* =349.73, *SE* = 3.77), preview gap (*M* = 391.97, *SE* = 8.64), and conjunction (*M* = 488.71, *SE* = 10.28). There was also a significant interaction between condition and group, *F*(3, 84) = 10.80, *p* < .001, $\eta^2 = 0.28$. This interaction is explored for the simulated adults above, and it follows the same pattern here (see Figure 2.7). Efficiency decreased significantly with display size, *F*(1, 28) = 237.70, $p <$ .001, $\eta^2 = 0.90$. The group x display interaction failed to reach significance. The condition x display interaction was significant, *F*(1.64, 46.03) = 22.03, $p < .001$, $\eta^2 = 0.44$. However, the three-way interaction between group, condition and display failed to reach significance. Simulated children's efficiency slopes did not differ significantly from those of simulated adults.

Figure 2.7

Mean Efficiencies for Conditions and Display Sizes for Simulated Adults and Children



Note. Single-feature = blue; conjunction = orange; preview = grey; preview gap = yellow. Simulated adults = solid lines; simulated children = dashed lines.

2.2.4 Computational Modelling Discussion

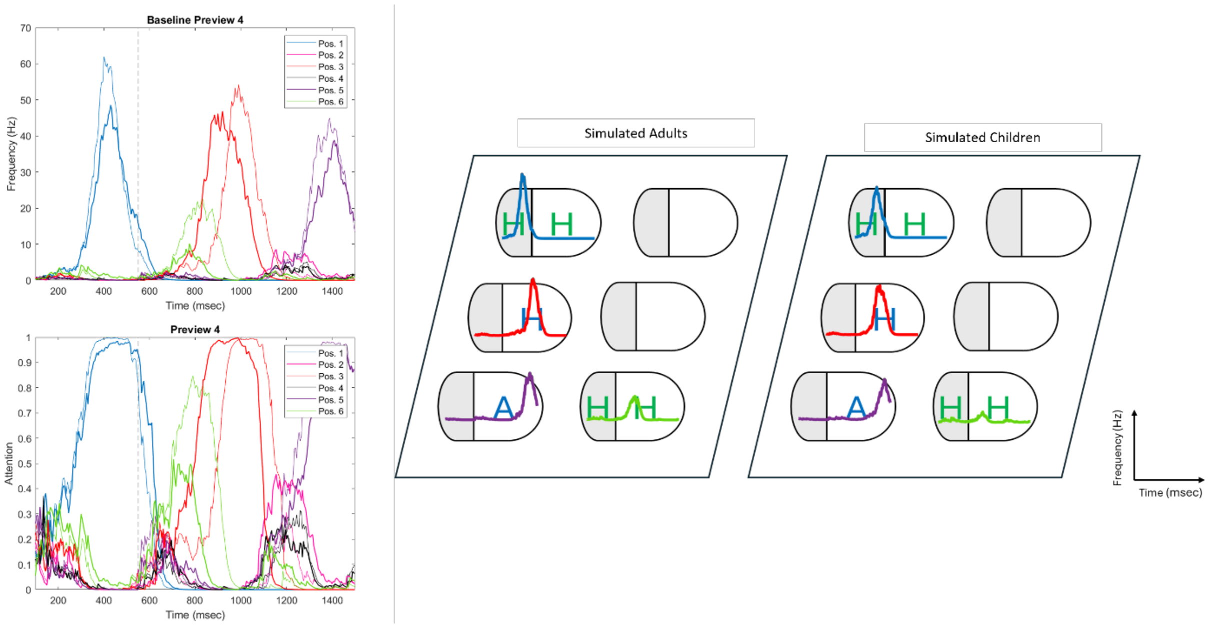
The aim of this computational modelling study was to investigate the mechanisms underlying children's ability to effectively allocate attention both across space and over time. Specifically, in the behavioural study of this chapter, children demonstrated a couple of key differences compared to adults. For one, children were generally slower and less accurate than adults, and this occurred across the single-feature, conjunction, preview and preview gap conditions. Furthermore, children were significantly less efficient (i.e., had steeper slopes) in the more effortful conjunction condition. Despite these difficulties, however, children were still able to use top-down attentional inhibition to suppress old items in preview condition as well as adults. Finally, although children were significantly worse than adults in the standard conjunction search, they performed similarly to adults in the preview gap condition. In this condition, although preview items are presented before the final display, the re-presentation of these items after the gap (at the same time new items onset) should offset the suppressive effects applied to these items. Therefore, at the time of the final display, search is essentially a conjunction search (Mavritsaki & Humphreys, 2016), and thus it follows that children would perform significantly worse than adults in this condition as well. However, this was not the case. These findings led to the hypothesis that four separate mechanisms contributed to children's performance in an independent manner, such that one neural difference contributed to one (and only one) behavioural difference: (1) weaker encoding of stimuli produces slower RTs and reduced accuracy; (2) reduced top-down expectancy for the target's features produces less efficient conjunction search; (3) increased active inhibition of preview items leads to a larger preview benefit; and (4) reduced temporal binding after the gap in the preview gap condition produces a larger preview gap benefit.

The first hypothesis tested was that weaker encoding of stimuli leads to the slower RTs and reduced accuracy. In the b-sSoTS model, visual information is encoded by the specific excitatory pools, of which there are six in each of the feature maps and in the location map. The strength of encoding here relies on the strength of the synaptic coupling between model neurons within a given specific excitatory pool. The coupling between these neurons is assumed to reflect the strength of the connections that occur between neurons a result of neuroplasticity. Neurons which fire in a correlated way, at an (almost) identical time are likely to encoding the same information, and thus their connection should be strong compared to neurons that fire in an uncorrelated way (Hebb, 1949). In the human brain, particularly in the primary visual cortex, neurons that encode the same information (e.g., lines of a specific orientation) are also in close spatial proximity (Cossell et al., 2015; Grill-Spector & Malach, 2004; Hubel & Wiesel, 1962). By envisioning these groups of neurons in the brain that all encode the same representation, one can better understand the notion of the specific excitatory neuron pools within the b-sSoTS model.

These reductions in the w_+ parameter did indeed simulate the longer RTs and lower accuracy rates observed in the children's real search data, in line with the hypothesis. Notably, however, this parameter change also produced the other differences in children's search that were originally hypothesized to be due to other mechanisms. For example, the effects of the reduced w_+ strength was particularly strong in the higher display size of the conjunction condition, leading to steeper conjunction efficiency slopes at 100.14 msec/item (compared to the 66.25 msec/item conjunction efficiency slopes in baseline b-sSoTS simulations; see Table 2.10). Importantly, while w_+ reductions led to worse performance in conjunction, performance actually improved in the two time-based attention conditions. In the preview condition, efficiency slopes became much closer to 0 (i.e., perfectly flat) at 2.98 msec/item (compared to the 9.97 msec/item baseline search slopes). In the preview gap condition, too, search slopes were more efficient at 53.26 msec/item, compared to the 77.50 msec/item search slopes in baseline. Accordingly, instead of reduced top-down expectancy to produce steeper conjunction search, increased active inhibition to produce more efficient preview search and decreased temporal binding to produce more efficient preview gap search – the best match for the children's data was found in a reduction of the w_+ parameter. These results thus demonstrate the wide-ranging effect of reduced synaptic strength in the developing brain.

Figure 2.8

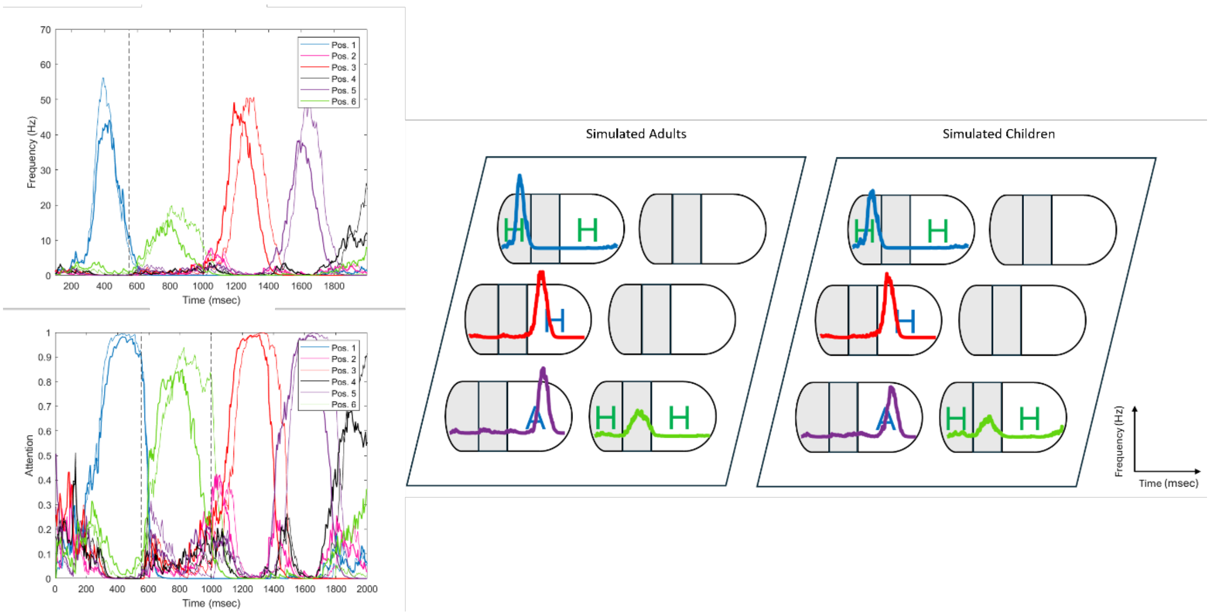
Spiking Activity in the Pools of the Location Map in the Preview Condition for Simulated Adults and Children



Note. On the right shows the spiking activity for each of the pools in the location map for adults (left) and children (right). The preview period is represented by the grey area, while the final search period is represented by the white area. The top left side shows the spiking activity for all pools in a combined graph. The bottom left shows the “attention” afforded to each of the items, which is determined by the contrast between spiking activity at the given position and the other positions in the map. For the graphs on the left side, simulated adults are represented by the thin lines while simulated children are represented by the thick lines. The reduced synaptic strength in the simulated children results in less activity across all positions. When applied to the preview condition, the reduced power of the preview distractor items allows the target to compete more easily, which produces efficient search.

Figure 2.9

Spiking Activity in the Pools of the Location Map in the Preview Gap Condition for Simulated Adults and Children



Note. On the right shows the spiking activity for each of the pools in the location map for adults (left) and children (right). The preview period is represented by the first grey area, the gap period is represented by the second grey area, and the final search period is represented by the white area. The top left side shows the spiking activity for all pools in a combined graph. The bottom left shows the “attention” afforded to each of the items, which is determined by the contrast between spiking activity at the given position and the other positions in the map. For the graphs on the left side, simulated adults are represented by the thin lines while simulated children are represented by the thick lines. The reduced synaptic strength in the simulated children results in less activity across all positions. When applied to the preview gap condition, the reduced power of the preview distractor items means that these items become fully suppressed before the final display, and this suppression is not as strongly offset by new items due to their reduced activity. This allows the target item to compete more easily, such that search in this condition is more efficient.

Rather than 4 mechanisms, each having a very specific effect, operating alongside each other at different points in time, the w_+ parameter has a widespread effect that evolves dynamically over time. This allows for this mechanism to have such different effects such that it results in less efficient search when attention is allocated to a particular location in space and more efficient search when attention is allocated to a particular moment in time. When all items appear simultaneously, such as they do in single-feature and conjunction, there is reduced firing for the target item, which means that it takes longer for it to gain strength over other competing distractor items (see Appendix Figure I.1). Furthermore, while the target was overall reduced in power, distractor items had a similar activation as baseline, thus leading to a decreased SNR. Accordingly, search was less efficient for the simulated children, and this was particularly true at display size 6 in conjunction, where the mean efficiency increased to approximately 610 msec (compared to ~ 534 msec in simulated adults). This loss of efficiency ultimately contributed to the steeper conjunction slopes in simulated children (see Figure 2.7).

In the preview and preview gap conditions, however, a different pattern emerges. First, it's important to note that although preview distractor items are eventually suppressed, these items initially compete for selection, and one of the items is attended (Mavritsaki et al., 2011). Indeed, preview items are effectively suppressed as a direct result of this initial capture, as higher firing rates allow more calcium to enter the cell. This increased intracellular calcium concentrations results in a faster time course for frequency adaptation compared to a low firing rate (Mavritsaki et al., 2011). In the reduced synaptic strength model, the firing rate for the attended distractor is reduced, and this does result in a lower level of intracellular calcium, there is actually little effect on the time course of frequency adaptation (see Appendix Figure I.2). Accordingly, since the initial distractors have less power and are still able to be suppressed through active and passive inhibition during the preview display (and gap display), these preview items end up competing less at the final display, thus allowing the target to win more easily (see Figure 2.8). More specifically, in the preview gap condition, this suppression of preview items continues in the final display even when old items re-appear after the gap (see Figure 2.9). The reduced firing rate from weaker synaptic strength in specific pools means that the additional activation used to counteract suppressive effects in the simulated adults is not as effective (Mavritsaki & Humphreys, 2016).

2.3 General Discussion

This chapter presents the first behavioural and computational modelling study. First, a behavioural study was conducted in which 7-to-12 year old children and adults were compared on four visual search conditions in order to examine how visual marking and temporal binding might differ in middle- to late-childhood. Here, the idea was that, since there is extensive literature detailing top-down differences during development generally, this might contribute to worse visual marking (i.e., active suppression of irrelevant distractors) in the preview condition. While conjunction search (which was used as a condition to identify preview and preview gap benefits here) also requires top-down attention, differences this age group have not always been observable at the behavioural level in past research (Donnelly et al., 2007; Mason et al., 2003, 2004). Therefore, it was expected that here, too, conjunction search slopes would be similar to adults while preview and preview gap search slopes would differ significantly.

However, the opposite occurred. Conjunction search was less efficient in children compared to adults, while search was similar between groups in preview and preview gap. Interestingly, while both of these results have occurred separately, they have not yet been reported as occurring together (Mason et al., 2003, 2004; Merrill & Conners, 2013; Merrill & Lookadoo, 2004; Zupan et al., 2018). This is particularly notable, as it goes against logic in that, if top-down attention differences arise in conjunction search, it would make sense that these differences arise again in the preview and preview gap conditions. Even if visual marking and temporal binding were adult-like by this age, top-down expectancy of the target item's features still contributes to effective search in preview and preview gap (Braithwaite & Humphreys, 2003; Mavritsaki et al., 2011). These top-down differences should have been particularly observable in the preview gap condition, as the suppressive effects of active and passive inhibition are offset, such that, when old items re-appear alongside new items after the gap, the search is effectively the same as a standard conjunction search (Mavritsaki & Humphreys, 2016). In addition to steeper conjunction slopes, children also demonstrated significantly longer RTs and reduced accuracy compared to adults, suggesting less efficient behaviour overall. This, either alone or in addition to top-down differences, could account for the particularly high conjunction slopes in children (Dockstader et al., 2012; Luna et al., 2015; Scantlebury et al., 2014; Uhlhaas et al., 2010). However, like top-down differences, it seems logical that this too would have affected preview and preview gap search.

Accordingly, from the behavioural results, four hypotheses were generated: (1) weaker encoding of stimuli produces slower RTs and reduced accuracy; (2) reduced top-down expectancy for the target's features produces less efficient conjunction search; (3) increased active inhibition of preview items leads to a larger preview benefit; and (4) reduced temporal binding after the gap in the preview gap condition produces a larger preview gap benefit. Next, using the b-sSoTS model, a neurocomputational model capable of performing these four visual search conditions, these hypotheses were evaluated. First, the baseline version of the b-sSoTS model was used to simulate the observed pattern of search slopes obtained by real adults. Then, the synaptic strength was reduced to simulate weaker encoding in children. This was followed by reductions in strength of top-down expectancy (applied by extra input to the pools representing the target's features), then both reduced synaptic strength and top-down expectancy together. From this, it was shown that reduced synaptic strength alone was able to provide a qualitative account for the results detailed in the behavioural study. This is in line with previous computational modelling work that has shown improvements in efficient behaviour (particularly in working memory tasks) can be attributed to increased synaptic strength over development (Edin et al., 2007; Macoveanu et al., 2006). This new version of the model was labelled the b-sSoTS-c model, where the “c” refers to “child.”

One important aspect to consider here is that the parameter changes to reduce synaptic strength does not provide a full account of the differences in the developing brain. Indeed, there are other notable mechanisms of development that also contribute to increased efficiency and improvements in top-down cognitive control. For one, improvements in efficiency require not only an increase in the signal, but a reduction in noise (Luna et al., 2015). In the human brain, one way this this is implemented (other than increases in synaptic strength) is through synaptic pruning (Averbeck, 2022; Fleming & McDermott, 2024; Lucrezia et al., 2023). Together, these improvements in the efficiency allow neural responses to have greater contrast and higher specificity (Edin et al., 2007). Another mechanism that contributes to improvements in cognitive control is the effect of increased myelination (Mabbott et al., 2006; Raja et al., 2022; Scantlebury et al., 2014). Indeed, as myelination increases the integrity of white matter pathways between regions, the speed of neural transmission increases while still maintaining a strong SNR (Bells et al., 2017; Lebel & Deoni, 2018). Finally, complex changes in dopaminergic and GABAergic transmission also contribute to the increase in SNR through excitatory and inhibitory neural activity (Caballero et al., 2016; Delevich et al., 2021; Flores-Barrera et al., 2014; Tarazi & Baldessarini, 2000; Tseng & O’Donnell, 2007). The role of these mechanisms on behavioural improvements in children have previously been explored using neurocomputational models (Edin et al., 2007; Macoveanu et al., 2006). Future work with b-sSoTS could potentially make additional alterations in the model to explore the developing brain more fully. Here, by using the b-sSoTS model to explore the hypotheses derived at the behavioural level, the role of synaptic strength in development is highlighted, and thus provides an account of how differences at the neural level can contribute to higher-level behaviour, even in unexpectedly contradictory ways.

2.4 Chapter Summary

While a wide body of research has been dedicated to revealing the mechanisms of selective visual attention in the stable adult state, much less is known about these mechanisms in the developing brain (Kim & Kastner, 2019; Lynn & Amso, 2023). As the integrity of selective visual attention in childhood is likely to contribute substantially to the development of numerous higher-level executive functions, it is important to understand how this function emerges in the typically developing brain (Bouzabou et al., 2021; King & Markant, 2020; Markant et al., 2015). This could ultimately provide more insight into how selective attention differences may contribute to behaviour in certain neurodevelopmental disorders like ADHD. In the present chapter, a behavioural study first showed that, compared to adults, 7- to 12-year-old children were overall slower and less accurate across four visual search tasks. Difficulties in efficient top-down control were evident through steeper slopes in the conjunction condition. However, these issues did not appear to extend into preview and preview gap search. To further investigate how this pattern of behaviour came about in children, the b-sSoTS model was then used to simulate children's search. These results showed that, instead of reductions in top-down attention, reduced synaptic strength in neurons encoding for stimuli was able to account for the less efficient search over space and adult-like search over time. The changes made to the model here yielded a new version, the b-sSoTS-c model. In the next chapter, a similar behavioural-modelling format is used, comparing children with low and high levels of ADHD symptoms. For the computational modelling portion of the next chapter, any parameter changes to simulate ADHD behaviour are made to the b-sSoTS-c model identified here.

Chapter 3: Exploring Time-Based Attention in Children with and without ADHD

In the previous chapter, a combination of behavioural and modelling methods provided insights into age-related differences in the mechanisms underlying visual attention. Specifically, it was shown that changes in synaptic strength contributes to differences observed in children's visual search performance. The parameter changes applied thus provide a baseline "child" version of the b-sSoTS model. In the present chapter, this combined methods approach is again used to examine ADHD-related differences in time-based attention. This chapter begins with a review of how ADHD-related differences are likely to contribute to differences in selective visual attention. Following this, the chapter will be divided into two, with the behavioural study reported before the computational modelling study. First, typically developing (TD) children with low and high levels of ADHD (determined by Conners 3 ADHD Index scores) are compared on preview and preview gap search. Indeed, ADHD-related differences in top-down control may affect visual marking (O'Conaill et al., 2015; Skalski et al., 2021; Wang et al., 2016). Furthermore, weaker connectivity and overall reduced neural efficiency could contribute to differences in temporal binding (Gonen-Yaacovi et al., 2016; Lin et al., 2015; Soman et al., 2023b). The results from the behavioural study are reported. In discussing these behavioural results, hypotheses concerning ADHD-related differences in attention are generated. In the second study of this chapter, these hypotheses are then tested using a neurocomputational model; specifically, the b-sSoTS-c model produced in the previous chapter. The overall outcome of the chapter demonstrates how new insights into ADHD can be uncovered when behavioural and modelling methods are combined.

3.1 Behavioural Study

3.1.1 Behavioural Background

As discussed in section 1.2, ADHD is a common neurodevelopmental disorder characterised by inattention, hyperactivity and impulsivity (APA, 2013). ADHD is considered to be a highly complex and heterogeneous disorder (Posner et al., 2020; Luo et al., 2019), as affected individuals vary substantially in their genetic risk (Faraone & Larsson, 2019), environmental contribution (Sonuga-Barke & Harold, 2018), and profile of neurocognitive impairments (Pievsky & McGrath, 2018). Children with ADHD demonstrate differences in working memory (Ramos et al., 2020), response inhibition (Bonham et al., 2021), decision-making (Dekkers et al., 2016), among other cognitive functions (Pievsky & McGrath, 2018). Ultimately, this highly prevalent and impairing disorder is associated with adverse outcomes that negatively impact affected individuals in terms of educational attainment (Fleming et al., 2017; Klein et al., 2012), interpersonal relationships and self-esteem (Harpin et al., 2016) as well as overall quality of life (Quintero et al., 2019). Accordingly, there is a distinct need to cultivate a deeper understanding of precisely what specific difficulties characterise ADHD, as well as how these difficulties arise.

While the precise neurobiological basis of ADHD remains poorly understood, neuroimaging studies have demonstrated substantial differences in the PFC, a key site in cognitive control and attention (Friedman & Robbins, 2022; Martinez-Trujillo, 2022). Indeed, children with ADHD have been shown to have reduced volume (Almeida et al., 2010; Bush et al., 2005; Hoogman et al., 2019), as well as reduced functional activity in the PFC (O'Conaill et al., 2015; Rubia et al., 1999; Skalski et al., 2021). Furthermore, studies indicate reduced functional connectivity between the PFC and other association cortices, evidenced by disorganised white matter tracts between these areas in children with ADHD (Dipnall et al., 2023; Makris et al., 2008; Soman et al., 2023b; Thomson et al., 2022). Indeed, much of the recent research investigating the neurobiological underpinnings of ADHD has focused on altered functional connectivity (Chen et al., 2019; Gao et al., 2019; Lin et al., 2015; Soman et al., 2023b). For example, Chen et al. (2019) compared typically developing children with drug-naïve children with ADHD to examine differences in functional connectivity using graph theory to analyse resting-state fMRI data. In addition to neuroimaging, participants also completed the Stroop colour-word task to assess cognitive control. The authors found that children with ADHD have weaker integration and segregation within regions of the frontal cortex, indicative of less efficient communication. Furthermore, reduced network efficiencies were correlated with worse top-down control, as measured by performance on the Stroop test (Chen et al., 2019). Taken together, evidence indeed supports of the notion that differences in the structure and function of the PFC likely contribute to symptoms and impairments in ADHD.

In addition to this neuroimaging data, the high efficacy of pharmaceutical drugs in the treatment of ADHD also provides important insights into the potential mechanisms of the disorder. As discussed in section 1.2.1, ADHD medications (both stimulants and non-stimulants) exert their beneficial effects by raising catecholamine neurotransmission within the PFC (Spencer et al., 2015; Spencer & Berridge, 2019). This means that these medications increase DA and NE levels within the PFC, which in turn allows for the reduction of irrelevant noise and for the increase of relevant signals (i.e., improved SNR; Kroener et al., 2009; Moore & Zirnsak, 2017; Pertermann et al., 2019). SNR is important for efficient neural communication and transfer of information across the brain, and it is also particularly important to working memory functions (Arnsten et al., 2024; Cools & Arnsten, 2022; Hauser et al., 2016). Indeed, in order for items to be held online in WM, delay cells representing the stimuli must fire in the absence of visual stimulation (Arnsten et al., 2010; Goldman-Rakic, 1995). Thus, a high SNR supports strong representations in working memory, and these representations, in turn, produce robust top-down attention biases (Panichello & Buschman, 2021). Collectively, both neural and network level evidence suggests that children with ADHD are likely to experience difficulty in selective attention as well as other tasks that rely on PFC involvement.

At the behavioural level, ADHD-related differences in selective attention have been demonstrated in the spatial realm using Posner orienting tasks and conjunction search (Mullane & Klein, 2008; Nigg et al., 1997; O’Conaill et al., 2015; Shalev & Tsal, 2003; Skalski et al., 2021; Tsal et al., 2005), although not consistently so (Hazell et al., 1999; Mason et al., 2003, 2004; Roberts et al., 2018; see section 1.2.1). In contrast to location- and feature-based attention, much less is known about how ADHD affects time-based attention. Using preview search to examine the top-down suppression of old distractor items (i.e., visual marking) in ADHD, Mason et al. (2003) found that children with ADHD did not differ significantly from TD children. Both groups were able to generate preview benefits, with search more efficient than the typical conjunction task (although not as efficient as single-feature; Mason et al., 2003). In a follow-up study, Mason et al. (2004) found again that both groups were able to generate a robust preview benefit (here, as efficient as single-feature).

In their follow-up study, Mason et al. (2004) also used a preview search condition that incorporated singleton final display to examine how the suppressive effects of visual marking carry over from preview to final displays. In one condition, a preview display consisting of green vertical rockets was displayed before the remaining items - red horizontal rocket distractors, one singleton green vertical rocket, and the red vertical rocket target appeared in the final display. A previous study using this singleton distractor preview condition found that adults experience less interference (i.e., faster RTs) in this condition due to the “carry-over” inhibition of preview-item features (Olivers & Humphreys, 2003). Surprisingly, both ADHD and non-ADHD children experienced *more* interference (i.e., slower RTs) in this condition. The authors proposed that children may find the top-down control needed to successfully mark old items demanding, thus leading to a loss of the effortful inhibition in the final display. In a second condition, the same preview display was followed by red horizontal rocket distractors and a green vertical rocket target. Similar to adults, children’s performance was slower in this singleton target condition (Olivers & Humphreys, 2003). However, children with ADHD were significantly slower in this condition compared to their non-ADHD peers. The authors proposed children with ADHD struggle to effectively manage their top-down control across time in order to switch from a negative set (e.g., inhibition of old items) to a positive one (e.g., selection of the target; Mason et al., 2004).

In a third and final follow-up study by Mason et al. (2005), the authors used a rapid serial visual presentation (RSVP) task to further understand how children with ADHD process distractors over time. They found that both children with ADHD and their non-ADHD peers experienced attentional capture by a singleton distractor that shared its colour (red) with the target item. However, unlike TD children, children with ADHD were involuntarily captured (i.e., experienced an attentional blink) by a singleton distractor that did not share its colour with the target item. The authors proposed that these results also demonstrated that children with ADHD experience difficulty in the ability to maintain top-down control, particularly when required to do so over time (Mason et al., 2005). Thus, in addition to previous literature that indicates children with ADHD struggle to allocate attention effectively across space (Guo et al., 2023; Karatekin & Asarnow, 1998; Skalski et al., 2021; Tsal et al., 2005; Wang et al., 2016), these three studies by Mason et al. indicate this difficulty also extends to the temporal realm. Furthermore, these studies demonstrate that while children with ADHD are able to generate a preview benefit, they are likely impaired in some of the key functions that allow for efficient visual marking. As such, further research is needed to understand how time-based attention operates in ADHD.

Differences may not always reveal themselves through behavioural measures, and neuroimaging may uncover differences at the neural level in the absence of overt behavioural differences. Indeed, EEG-imaging of visual search tasks has shown that children with ADHD have reduced P3a and N2pc amplitudes compared to their TD counterparts, reflecting less efficient orienting and allocation of attentional resources to target items (Arnett et al., 2023; Guo et al., 2023; Salomone et al., 2020; Wang et al., 2016, 2017). Furthermore, it's been shown that these neural indices become normalised with the administration of psychostimulant medication (Guo et al., 2023), suggesting that these differences likely involve catecholamine neurotransmission within the PFC. In addition to the P3 and N2pc ERPs, Wang et al. (2016) also showed that children with ADHD had a smaller P_D amplitude compared to their TD counterparts, indicating weaker suppression of irrelevant distractor items. ADHD-related differences in selective attention have also been demonstrated using fMRI during visual search tasks. For instance, O'Conaill et al. (2015) showed that individuals with ADHD show less overall activation than TD children in conjunction search, particularly in the TPJ. These neural indices of attention, particularly the N2pc and the P_D, have been found in ERP studies in preview search task (Berggren & Eimer, 2018). Furthermore, it has been shown that the TPJ is a key site in the computation of saliency in preview search (Mavritsaki et al., 2010, 2011). Accordingly, these findings indicate that ADHD-related differences in time-based attention very likely exist, although may not always be observable at the behavioural level.

Indeed, the previous literature supports the idea that children with ADHD may experience difficulties in the top-down suppression of old preview items (Berggren & Eimer, 2018; Mason et al., 2004, 2005; Wang et al., 2016). This notion also appears to be heavily supported by neuroimaging evidence that shows children with ADHD have weaker functional activity in the areas that support top-down control (i.e., the PFC and its networks), and weaker P_D amplitudes, which have been shown to occur during the preview period (Berggren & Eimer, 2018). A second mechanism involved in time-based attention, temporal binding, has yet to be examined in ADHD. Temporal binding relies on fast and efficient communication between neurons encoding the to-be-bound information (Singer, 2015, 2021). As discussed above, a large body of research has been dedicated to examining how connectivity differs in the ADHD-brain, and it’s been shown that these individuals demonstrate alterations in small-worldedness (Chen et al., 2019; Jiang et al., 2019; Lin et al., 2015; Wang et al., 2009; Wang et al., 2020; Wu et al., 2023). Small-worldedness in neural networks means that there is highly efficient communication between nodes despite anatomical distance (Bullmore & Sporns, 2012). Accordingly, alterations in connectivity in the ADHD brain may contribute not only to differences in top-down control, but also in more bottom-up functions, like temporal binding.

Aims of Study. The present study uses preview and preview gap search to identify ADHD-related differences in two time-based attention functions, visual marking and temporal binding. While the previous work by Mason et al. (2003, 2004, 2005) demonstrated that children with ADHD are able to generate a sufficient preview benefit, these studies also indicate that the mechanisms underlying this ability may differ somewhat in children with ADHD. This is further supported by other neuroimaging evidence demonstrating differences in the neural signatures of these attentional functions (Guo et al., 2023; O'Conaill et al., 2015; Wang et al., 2016). Accordingly, the present study aims to: (1) determine whether the results of the Mason et al. (2003) study are replicable; (2) further investigate whether differences in temporal binding may affect preview search in ADHD; and (3) establish a dataset with these groups to be subsequently used in simulations with the b-sSoTS-c model (see 3.2).

ADHD is a dimensional disorder, with symptoms and impairments appearing in the general population (Asherson & Trzaskowski, 2015; Larsson et al., 2012). Accordingly, in the present study, parent responses on the Conners 3 ADHD Index (Conners 3AI; Conners, 2008) were used in TD children to distinguish between children with low and high ADHD symptoms, according to their Conners 3AI scores. These two groups were matched on age, intelligence and academic achievement using WISC-IV and WRAT-4 subtests (see Table 3.1). Children with ADHD demonstrate difficulties in the top-down control of attention (Mullane & Klein, 2008; O'Conaill et al., 2015; Skalski et al., 2021; Wang et al., 2016). Therefore, it is hypothesized that these difficulties may contribute to reduced visual marking of old distractor items and thus increased interference with new items during search. If visual marking is indeed reduced in the high ADHD group, this would be evident in a reduced preview benefit compared to their low ADHD peers.

Although the ADHD literature often tends to focus on differences in more effortful, directed functions of attention, these individuals may also demonstrate differences in bottom-up attention, such as the ability to efficiently bind information by common onset. Therefore, it is further hypothesized that ADHD-related differences will contribute to reduced temporal binding. As previously discussed, proper temporal binding results in the loss of the preview benefit in the preview gap condition. In healthy adults, this is evident in preview gap slopes that are as steep as conjunction slopes (Mavritsaki & Humphreys, 2016; Watson & Humphreys, 1997). If temporal binding is reduced in the high ADHD group, this would be evident a higher preview gap benefit compared to the low ADHD group.

3.1.2 Behavioural Method

Participants. A total of 61 children were recruited through six primary and secondary schools in Birmingham, UK. Schools were contacted through either letter, email, or phone to the school's head teacher. Prior to any contact with students, the head teacher's written informed consent was obtained (see Appendix B). Upon consent from the head teacher, all students in Years 4, 5, and 6 (between 7- and 12-years old) were offered a participant information sheet (see Appendix A) and consent form for their parents or guardians (see Appendix B). Prior to the experiment, each child also provided their written consent to participate in the study. In exchange for their participation, students received a Certificate of Completion (see Appendix C). Ethical approval for this study was granted by the Business, Law, and Social Sciences Ethics Committee at Birmingham City University.

Previous studies of preview search in children with and without ADHD (Mason et al., 2004, 2005; Mason et al., 2003) compared a group of thirty children with ADHD to a group of thirty age- and IQ-matched TD children. In the present study, the high Conners 3AI group consisted of 28 participants whose scores on the Conners 3 ADHD Index (Conners, 2008) indicated a high level of ADHD symptoms. Within this high Conners 3AI group, there were 18 (64.30%) males and 10 (35.70%) females. The mean age was 9.35 years (*SD* = 1.16). The low Conners 3AI group comprised of 33 participants whose scores on the Conners 3AI indicated a low/average level of ADHD symptoms. For the low ADHD group, there were 12 (36.40%) males and 21 (63.60%) females. The mean age was 9.68 years (*SD* = 0.91). All participants reported having normal or corrected-to-normal vision. Exclusionary criteria included a history of serious mental or physical medical conditions, such as epilepsy. A final exclusionary criterion was a previous diagnosis of ADHD and/or previous psychostimulant use. This was to ensure that there was no previous exposure to ADHD treatment, which has been shown to have both short- and long-term effects on brain structure and function (Kowalczyk et al., 2019; Mizuno et al., 2022; Schweren et al., 2013). As no participant met these exclusionary criteria, none were excluded from the study.

To ensure there were no significant differences between groups in age or intelligence, a one-way ANOVA was conducted. There was no significant difference between groups on age, $F(1, 60) = 1.64$, $p = .205$, $\eta^2 = .03$, WISC-IV DQ scores, $F(1, 60) = 0.69$, $p = .408$, $\eta^2 = .01$, WRAT-4 Read subtest scores, $F(1, 60) = 0.90$, $p = .2346$, $\eta^2 = .02$, or WRAT-4 Spell subtest scores, $F(1, 60) = 0.74$, $p = .392$, $\eta^2 = .01$. Table 3.1 shows these results.

Table 3.1

Means and Standard Deviations on Age and Intelligence Measures for Groups

Measure	Low Conners 3AI	High Conners 3AI	*p*
Age (in months)	116.21 (10.87)	112.14 (13.94)	.205
WISC-IV DQ	98.31 (13.11)	101.07 (12.62)	.408
WRAT-4 Read	107.64 (11.90)	110.25 (9.07)	.346
WRAT-4 Spell	117.55 (13.85)	120.54 (13.08)	.392

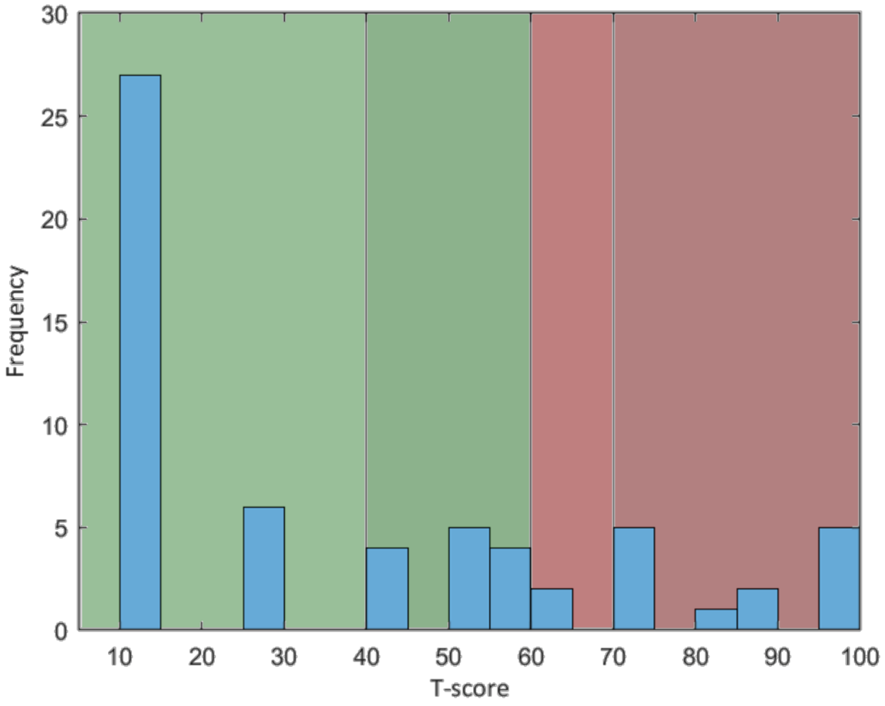
Note. Standard deviations are presented in parentheses. WISC-IV DQ = Wecshler's Intelligence Scale for Children (4th Edition) Deviation Quotient; WRAT-4 Read/Spell = Wide Range Achievement Test (4th Edition) Reading/Spelling subtest.

Materials. ***Conners 3 ADHD Index.*** The Conners 3 ADHD Index (Conners 3AI; Conners, 2008) is a standalone index form used to predict an individual's membership into either ADHD or general population groups. Parents were asked to complete this 10-item scale, in which they consider the frequency and accuracy of statements that describe their child's behaviour within the past month (see Appendix J). Answers range from 0 to 3, where 0 = Not true at all (Never, Seldom); 1 = Just a little true (Occasionally); 2 = Pretty much true (Often, Quite a bit); and 3 = Very much true (Very Often, Quite Frequently). Interrater reliability correlations for the Conners 3AI standalone index form are strong, with a mean adjusted *r* = .84 for the general population. Internal consistency (α = .82) is also good for the general population.

The 10 items of the Conners 3AI standalone index form are scored in two distinct methods, yielding a *T*-score and a probability score (Conners, 2008). For the first of these, the raw score of the items are summed and then converted into a *T*-score, which has been normalised for the participant's age and gender. *T*-scores can fall into one of four categories that depict the level to which the participant’s responses are similar to youth with ADHD for their age/gender (see Appendix Table L.1), with higher *T*-scores indicating a greater presence of ADHD symptoms. Previous research has used this *T*-score method in samples of typically developing youth to examine the relationship between continuous variations in ADHD traits and variables of interest, such as neuronal markers of salience processing (Hilger et al., 2020), volume of subcortical structures (Connaughton et al., 2024), and medication adherence (Silverstein et al., 2023). Here, in adherence with the Conners 3 manual, the Conners 3AI *T*-score is considered alongside the probability score. Using the same 10 item scale, the probability score is computed through a transposed scoring system, which yields a probability between 11-99%. This probability score indicates the percentage of time that the score occurred in clinically diagnosed cases of ADHD as opposed to non-cases (Conners, 2008). Probability scores fall into one of six categories (see Appendix Table L.2). The distribution of *T*-scores and probability scores for the present study are shown in Figure 3.1 and Figure 3.2, respectively.

Figure 3.1

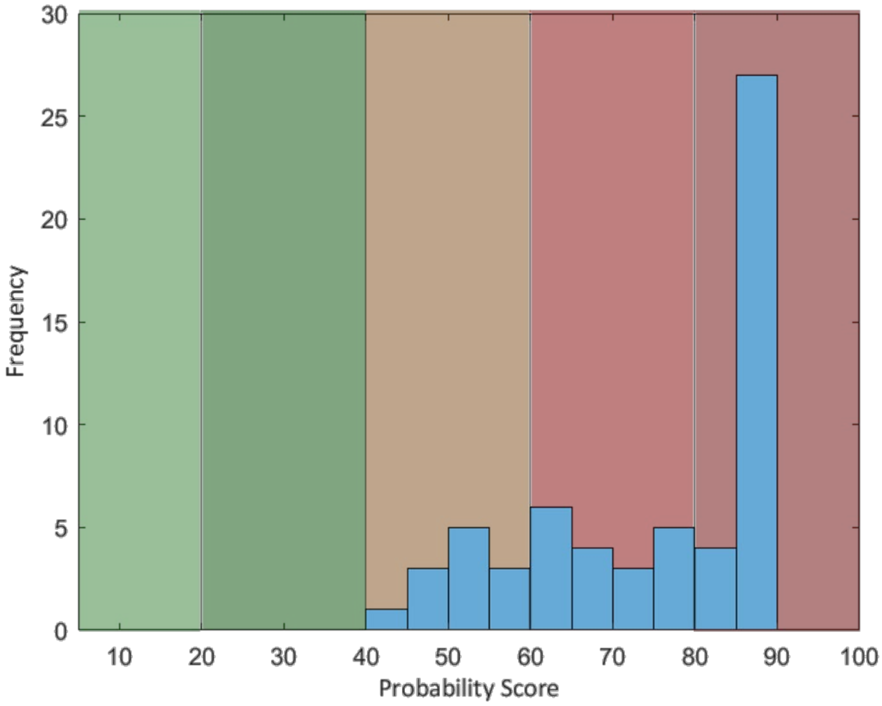
Frequency Distribution of Conners 3AI T-scores



Note. The first score of the C3AI standalone index is the *T*-score. *T*-scores less than 40 are interpreted as a low score (light green shading); *T*-scores between 40 and 59 indicate an average score (darker green shading); scores between 60 and 69 are interpreted as an elevated score (lighter red shading); and *T*-scores equal to or greater than 70 are very elevated scores (see Appendix Table L.1; Conners, 2008).

Figure 3.2

Frequency Distribution of Conners 3AI Probability Scores



Note. In addition to the C3AI *T*-score, the C3AI standalone index also considers a probability score. Scores below 20% indicate a very low probability of ADHD (light green shading); scores between 20 and 39 indicate a low probability of ADHD (darker green shading); scores between 40 and 60 are interpreted as a borderline probability of an ADHD diagnosis (orange shading); scores between 61 and 79 indicate a high probability (lighter red shading); and scores above 80 indicate a very high probability of an ADHD diagnosis (darker red shading; see Appendix Table L.2; Conners, 2008).

Importantly, there were often discrepancies between an individual's *T*-score and probability score. Accordingly, group identity for each participant here was determined using the Conners 3 manual guidelines (see Table 3.2) and this process was advised and overseen by a clinician.

Table 3.2

Conners 3AI Interpretation Guidelines

Discrepancy Type	Probability Score	*T*-score	Interpretation Guidelines
Both scores are elevated	≥ 61%	≥ 60	The responses are very similar to those describing youth with ADHD. More of the key features of ADHD are present than expected for this age and gender.
Borderline probability score; *T*-score is elevated	51-60%	≥ 60	The responses are somewhat similar to those describing youth with ADHD. More of the key features of ADHD are present than expected for this age and gender.
Only *T*-score is elevated	≤ 50%	≥ 60	The responses are more similar to those describing youth in the general population than those describing youth with ADHD, but key features of ADHD are occurring in excess of what is typical for that youth's age and gender. The assessor may wish to consider alternate explanations for why the *T*-score could be elevated.
Only probability score is elevated	≥ 61%	≤ 59	The responses are very similar to those describing youth with ADHD, but key features of ADHD are at (or below) developmental expectations for that age and gender. Although the youth's responses are like those of youth with ADHD, the current presentation is not atypical for this age and gender. The assessor should give careful consideration as to whether the symptoms are present in excess of developmental expectations.
Borderline probability score; *T*-score is average/low	51-60%	≤ 59	The responses are somewhat similar to those describing youth with ADHD, but any key features of ADHD that are present are at (or below) developmental expectations for that age and gender.
Both scores are average or below	< 50%	≤ 59	The responses are more similar to those describing youth in the general population than those describing youth with ADHD. Any key features that are present are at or below developmental expectations for that age and gender.

Note. Top two (red shading) indicate the child was automatically assigned to the High Conners 3AI group. Participants whose score fell in the middle two (orange shading) were analysed on a case-by-case basis, with the top one more likely to be assigned to the high Conners 3AI group, and the lower one to be assigned to the low Conners 3AI group. Scores that fell into the bottom two categories (green shading) were automatically assigned to the low Conners 3AI group. From *Conners 3rd Edition*, by C.K. Conners, 2008, p. 83. Copyright 2008 by Multi-Health Systems, Inc.

Weschler's Intelligence Scale for Children, 4th Edition (WISC-IV). The Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV; Wechsler, 2003) is a psychometric test used to assess cognitive abilities of children aged between 6- and 16-years of age. In the present experiment, due to time limitations, Sattler's (1982) recognised short form (updated for the WISC-IV) was used. The measure of estimated IQ generated by this short-form is determined by standardised data and a formula that considers subtest unreliability (Sattler, 1982). The procedure used to calculate the deviation quotients for the short form here is detailed in Appendix K. Four subtests were used - Block Design, Vocabulary, Similarities, and Picture Completion. This variation of the Sattler's (1982) short form was also used in previous investigations of preview search in children with and without ADHD (Mason et al., 2003, 2004, 2005).

Wide Range Achievement Test, 4th Edition, (WRAT-IV). The Wide Range Achievement Test, 4th Edition (WRAT-4; Wilkinson & Robertson, 2006) is a commonly used measure of basic academic skills for individuals aged 5 and over. It consists of four subtests, including Word Reading, Sentence Comprehension, Spelling and Math Computation. Similar to previous studies of preview search in ADHD (Mason et al., 2003, 2004, 2005), the present study used the Word Reading and Spelling subtests only. The WRAT-4 has high levels of internal consistency, ranging from .92 to .98.

Stimuli and Equipment. The experiments were run using custom software written OpenSesame version 3.3 (Mathôt et al., 2012), which recorded each participant's scores. Experimental software ran on a Lenovo ThinkPad Yoga 12 laptop computer with an Intel Core i5 graphics card. Stimuli were displayed on a 12.5" digitized LCD screen 1920 x 1080 pixels, running at 60 Hz. Stimuli were viewed from approximately 50 cm. In all conditions, the target items were always a blue [RGB = 0, 0, 225] letter H. Distractor items were green [RGB = 0, 128, 0] letter Hs and blue letter As.

Design. The design was a 2 (group) x 4 (condition) x 3 (display size) mixed design. Group was a between-subjects factor with two levels (low Conners 3AI or high Conners 3AI). Condition was a within-subjects factor with four levels (single-feature, conjunction, preview or preview gap). Display size was also a within-subjects factor with three levels. For single-feature, the display sizes were 2, 4 or 8. For conjunction, preview and preview gap, the display sizes were 4, 8 or 16. Mean RTs and accuracies were calculated for each participant, condition, and display size.

Procedure. The visual search task procedure here was identical to that described in the previous chapter (see section 2.1.2 and Figure 2.1). All children were tested at their school's campus during a typical school day. Each school was asked to provide a quiet room with a table and chairs for children to be tested individually by the researcher. To provide minimal interruption to student's daily class schedule, the experiment was divided into two sessions. The visual search task (which was completed in the first session) lasted approximately twenty to thirty minutes. Participants were required to complete the search task by locating a blue letter "H" (target) among distractors. On each trial, they were to indicate whether the target was to the left or right of a white fixation cross. If the target was to the left of the fixation cross, participants were instructed to press the "q" key on a standard keyboard. If the target was to the right of the fixation cross, participants were instructed to press the "p" key. Participants completed 240 trials each, split evenly across the four conditions to give 60 trials in each condition. Within each condition, trials were again evenly split to give 20 trials for each display size. Each condition began with 5 practice trials. Conditions were blocked and followed the same sequence of single-feature, conjunction, preview, and preview gap for each participant. Participants were told to respond as quickly and accurately as possible. No feedback was given for either correct or incorrect responses. The WISC-IV and WRAT-IV were then completed on a different day. The full experimental procedure took approximately 60 to 90 minutes.

Data Analysis. In cases where Mauchley's test had indicated that the assumption of sphericity was violated, the Greenhouse-Geisser correction was used when estimates of sphericity were less than 0.75. When estimates of sphericity were greater than 0.75, the Huynh-Feldt correction was used. RTs were sorted for each participant, condition, and display size (see Table 3.3). Mean correct RTs (in msec) were calculated for each participant. Responses were excluded from analysis if they were (1) incorrect, (2) below 200 msec, or (3) more than 3 standard deviations above or below the individual's overall mean for a given condition and display size (in line with previous studies that have examined ADHD using preview search; Mason et al., 2003, 2004). Accuracy rates reflect the number of correct trials (out of 60, see above) for each participant, condition and display size (see Table 3.4). The RT-display size functions were calculated using the display sizes 4, 8 and 16 for all conditions (see Table 3.5; see Watson & Humphreys, 1997). Mean RTs and accuracy rates were also combined to create an efficiency index (mean RT/accuracy) so that accuracy would be considered alongside latency (Townsend & Ashby, 1983). Notably, this efficiency index is important for comparing these behavioural results with the computational modelling results in the next part of this chapter. Here, since accuracies are relatively high (lowest accuracy at 93.32%), the efficiency results do not differ from the pattern of results that occur with mean RT.

Table 3.3

Mean RTs for Low and High Conners 3AI Groups in Each Condition and Display Size

Condition	Low Conners 3AI		High Conners 3AI	
	Mean	*SD*	Mean	*SD*
Single-feature 2	853.00	246.08	945.92	277.87
Single-feature 4	934.68	267.60	1000.92	305.95
Single-feature 8	1004.69	293.13	1128.52	305.46
Conjunction 4	1082.68	304.29	1290.28	434.12
Conjunction 8	1301.99	347.42	1463.93	407.69
Conjunction 16	1650.76	405.72	1896.18	617.67
Preview 4	945.29	278.28	1035.90	341.55
Preview 8	1037.07	331.58	1170.38	369.99
Preview 16	1175.03	346.86	1390.98	553.68
Preview gap 4	988.79	278.83	1175.88	438.43
Preview gap 8	1154.67	365.75	1275.45	343.57
Preview gap 16	1439.11	421.11	1567.93	481.26

Table 3.4

Mean Accuracy Rates for Low and High Conners 3AI Groups in Each Condition and Display Size

Condition	Low Conners 3AI		High Conners 3AI	
	Mean	*SD*	Mean	*SD*
Single-feature 2	94.70	6.24	93.57	5.91
Single-feature 4	93.48	5.23	93.04	5.98
Single-feature 8	94.70	5.72	92.32	5.35
Conjunction 4	93.64	6.28	93.39	5.78
Conjunction 8	93.64	7.32	93.93	6.14
Conjunction 16	93.33	7.47	92.68	7.26
Preview 4	93.48	5.93	93.04	5.67
Preview 8	93.18	4.97	93.04	5.98
Preview 16	94.24	6.01	94.64	5.43
Preview gap 4	94.24	5.17	95.18	5.00
Preview gap 8	94.39	4.96	93.04	5.67
Preview gap 16	92.42	9.61	92.32	6.16

Note. Percentages are shown.

Table 3.5

Slope Statistics for the Low and High Conners 3AI Groups

Group/Statistic	SF	CJ	PV	PVG
Low Conners 3AI				
Slope	12.01	46.80	18.87	37.25
Intercept	818.00	908.31	876.31	846.57
Linearity (%)	97.26	99.82	99.72	99.92
High Conners 3AI				
Slope	15.32	51.00	29.30	33.23
Intercept	882.12	1074.20	925.60	1029.60
Linearity (%)	99.37	99.87	99.87	99.63

Note. SF = single-feature; CJ = conjunction; PV = preview; PVG = preview gap.

3.1.3 Behavioural Results

Relationship Between ADHD and Search Benefit. The relationship between level of ADHD and search benefit was also examined. Table 3.6 shows the relationship between search efficiency and participant characteristics, including age, intelligence (as measured by WISC-IV DQ, WRAT-4 Reading and Spelling), and level of ADHD-traits. The Conners 3 ADHD Index is a 10-item scale which yields two scores: a *T*-score and a probability score. These scores are combined to determine overall level of ADHD traits (Conners, 2008). In the present study, these continuous scores were used to establish categorical groups of either low or high levels of ADHD. In order to examine the relationship between levels of ADHD and performance, the two measures that make up the Conners 3 ADHD Index were separated. PB index scores, $W = 0.786$, $p < .001$, PGB index scores, $W = 0.832$, $p < .001$, ADHD Index scores, $W = 0.828$, $p < .001$, and ADHD probability scores, $W = 0.831$, $p < .001$, were all non-normal. Accordingly, a Kendall's tau b correlation analysis was used to investigate the relationship between variables. The PB was not significantly related to the ADHD Index T-score, $\tau = -.133$, $p = .162$, or the ADHD Probability score, $\tau = -.114$, $p = .222$. While the PGB was not significantly related to the ADHD Probability score, $\tau = .146$, $p = .116$, it was significantly related to the ADHD Index T-score, $\tau = .233$, $p < .05$, 95% CI [0.07, 0.39].

Table 3.6

Correlation Matrix of Participant Characteristics and Benefit Indices

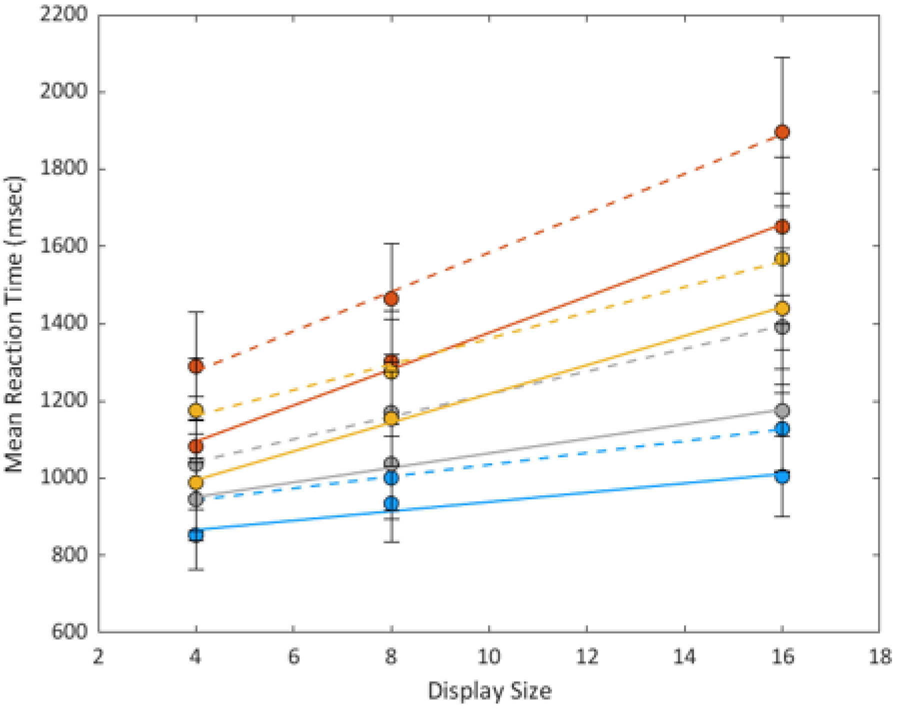
	Age	WISC-IV DQ	WRAT-4 Read	WRAT-4 Spell	Conners 3AI *T*-score	Conners 3AI Probability Score
Preview Benefit	**.104**	**.055**	**.039**	**.101**	**-.133**	**-.114**
Preview Gap Benefit	-.182*	.144	.175*	-.066	.233*	.146
Age	-					
WISC-IV	-.146	-				
WRAT-4 Read	-.278**	.385**	-			
WRAT-4 Spell	-.180*	.230*	.282**	-		
Conners 3AI *T*-score	-.108	.055	.083	.070	-	
Conners 3AI Probability Score	-.097	.175	.163	.060	.707**	-

Note. Values reflect Kendall's statistic, τ. * significance at < .05, ** significance at < .01.

Omnibus 2 x 4 x 3 ANOVAs. ***2 x 4 x 3 ANOVA – Mean RTs.*** Mean RTs for correct trials were analysed first using a 2 (group) x 4 (condition) x 3 (display size) mixed ANOVA. Group (low Conners 3AI x high Conners 3AI) was a between-subjects factor. Condition (single-feature x conjunction x preview x preview gap) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction, preview and preview gap) were within-subjects factors. Levene's test revealed that variances were homogeneous for all levels of the repeated measure variables (all *p*s ≥ .14). Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 6.14$, $p < .05$, and for the Condition x Display interaction, $\chi^2(20) = 42.11$, $p < .01$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity (ε = .952 and ε = .886, respectively). There was no significant difference between groups, $F(1, 59) = 3.30$, $p = .07$, partial $\eta^2 = .05$. RTs did differ between conditions, reflected by a significant main effect of Condition, $F(3, 177) = 89.96$, $p < .001$, partial $\eta^2 = .59$. Post-hoc pairwise comparisons using the Bonferroni correction showed that there were significant differences between each of the conditions (*p*s < .001). Single-feature had the fastest RTs (*M* = 977.95, *SE* = 34.86), followed by preview (*M* = 1125.77, *SE* = 45.02), preview gap (*M* = 1266.97, *SE* = 47.02) and finally conjunction (*M* = 1447.64, *SE* = 50.71). Group failed to significantly interact with condition, $F(3, 177) = 1.09$, $p = .35$, partial $\eta^2 = .02$. RTs increased significantly with display size, $F(1.90, 112.33) = 205.64$, $p < .001$, partial $\eta^2 = .77$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences (at $p < .001$) between each of the three display sizes. The Group x Display interaction failed to reach significance, $F(2, 118) = 1.26$, $p = .29$, partial $\eta^2 = .02$. The interaction between condition and display, however, was significant, $F(5.32, 313.59) = 25.32$, $p < .001$, partial $\eta^2 = .30$. Further analysis was undertaken to further explore this significant interaction, which is presented below. Finally, the Group x Condition x Display interaction failed to reach significance, $F(6, 354) = 1.13$, $p = .35$, partial $\eta^2 = .02$. The slopes for each condition, display size and group are shown in Figure 3.3.

Figure 3.3

Mean RTs for Each Condition and Display Size in the Low and High Conners 3AI Groups



Note. The low Conners 3AI group is represented by the regular lines and the high Conners 3AI group is represented by the dashed lines. Single-feature = Blue; conjunction = orange; preview = grey; preview gap = yellow. Error bars represent ±2 *SE*s.

2 x 4 x 3 ANOVA – Accuracy. Accuracy rates were analysed next using a 2 (group) x 4 (condition) x 3 (display size) mixed ANOVA. Group (low Conners 3AI x high Conners 3AI) was a between-subjects factor. Condition (single-feature x conjunction x preview x preview gap) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction, preview and preview gap) were within-subjects factors. Levene's test revealed that variances were homogeneous for all levels of the repeated measure variables (all *p*s ≥ .18). Mauchley's test indicated that the assumption of sphericity had been met for the main effects of Condition and Display, as well as the interaction between condition and display. None of the main effects reached significance. Similarly, none of the two- or three-way interactions reached significance (see Appendix Table L.3 for all omnibus ANOVA statistics).

2 x 4 x 3 ANOVA – Efficiency. Finally, efficiencies were analysed using a 2 (group) x 4 (condition) x 3 (display size) mixed ANOVA. Group (low Conners 3AI x high Conners 3AI) was a between-subjects factor. Condition (single-feature x conjunction x preview x preview gap) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction, preview and preview gap) were within-subjects factors. Levene's test revealed that variances were homogeneous for all levels of the repeated measure variables (all *p*s ≥ .14). Mauchley's test indicated that the assumption of sphericity had been violated for the interaction of condition and display, $\chi^2(20) = 52.88$, $p < .001$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .871$). Groups were not significantly different, $F(1, 59) = 3.25$, $p = .08$, partial $\eta^2 = .05$. Efficiencies did significantly differ between conditions, $F(3, 177) = 3.30$, $p < .001$, partial $\eta^2 = .59$. Post-hoc pairwise comparisons using the Bonferroni correction showed that each condition differed from the others, such that efficiencies in single-feature were lowest (*M* = 1054.75, *SE* = 41.61), followed by preview (*M* = 1204.25, *SE* = 47.19), preview gap (*M* = 1364.72, *SE* = 54.95) and conjunction (*M* = 1558.81, *SE* = 56.05). Condition failed to interact significantly with group, $F(3, 177) = 0.77$, $p = .52$, partial $\eta^2 = .01$. Efficiency decreased significantly as display size increased, $F(2, 118) = 189.55$, $p < .001$, partial $\eta^2 = .76$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences (at $p < .001$) between each of the three display sizes. Display did not interact with group, $F(2, 118 = 0.32$, $p = .32$, partial $\eta^2 = .02$. However, display did significantly interact with condition, $F(5.22, 308.16) = 20.70$, $p < .001$, partial $\eta^2 = .26$. The three-way interaction between group, condition, and display failed to reach significance, $F(6, 354) = 0.86$, $p = .50$, partial $\eta^2 = .01$.

Follow Up 2 x 2 x 3 ANOVAs. The complete statistics for the follow-up mean RT and efficiency ANOVAs are presented in Appendix Table L.4 and Appendix Table L.5, respectively.

***Single-feature vs. Conjunction: Mean RTs*.** Mean RTs were analysed using a 2 (condition) x 3 (display size) ANOVA. Condition (single-feature x conjunction) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 11.89$, $p < .01$, and for the Condition x Display interaction, $\chi^2(2) = 9.26$, $p = .01$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .868$ and $\varepsilon = .897$, respectively). Mean RTs were significantly faster in the single-feature condition, $F(1, 60) = 237.78$, $p < .001$, partial $\eta^2 = .80$, and increased with display size, $F(1.74, 104.10) = 182.66$, $p < .001$, partial $\eta^2 = .75$. There was significant Condition x Display interaction, $F(1.79, 107.66) = 63.78$, $p < .001$, partial $\eta^2 = .52$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for single-feature (all *p* < .001s) and for conjunction (all *p* < .001s). Compared to single-feature (*M* = 69.43, *SD* = 140.54), the conjunction condition (*M* = 198.35, *SD* = 196.38) had a significantly larger mean difference between the two lower display sizes, $t(60) = -4.08$, $p < .001$. Between the larger two display sizes, the conjunction condition (*M* = 387.09, *SD* = 287.79) also had a significantly larger mean difference compared to single-feature (*M* = 96.44, *SD* = 140.15), $t(60) = -7.79$, $p < .001$. RTs increased with display size to a greater extent in the conjunction condition.

***Single-feature vs. Conjunction: Efficiency*.** Efficiency was analysed using a 2 (condition) x 3 (display size) ANOVA, where condition (single-feature x conjunction) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 7.28$, $p < .05$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .922$). Search was significantly more efficient in the single-feature condition, $F(1, 60) = 211.10$, $p < .001$, partial $\eta^2 = .78$. Efficiency decreased as display size increased, *F*(1.84, 110.61) = 146.87, $p < .001$, partial $\eta^2 = .71$. There was significant Condition x Display interaction, *F*(2, 118) = 41.66, $p < .001$, partial $\eta^2 = .42$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for single-feature (all $p < .001$s) and for conjunction (all $p < .001$s). Compared to single-feature (*M* = 82.66, *SD* = 171.82), the conjunction condition (*M* = 221.69, *SD* = 286.21) had a significantly larger mean difference between the two lower display sizes, *t*(60) = -3.10, *p* = .003. Between the larger two display sizes, the conjunction condition (*M* = 442.02, *SD* = 355.72) also had a significantly larger mean difference compared to single-feature (*M* = 107.23, *SD* = 189.92), *t*(60) = -6.58, $p < .001$. Efficiency decreased as display size increased to a greater extent in the conjunction condition.

***Conjunction vs. Preview: Mean RTs*.** Mean RTs for correct trials were analysed using a 2 (condition) x 3 (display) ANOVA, where condition (conjunction x preview) and display size (4 x 8 x 16) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 17.18$, $p < .001$, and for the Condition x Display interaction, $\chi^2(2) = 18.68$, $p < .001$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .817$ and $\varepsilon = .804$, respectively). Overall, RTs were faster in the preview condition, *F*(1, 60) = 103.30, $p < .001$, partial $\eta^2 = .63$, and increased with display size, *F*(1.63, 98.01) = 148.04, $p < .001$, partial $\eta^2 = .71$. The Condition x Display interaction was significant, *F*(1.61, 96.49) = 29.02, $p < .001$, partial $\eta^2 = .33$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for conjunction (all $p < .001$s) and for preview (all $p < .001$s). Compared to preview (*M* = 111.38, *SD* = 161.64), the conjunction condition (*M* = 198.35, *SD* = 196.38) had a significantly larger mean difference between the two lower display sizes, *t*(60) = -3.10, *p* = .003. Between the larger two display sizes, the conjunction condition (*M* = 387.09, *SD* = 287.79) also had a significantly larger mean difference compared to preview (*M*

=175.89, *SD* = 265.65), *t*(60) = -4.83, $p < .001$. This indicates the presence of a preview benefit, as RTs increased with display size to a greater extent in the conjunction condition.

Conjunction vs. Preview: Efficiency. Efficiency was analysed using a 2 (condition) x 3 (display size) ANOVA. Condition (conjunction x preview) and display size (4 x 8 x 16) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 6.70$, $p < .05$, and for the Condition x Display interaction, $\chi^2(2) = 13.61$, $p < .001$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .929$ and $\varepsilon = .850$, respectively). Search was significantly more efficient in the preview condition, *F*(1, 60) = 100.98, $p < .001$, partial $\eta^2 = .63$. Efficiency decreased as display size increased, *F*(1.86, 111.52) = 120.69, $p < .001$, partial $\eta^2 = .67$. There was significant Condition x Display interaction, *F*(1.70, 101.98) = 27.43, $p < .001$, partial $\eta^2 = .31$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for conjunction (all *p* < .001s) and for preview (all *p* < .001s). Compared to preview (*M* = 118.87, *SD* = 188.63), the conjunction condition (*M* = 221.69, *SD* = 286.21) had a significantly larger mean difference between the two lower display sizes, *t*(60) = -2.83, $p = .006$. Between the larger two display sizes, the conjunction condition (*M* = 442.02, *SD* = 355.72) also had a significantly larger mean difference compared to preview (*M* = 171.02, *SD* = 289.39), *t*(60) = -4.67, $p < .001$. Efficiency decreased as display size increased to a greater extent in the conjunction condition.

Single-feature vs. Preview: Mean RTs. Mean RTs for correct trials were analysed using a 2 (condition) x 3 (display) ANOVA with condition (single-feature x preview) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for preview) as within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 12.04$, $p < .01$, and for the Condition x Display interaction, $\chi^2(2) = 7.84$, $p < .05$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .866$ and $\varepsilon = .915$, respectively). Mean RTs did not significantly differ between the two groups. RTs were faster in the single-feature condition, *F*(1, 60) = 22.64, $p < .001$, partial $\eta^2 = .28$, and increased with display size, *F(*1.73, 103.91) = 81.91, $p < .001$, partial $\eta^2 = .58$. The Condition x Display interaction was also significant, *F*(1.83, 109.76) = 6.52, $p < .01$, partial $\eta^2 = .10$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for single-feature (all $p < .001$s) and for preview (all $p < .001$s). The single-feature (*M* = 69.43, *SD* = 140.54) and preview conditions (*M* = 111.38, *SD* = 161.64) did not differ significantly at the two lower display sizes, *t*(60) = -1.51, *p* = .137. Between the larger two display sizes, the preview condition (*M* =175.89, *SD* = 265.65) had a significantly larger mean difference compared to single-feature (*M* = 96.44, *SD* = 140.15), *t*(60) = -7.79, *p* = .043. Search in single-feature was more efficient than in preview.

Single-feature vs. Preview: Efficiency. Efficiency was analysed using a 2 (condition) x 3 (display size) ANOVA with condition (single-feature x preview) and display size (2, 4, 8 for single-feature; 4 x 8 x 16 for preview) as within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 11.41$, $p < .01$, and for the Condition x Display interaction, $\chi^2(2) = 6.78$, $p < .05$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .873$ and $\varepsilon = .928$, respectively). Search was significantly more efficient in the single-feature condition, *F*(1, 60) = 21.90, $p < .001$, partial $\eta^2 = .27$. Efficiency decreased as display size increased, *F*(1.75, 104.72) = 64.07, $p < .001$, partial $\eta^2 = .52$. There was significant Condition x Display interaction, *F*(1.86, 111.41) = 3.22, $p < .05$, partial $\eta^2 = .05$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for single-feature (all $p < .001$s) and for preview (all $p < .001$s). The single-feature (*M* = 82.66, *SD* = 171.82) and preview (*M* = 118.87, *SD* = 188.63) conditions did not differ significantly between the two lower display sizes, *t*(60) = -1.11, *p* = .272. Between the larger two display sizes, the preview (*M* = 171.02, *SD* = 289.39) and single-feature (*M* = 107.23, *SD* = 189.92) conditions also did not significantly differ, $t(60) = -1.48$, $p = .146$. Efficiency decreased as display size increased to a greater extent in the preview condition.

Conjunction vs. Preview Gap: Mean RTs. Mean RTs for correct trials were analysed using a 2 (condition) x 3 (display) ANOVA with condition (conjunction x preview gap) and display size (4 x 8 x 16) as within-subjects factors. Mauchley's test indicated that the assumption of sphericity was met for all within-subjects effects. Mean RTs did not differ significantly between groups. RTs were faster in the preview gap condition, $F(1, 60) = 31.29$, $p < .001$, partial $\eta^2 = .34$, and increased with display size, $F(2, 120) = 174.69$, $p < .001$, partial $\eta^2 = .74$. The Condition x Display was significant, $F(2, 120) = 10.53$, $p < .001$, partial $\eta^2 = .15$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for conjunction (all $p < .001$s) and for preview gap (all $p < .001$s). Compared to preview gap ($M = 135.44$, $SD = 255.32$), the conjunction condition ($M = 198.35$, $SD = 196.38$) had a significantly larger mean difference between the two lower display sizes, $t(60) = 2.08$, $p = .042$. Between the larger two display sizes, the conjunction condition ($M = 387.09$, $SD = 287.79$) had a significantly larger mean difference compared to preview gap ($M = 288.13$, $SD = 209.93$), $t(60) = 2.70$, $p = .009$. RTs increased with display size more so in the conjunction condition.

Conjunction vs. Preview Gap: Efficiency. Efficiency was analysed using 2 (condition) x 3 (display size) ANOVA where condition (conjunction x preview gap) and display size (4 x 8 x 16) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the Condition x Display interaction, $\chi^2(2) = 7.85$, $p < .05$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .915$). Search was significantly more efficient in the preview gap condition, $F(1, 60) = 25.73$, $p < .001$, partial $\eta^2 = .30$. Efficiency decreased as display size increased, $F(2, 120) = 152.11$, $p < .001$, partial $\eta^2 = .72$. There was significant Condition x Display interaction, $F(1.83, 109.74) = 4.93$, $p < .05$, partial $\eta^2 = .08$. Post-hoc comparisons using the

Bonferroni correction showed significant differences at each of the three display sizes for conjunction (all $p < .001$s) and for preview gap (all $p < .001$s). The preview gap (*M* = 154.15, *SD* = 258.51) and conjunction (*M* = 221.69, *SD* = 286.21) conditions did not significantly differ between the two lower display sizes, $t(60) = 1.84$, $p = .072$. Between the larger two display sizes, the conjunction (*M* = 442.02, *SD* = 355.72) and preview gap (*M* = 346.35, *SD* = 281.03) also failed to significantly differ, $t(60) = 1.50$, $p = .138$.

Single-feature vs. Preview Gap: Mean RTs. Mean RTs for correct trials were analysed using a 2 (condition) x 3 (display) ANOVA. Condition (single-feature x preview gap) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for preview) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity was met for all within-subjects effects. Mean RTs did not significantly differ between groups. RTs were faster in the preview condition, $F(1, 60) = 79.50$, $p < .001$, partial $\eta^2 = .57$, and increased with display size, $F(2, 120) = 135.52$, $p < .001$, partial $\eta^2 = .69$. There was a significant Condition x Display interaction, $F(2, 120) = 31.43$, $p < .001$, partial $\eta^2 = .34$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for single-feature (all $p < .001$s) and for preview gap (all $p < .001$s). The single-feature (*M* = 69.43, *SD* = 140.54) and the preview gap (*M* = 135.44, *SD* = 255.32) did not differ significantly between the two lower display sizes, $t(60) = -1.86$, $p = .068$. Between the larger two display sizes, the preview gap condition (*M* = 288.13, *SD* = 209.93) had a significantly larger mean difference compared to single-feature (*M* = 96.44, *SD* = 140.15), $t(60) = -6.05$, $p < .001$.

Single-feature vs. Preview Gap: Efficiency. Efficiency was analysed using a 2 (condition) x 3 (display size) ANOVA where condition (single-feature x preview gap) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for preview gap) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been met for all within-subjects effects. Search was significantly more efficient in the single-feature condition, $F(1, 60) = 63.64$, $p < .001$, partial $\eta^2 = .52$.

Efficiency decreased as display size increased, *F*(2, 120) = 119.63, $p < .001$, partial $\eta^2 = .67$. There was significant Condition x Display interaction, *F*(2, 120) = 29.61, $p < .001$, partial $\eta^2 = .33$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for single-feature (all $p < .001$s) and for preview gap (all $p < .001$s). The single-feature (*M* = 82.66, *SD* = 171.82) and preview gap (*M* = 154.15, *SD* = 258.51) conditions did not significantly differ between the two lower display sizes, *t*(60) = -1.80, *p* = .076. Between the larger two display sizes, the preview gap condition (*M* = 346.35, *SD* = 281.03) also had a significantly larger mean difference compared to single-feature (*M* = 107.23, *SD* = 189.92), *t*(60) = -5.77, $p < .001$. Efficiency decreased as display size increased to a greater extent in the preview gap condition.

Preview vs. Preview Gap: Mean RTs. Mean RTs for correct trials were analysed using a 2 (condition) x 3 (display) ANOVA. Condition (preview x preview gap) and (4 x 8 x 16) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity was met for all within-subjects effects. RTs were faster in the preview condition, *F*(1, 60) = 28.73, $p < .001$, partial $\eta^2 = .32$, and increased with display size, *F*(2, 120) = 115.11, $p < .001$, partial $\eta^2 = .66$. The Condition x Display interaction was significant, *F*(2, 120) = 7.41, $p < .001$, partial $\eta^2 = .11$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for preview (all $p < .001$s) and for preview gap (all $p < .001$s). The preview (*M* = 111.38, *SD* = 161.64) and the preview gap (*M* = 135.44, *SD* = 255.32) did not differ significantly between the two lower display sizes, *t*(60) = -0.66, *p* = .513. Between the larger two display sizes, the preview gap condition (*M* = 288.13, *SD* = 209.93) had a significantly larger mean difference compared to preview (*M* = 175.89, *SD* = 265.65), *t*(60) = -3.11, *p* = .003. RTs increased with display size more so in the preview gap condition.

Preview vs. Preview Gap: Efficiency. Efficiency was analysed using 2 (condition) x 3 (display size) ANOVA. Condition (preview x preview gap) and display size (4 x 8 x 16) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 7.14$, $p < .05$, and for the Condition x Display interaction, $\chi^2(2) = 10.08$, $p < .01$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .924$ and $\varepsilon = .888$, respectively). Search was significantly more efficient in the preview condition, $F(1, 60) = 24.11$, $p < .001$, partial $\eta^2 = .29$. Efficiency decreased as display size increased, $F(1.85, 110.83) = 120.10$, $p < .001$, partial $\eta^2 = .67$. There was significant Condition x Display interaction, $F(1.73, 106.51) = 10.98$, $p < .001$, partial $\eta^2 = .16$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for preview (all $p < .001$s) and for preview gap (all $p < .001$s). The preview (*M* = 118.87, *SD* = 188.63) and preview gap (*M* = 154.15, *SD* = 258.51) conditions did not significantly differ between the two lower display sizes, $t(60) = -0.94$, $p = .350$. Between the larger two display sizes, the preview gap condition (*M* = 346.35, *SD* = 281.03) had a significantly larger mean difference compared to preview (*M* = 171.02, *SD* = 289.39), $t(60) = -3.34$, $p = .001$. Efficiency decreased as display size increased to a greater extent in the preview gap condition.

Preview and Preview Gap Benefit. Children with low and high Conners 3AI scores were also compared on PB and PGB index values. As discussed in section 2.1.3, these indices provide a nonbiased measure of behavioural benefit obtained from the temporal elements included in these two conditions. For each participant, the two index equations (see Equations 1 and 2) were calculated. The resulting index values fall between 0 and 1 and are interpreted as the percentage of old items suppressed from competition in the final display. Values tending toward 1 reflect a larger benefit, such that a value of 1 reflects 100% of old items were successfully inhibited. In contrast, values tending toward 0 reflect a smaller benefit to search in these conditions, where a value of 0 indicates none (0%) of the preview items were successfully suppressed, and therefore, all items competed at the final display.

The values of the PB index showed that the preview benefit was numerically larger for children in the low Conners 3AI group (*M* = 0.848, *SE* = 0.063) compared to the high Conners 3AI group (*M* = 0.612, *SE* = 0.143). However, this difference was not statistically significant, t(37.41) =1.52[1], *p* = 0.138 (two-sided), *d* = 0.410, 95% CI [-0.08, 0.55]. The effect size was small-medium. PB index values in the high Conners 3AI group were non-normal, *W* = 0.751, *p* < .001, but were normal in the low Conners 3AI group, *W* = 0.974, *p* = .599. For the low Conners 3AI group, the PB contained two outliers at the lower end of the scale with values equal to or less than 0.2 and one outlier at the higher end of the scale with a value equal to or greater than 1.8. For the high Conners 3AI group, the PB contained three outliers at the lower end of the scale with values equal to or less than -0.6.

The PGB index values showed that low Conners 3AI children had a numerically smaller benefit in the preview gap condition (*M* = 0.452, *SE* = 0.098) than high Conners 3AI children (*M* = 0.809, *SE* = 0.165). However, this difference also failed to reach statistical significance, t(59) =-1.92, p = .059 (two-sided p), d = -0.494, 95% CI [-0.73, 0.01]. The effect size was medium. PGB index values in the high Conners 3AI group, *W* = 0.766, *p* < .001, and in the low Conners 3AI group, *W* = 0.29, *p* < .05, were both non-normal. For the low Conners 3AI group, the PGB contained one outlier at the lower end of the scale with a value equal to or less than -1.2 and one outlier at the higher end of the scale with a value equal to or greater than 2.2. For the high Conners 3AI group, the PGB contained three outliers at the lower end of the scale with values equal to or less than -0.32 and two outliers at the higher end of the scale with values equal to or greater than 2.31. PB and PGB values are listed in Table 3.7 and shown in Figure 3.4.

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[1] Levene's test for equality of variances was violated, *F*(1, 59) = 4.58, *p* < .05. Therefore, a *t* statistic not assuming homogeneity of variance was computed.

Table 3.7

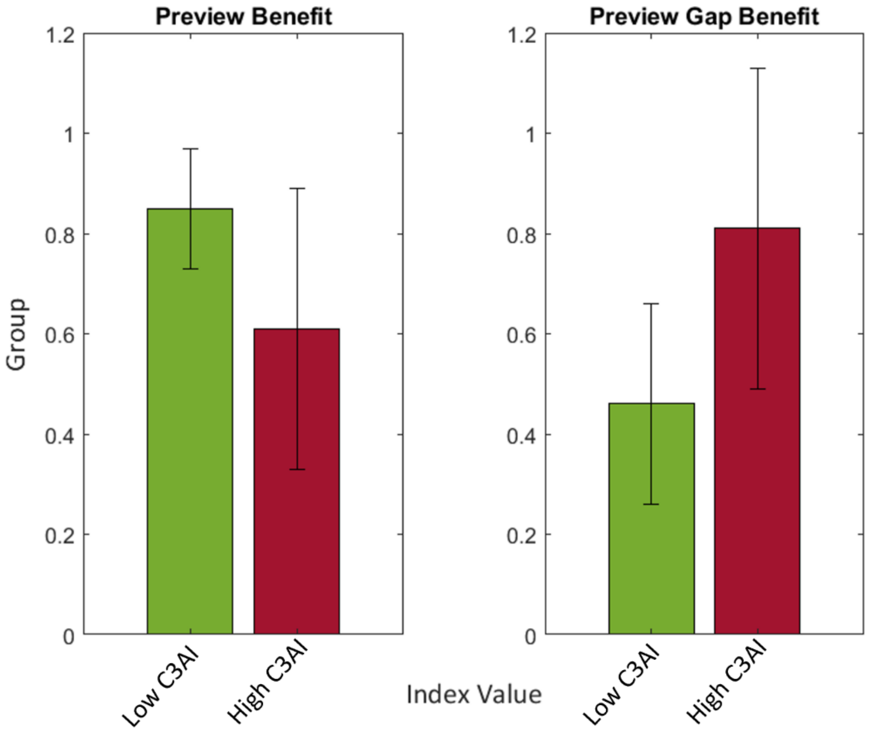
Mean Index Values, Standard Deviations, and T-test Statistics for Low and High Conners 3AI Groups

Index	Low Conners 3AI		High Conners 3AI		t(59)	*p*[b]	Cohen's *d*
	M	*SD*	*M*	*SD*			
PB	0.848	0.362	0.612	0.754	1.516[a]	.138	0.410
PGB	0.452	0.567	0.809	0.872	-1.924	.059	- 0.494

Note. [a] Equal variances not assumed.[b] Two-sided.

Figure 3.4

Preview and Preview Gap Benefit Index Values for the Low and High Conners 3AI Groups



Note. Values of 0 indicate no benefit – none of the old items could be sufficiently suppressed in the competition for selection, and therefore search was as inefficient as if all items had been presented simultaneously. Values of 1 indicate the maximum benefit – all old items were sufficiently suppressed, and therefore competition for selection occurred amongst only the new items. While PB values typically trend more toward 1, PGB values tend more toward 0. Error bars represent ±2 *SE*.

Exploratory Analysis of Preview Gap Benefit. Temporal binding relies on fast and efficient neural communication within- and between- regions (Singer, 2015, 2021). As children with ADHD have demonstrated differences in connectivity and SNR (Castellanos & Aoki, 2016; Pertermann et al., 2019; Wang et al., 2009; Wu et al., 2023), it was hypothesised that, for the high Conners 3AI group, these mechanisms would contribute to weakened temporal binding and thus *more* efficient search in the preview gap condition relative to the low Conners 3AI group. This hypothesis was partially supported by the finding that level of ADHD was significantly related to level of search benefit in the preview gap condition. However, the hypothesis was not supported by the results of the ANOVAs, which showed that both low and high Conners 3AI groups experienced a similar loss of the preview benefit in the preview gap condition. In light of these contradictory results, additional exploratory analysis was undertaken to investigate slopes in the preview gap condition for each group.

Low Conners 3AI Group: Mean RTs. Mean RTs were analysed using a 2 (condition) x 3 (display) ANOVA, with condition (preview x preview gap) and display size (4 x 8 x 16) as within-subjects factors. RTs were significantly faster in the preview condition, $F(1, 32) = 18.48$, $p < .001$, partial $\eta^2 = .37$. RTs also increased with display size, $F(2, 64) = 90.23$, $p < .001$, partial $\eta^2 = .74$. Post hoc pairwise comparisons using the Bonferroni correction showed significant differences (at $p < .001$) between each of the display sizes. Finally, there was a significant Condition x Display interaction, *F*(2,

54) = 12.70, $p < .001$, partial $\eta^2 = .28$, indicating that there was a loss of the preview benefit in the preview gap condition for the low Conners 3AI group.

Low Conners 3AI Group: Efficiency. Efficiencies were analysed using a 2 (condition) x 3 (display) ANOVA, with condition (preview x preview gap) and display size (4 x 8 x 16) as within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the interaction of condition and display, $\chi^2(2) = 12.01$, $p < .001$. Accordingly, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .757$). Search was significantly more efficient in the preview condition, $F(1, 32) = 13.60$, $p < .001$, partial $\eta^2 = .30$. Efficiency decreased as display size increased, $F(2, 64) = 92.16$, $p < .001$, partial $\eta^2 = .74$, and this occurred more so in the preview gap condition, indicated by a significant interaction between condition and display, $F(2, 64) = 10.31$, $p < .001$, partial $\eta^2 = .24$.

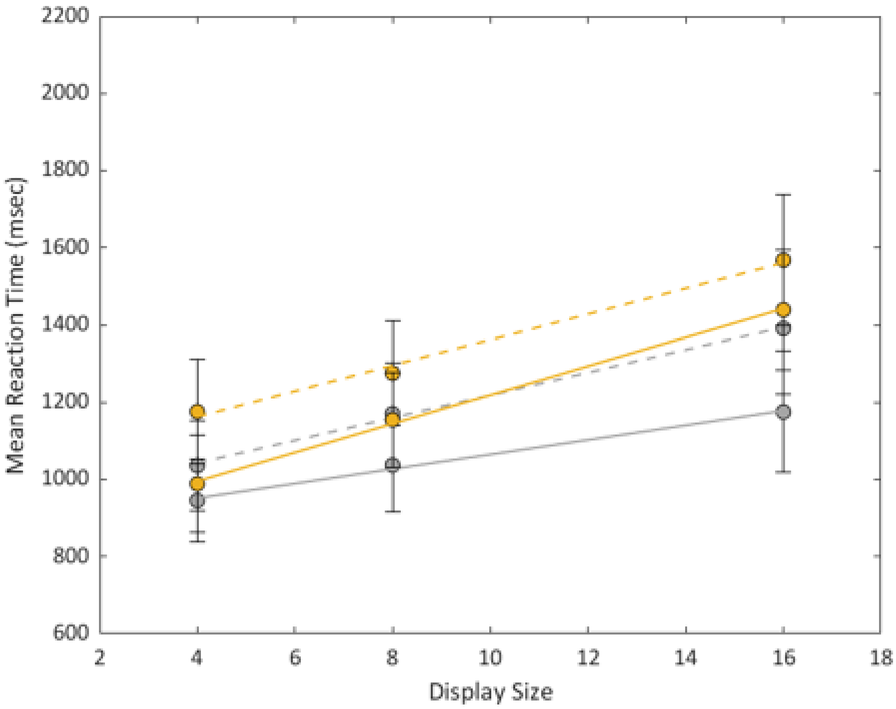
High Conners 3AI Group: Mean RTs. Mean RTs were analysed using a 2 (condition) x 3 (display) ANOVA, with condition (preview x preview gap) and display size (4 x 8 x 16) as within-subjects factors. RTs were significantly faster in the preview condition, $F(1, 27) = 10.74$, $p < .01$, partial $\eta^2 = .28$. Overall, RTs increased with display size, $F(2, 54) = 40.47$, $p < .001$, partial $\eta^2 = .60$. Post hoc pairwise comparisons using the Bonferroni correction showed significant differences (at $p < .01$ and $p < .001$, respectively) between each of the display sizes. The Condition x Display interaction failed to reach significance, $F(2, 54) = 0.68$, $p = .50$, partial $\eta^2 = .03$, indicating that, for the high Conners 3AI group, slopes in the preview gap condition were not significantly steeper than those in the preview condition. In other words, the preview benefit was not lost in the preview gap condition (see Figure 3.5).

High Conners 3AI Group: Efficiency. Efficiencies were analysed using a 2 (condition) x 3 (display size) ANOVA, with condition (preview x preview gap) and display size (4 x 8 x 16) as within-subjects factors. Search was significantly more efficient in the preview condition, $F(1, 27) = 10.18$, $p <$

.01, partial η^2 = 27. Efficiency decreased as display size increased, *F*(2, 54) = 41.58, *p* < .001, partial η^2 = .61, and this occurred similarly for each condition, as the interaction between condition and display failed to reach significance, *F*(2, 54) = 2.11, *p* = .13, partial η^2 = .07.

Figure 3.5

Mean RTs for Each Display Size in the Preview and Preview Gap in the Low and High Conners 3AI Groups



Note. The low Conners 3AI group is the regular lines, the high Conners 3AI group is the dashed lines. Preview = grey; preview gap = yellow. Error bars represent ±2 *SE*.

3.1.4 Behavioural Discussion

The present study aimed to identify differences in visual marking and temporal binding between children with low and high Conners 3AI scores using preview and preview gap search. In preview search, the final display is identical to that of a traditional conjunction condition. However, a preview search has an additional temporal element: one set of distractor items is displayed alone before the second set of distractors and target item appear alongside. Under these conditions, search is significantly more efficient compared to conjunction and can even become as efficient as single-feature. This increase in efficiency, referred to as the preview benefit, occurs when old preview items are actively suppressed in order to prioritise new items - a process known as visual marking (Watson & Humphreys, 1997). In ADHD, however, individuals demonstrate differences in the top-down control of attention (Guo et al., 2023; Mullane & Klein, 2008; Wang et al., 2016, 2017). As such, these differences could result in reduced visual marking of old items. Accordingly, it was hypothesized that visual marking difficulties in the high Conners 3AI group would yield a reduced preview benefit, evident by less efficient search in the preview condition compared to the low Conners 3AI group. Contrary to the hypothesis, however, groups did not differ in the preview benefit. Slopes in the preview condition (although not reaching the level of single-feature efficiency) were still significantly more efficient than conjunction slopes, indicating a clear preview benefit. Furthermore, this pattern held for both groups. These results indicate that children with high levels of ADHD symptoms are able to visually mark old items sufficiently well to generate a preview benefit similar to their low-ADHD-symptom peers (Watson & Humphreys, 1997). This finding is consistent with previous investigations of visual marking in children with and without ADHD that also found no differences between groups' preview benefit (Mason et al., 2003, 2004).

This particular outcome is significant as it demonstrates that, despite previous literature evidencing difficulty in top-down control in ADHD (Guo et al., 2023; Mullane & Klein, 2008; Skalski et al., 2021; Wang et al., 2016, 2017), these do not appear to give rise to behaviourally observable differences in the ability to visually mark old items. It is indeed surprising that this outcome should occur. On the one hand, two previous studies also found that children with ADHD are able to generate a preview benefit (Mason et al., 2003, 2004). On the other hand, these previous studies by

Mason et al. (2004, 2005) also show other indications of closely related time-based attention differences in ADHD. Furthermore, children with ADHD have positively shown a reduced amplitude in the P_D ERP (Wang et al., 2016), which provides a measure of distractor suppression and has been shown to occur during the preview period (Berggren & Eimer, 2018). Finally, visual marking seems has been shown to be very sensitive to changes in top-down attention. For example, in the original publication, Watson & Humphreys (1997) showed that adding a WM task (thus reducing the available capacity for distractor suppression) during the preview period reduces the preview benefit (Watson & Humphreys, 1997). Accordingly, it would follow that individuals with inherent top-down difficulties would be susceptible to difficulty in visual marking. However, children with high Conners 3AI scores have no more difficulty in the preview condition than their low-Conners-3AI-score peers. This behavioural outcome thus indicates no effect of ADHD on visual marking.

In addition to visual marking, temporal binding also contributes to the preview benefit, and this temporal binding process can be parsed out using the preview gap condition. In the preview gap condition, old items are offset after the preview, leaving a blank "gap" display for a brief period. After this gap display, old items re-appear in their original positions and new items appear alongside. Initial reports showed that, under preview gap conditions, the preview benefit was abolished, with slopes becoming as inefficient as conjunction search (Watson & Humphreys, 1997). Computational modelling work has since demonstrated that the loss of the preview benefit is due to increased temporal binding activity that occurs when all items appear simultaneously (Mavritsaki & Humphreys, 2016). Importantly, this temporal binding activity requires fast and efficient communication between the neurons encoding the item’s features (Singer, 2015, 2021; Uhlhaas et al., 2010). This kind of communication relies on efficient within- and between-network connectivity within the brain, something that is often shown to be atypical in ADHD (Gao et al., 2019; Jiang et al., 2019; Lin et al., 2015; Wang et al., 2009; Wu et al., 2023). Accordingly, it was hypothesized that reduced temporal binding in the high Conners 3AI group would yield a larger benefit in the preview gap condition compared to the low Conners 3AI group. However, contrary to the hypothesis, the benefit in the preview gap condition was similar for both groups: search was significantly more efficient than conjunction, but less efficient that single-feature and preview.

On one hand, there was no significant difference between the groups on preview gap performance. On the other hand, there was a significant relationship between level of ADHD symptoms and preview gap benefit as measured by the PGB index (see Table 3.6). Children were separated into either low or high ADHD groups based on the Conners 3 ADHD Index. The C3AI consists of two components: a *T*-score and a probability score. Both scores are then taken into consideration to determine overall likelihood of ADHD (Conners, 2008). Here, the *T*-score on the ADHD Index (but not the probability score) was significantly related with the preview gap benefit index. Considering this, and guided by the apriori hypothesis, additional exploratory analysis was undertaken to examine search patterns within each group. The aim was to explore how preview slopes compared to preview gap slopes in each group, as it was hypothesized that preview gap search would be *more* efficient in the high Conners 3AI group. Indeed, this exploratory analysis showed that, in the low Conners 3AI group, there was a loss of the preview benefit in the preview gap condition, with slopes in the preview gap were significantly less efficient than those in preview (~19 msec/item slopes in preview; ~47 msec/item slopes in preview gap; see Table 3.5). In the high Conners 3AI group, there was a continued benefit in preview gap condition, with slopes similar to those in preview (~33 msec/item slopes in preview; ~29 msec/item slopes in preview gap). These findings indicate that temporal binding should be studied further. Next, this is addressed by examining the biological plausibility of temporal binding differences in ADHD by using the b-sSoTS-c model developed in the previous chapter. Specifically, parameter changes will be made according to the hypothesis of reduced temporal binding in ADHD, and with these parameter changes, the model will then perform preview and preview gap search to determine whether there’s a match with the RT slopes of high Conners 3AI children here.

3.2 Computational Modelling Study

3.2.1 Computational Modelling Background

As discussed previously, ADHD is associated with a very wide range of neurocognitive impairments across domains and tasks (Onandia-Hinchado et al., 2021; Pievsky & McGrath, 2018). Indeed, it has even been shown that patterns of neurocognitive performance differ between individuals (Arnett et al., 2023; Tsal et al., 2005; Willcutt et al., 2005). While currently there is no unifying theory capable of explaining the pathophysiology of ADHD, neuroimaging evidence indicates alterations in the structure and connectivity in the ADHD brain, particularly in frontal regions (Kowalczyk et al., 2022; Soman et al., 2023b; Wu et al., 2023; Zhang et al., 2023). Furthermore, ADHD medications target DA and NE transmission in these frontal regions (Gamo et al., 2010; Quintero et al., 2022; Spencer et al., 2015) and modulation of these catecholamines is thought to improve the SNR, thus enhancing relevant signals and attenuating irrelevant signals (Pertermann et al., 2019). This ultimately allows for representations that remain strong even in the face of noise (Arnsten et al., 2024; Berridge & Arnsten, 2015). Accordingly, the neurobiological mechanisms involved in ADHD strongly point to differences in selection (Hauser et al., 2016a). However, it is still unclear how these selection difficulties give rise to the impairments and symptoms observed at the behavioural level. As such, ADHD can be considered a prime example of the explanatory gap between neural level mechanisms and behavioural level symptoms. One way to close this gap is to use neurocomputational models capable of performing tasks (Hauser et al., 2016a; Kriegeskorte & Douglas, 2018; Montague et al., 2012).

Surprisingly, computational modelling has not been particularly popular in the field of ADHD research. Indeed, most of the computational modelling work for ADHD has utilised either sequential sampling models, such as the Diffusion Drift Model (Haller et al., 2021; Huang-Pollock et al., 2012; Ziegler et al., 2016), Bayesian cognitive models (Cai et al., 2023; Z. Jiang et al., 2023; Mowinckel et al., 2017; Weigard et al., 2016, 2018), or reinforcement learning models (Addicott et al., 2021; Cockburn & Holroyd, 2010; Katabi & Shahar, 2024; Véronneau-Veilleux et al., 2022). Importantly, while these types of models may be able to provide some explanation for behavioural data, oftentimes they fall short in the ability to link this to the underlying neurobiological mechanisms. Some reinforcement learning models, which are often ANNs, are indeed inspired by biological mechanisms in ADHD, and this has provided some key insights into ADHD (Frank et al., 2007; Véronneau-Veilleux et al., 2022). Frank et al. (2007) developed a computational model of working memory based on the prefrontal cortex and basal ganglia (O'Reilly et al., 2001). This model was able to simulate behavioural data and was also able to show how these related to certain catecholamine differences. Specifically, the authors showed that differences in NE contribute to RT variability, while differences in DA contribute to distractor interference in working memory (Frank et al., 2007). These types of insights are key to developing a better understanding of how impairments at the neural level give rise to the complex behavioural symptoms of ADHD (Hauser et al., 2016b; Ziegler et al., 2016). However, Frank et al.'s (2007) model appears to be the one of very few neurocomputational models that aims to understand ADHD (see also, Véronneau-Veilleux et al., 2022).

Aims of Study. In the present study, neurocomputational modelling is used to explore the hypotheses set forth in the previous behavioural study. Specifically, the b-sSoTS-c model developed in the previous chapter will be used to examine whether differences in temporal binding account for the close preview and preview gap slopes in the high ADHD group. As discussed previously (see section 1.1.3), temporal binding refers to the binding of separable features into a perceptual whole based on their common temporal onset. While temporal binding is indeed considered to be more of a bottom-up mechanism of attention (Humphreys et al., 2005; Jiang et al., 2002; Watson et al., 2003), this function is complex and relies on the very fast and efficient communication between distinct neurons that are encoding for the information that will become bound (Singer, 2015, 2021; Uhlhaas et al., 2010). As neural communication within- and between regions becomes progressively more efficient across development (Barnea-Goraly et al., 2005; Lebel & Deoni, 2018; Luna et al., 2015), and this type of effective connectivity is typically disrupted in ADHD (Cubillo et al., 2010; Kowalczyk et al., 2022; Wu et al., 2023), it follows that this function may be affected in ADHD.

Previous work has shown that intact temporal binding both contributes to the benefit in the preview condition and to the loss of the that benefit in the preview gap condition (Mavritsaki & Humphreys, 2016). In the previous behavioural study, it was shown that level of ADHD trait was significantly related to the benefit generated in the preview gap condition. Furthermore, an exploratory analysis showed that, unlike the low Conners 3AI group, the preview benefit was maintained in the preview gap condition for the high Conners 3AI group. These findings thus led to the proposal that temporal binding may indeed be reduced in ADHD. Accordingly, this hypothesis will be tested here. Specifically, temporal binding in the b-sSoTS-c model will be reduced, and simulations will be run in order to determine whether this produces a similar pattern of results observed in the behavioural study.

3.2.2 Computational Modelling Method

Description of Model. The architecture of the b-sSoTS model (which is held in the b-sSoTS-c model), its neuronal characteristics, and the use of mean-field approach to set the model parameters are detailed in section 2.2.2.

Search Conditions. The model was designed to simulate four search conditions: single-feature, conjunction, preview and preview gap, identical to those described in section 2.2.2 and shown in Figure 2.1.

Data Analysis. Similar to the previous chapter, there were 300 runs for each simulation. To create one “participant,” 20 runs were grouped per condition and display size. This was done 15 times to create data for 15 “participants.” It was key that the data analysis procedure for these simulated participants match that of the human participants in the behavioural study. To this end, mean RTs were calculated for each simulated participant in each condition and display size. A run (similar to a single trial in behavioural data) was excluded from analysis if it was (1) incorrect or (2) more than 2 standard deviations above or below the “participant’s” mean. Accuracy was also recorded for each participant, condition and display size. The mean RTs and accuracies were then used to create an efficiency index (mean RT/accuracy) so that accuracy of responses was also considered in addition to latency (Townsend & Ashby, 1983).

3.2.3 Computational Modelling Results

In the previous chapter, it was shown that, in general, children’s visual search performance can be characterised (at least in part) by reduced synaptic strength modelled in the b-sSoTS-c model (see section 2.2). This assumption is maintained here, and it is proposed that any ADHD differences occur in addition to the developmental reduction in synaptic strength. The low Conners 3AI group is comprised of children whose behaviour is similar to that seen in youth in the general population (as compared to youth with ADHD, see Table 3.2). Accordingly, it is assumed that this group’s performance can be simulated using the b-sSoTS-c model. First, the data for the simulated low Conners 3AI group was created into a dataset, and, to match behavioural methods, this data was analysed using a repeated-measures ANOVA to determine the pattern of slopes. Mean efficiencies and efficiency slopes for the simulated low Conners 3AI group are shown in Table 3.8 and Table 3.9.

Table 3.8

Mean Efficiencies for Each Condition and Display Size in the Simulated Low Conners 3AI Group

Condition	Mean	*SD*
Single-feature 4	300.02	15.41
Single-feature 6	350.60	19.57
Conjunction 4	409.24	34.55
Conjunction 6	609.53	136.88
Preview 4	338.19	25.93
Preview 6	344.14	18.21
Preview Gap 4	307.22	26.34
Preview Gap 6	413.73	73.95

Note. The efficiency index values are calculated by dividing mean RTs by the accuracy (Townsend & Ashby, 1983).

Table 3.9

Slope Statistics for the Simulated Low Conners 3AI Group in the Four Conditions

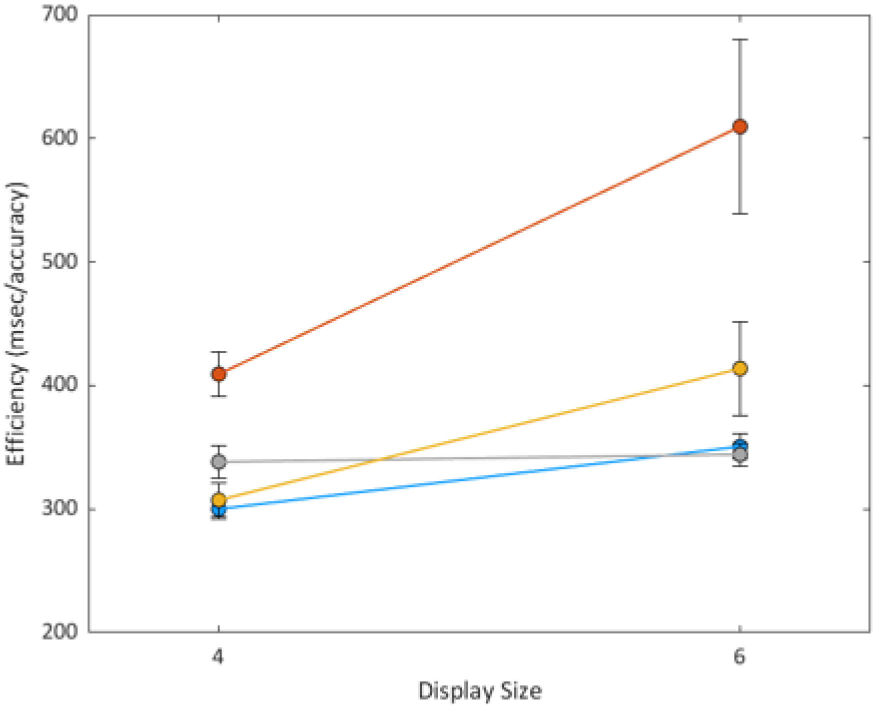
Condition	Slope (msec)
Single-feature	25.29
Conjunction	100.14
Preview	2.98
Preview Gap	53.26

Note. Slopes calculated with the two display sizes, 4 and 6.

Simulated Low Conners 3AI Children. ***4 x 2 ANOVA.*** Efficiency was analysed using a 4 (condition) x 2 (display size) repeated-measures ANOVA. Condition (single-feature x conjunction x preview x preview gap) and display size (4 x 6) were both within-subjects factors. Efficiencies in conjunction at display size 6 were non-normal, *W* = 0.82, *p* < .01, however, efficiencies in all other conditions/display sizes were normal. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Condition, $\chi^2(5) = 28.87$, *p* < .001, and for the Condition x Display interaction, $\chi^2(5) = 33.92$, *p* < .001. Accordingly, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = .469 and ε = .454, respectively). The main effect of condition was significant, *F*(1.41, 19.72) = 58.00, *p* < .001, partial $\eta^2 = .81$, as was the main effect of display, *F*(1, 14) = 90.88, *p* < .001, partial $\eta^2 = .87$. Finally, the interaction between condition and display was also significant, *F*(1.36, 19.09) = 13.28, *p* < .001, partial $\eta^2 = .49$. Accordingly, additional analysis was undertaken to explore this interaction. Efficiency slopes are shown in Figure 3.6.

Figure 3.6

Mean Efficiencies for Each Condition and Display Size for Simulated Low Conners 3AI Group



Note. Blue = single-feature; orange = conjunction; grey = preview; yellow = preview gap. Error bars represent ±2 SE.

Single-feature vs. Conjunction. Efficiency was analysed using a 2 (condition)) x 2 (display size) ANOVA. Condition (single-feature x conjunction) and display size (4 x 6) were both within-subjects factors. Search was significantly more efficient in the single-feature condition compared to conjunction, *F*(1,14) = 116.53, *p* < .001, partial η^2 = .89. Efficiency decreased as display size increased, *F*(1,14) = 39.61, *p* < .001, partial η^2 = .74. There was a significant Condition x Display interaction, *F*(1,14) = 14.80, *p* < .01, partial η^2 = .51. Post-hoc comparisons using the Bonferroni correction showed significant differences between the display sizes for both single-feature (*p* < .001) and conjunction (*p* < .001). Compared to single-feature (*M* = 50.57, *SD* = 24.37), the conjunction condition (*M* = 200.29, *SD* = 150.61) had a significantly larger mean difference between the two display sizes, *t*(14) = -3.85, *p* = .001. The efficiency slopes for single-feature and conjunction were 25.29 msec/item and 100.14 msec/item, respectively.

Preview vs. Conjunction. Efficiency was analysed using a 2 (condition)) x 2 (display size) ANOVA. Condition (preview x conjunction) and display size (4 x 6) were both within-subjects factors. Search was significantly more efficient in the preview condition, *F*(1,14) = 93.02, *p* < .001, partial η^2 = .87. Efficiency decreased as display size increased, *F*(1,14) = 34.95, *p* < .001, partial η^2 = .71. There was a significant Condition x Display interaction, *F*(1,14) = 19.67, *p* < .001, partial η^2 = .58. Post-hoc comparisons using the Bonferroni correction showed significant differences between the display sizes for conjunction (*p* < .001); however, there was no significant difference between display sizes in preview (*p* = .44). The efficiency slope for the preview condition was 2.98 msec/item.

Preview vs. Single-feature. Efficiency was analysed using a 2 (condition)) x 2 (display size) ANOVA. Condition (preview x single-feature) and display size (4 x 6) were both within-subjects factors. Search was significantly more efficient in the preview condition, *F*(1,14) = 9.18, *p* < .01, partial η^2 = .40. Efficiency decreased as display size increased, *F*(1,14) = 43.08, *p* < .001, partial η^2 = .76. There was a significant Condition x Display interaction, *F*(1,14) = 16.93, *p* < .01, partial η^2 = .56. Post-hoc comparisons using the Bonferroni correction showed significant differences between the display sizes for single-feature (*p* < .001); however, there was no significant difference between display sizes in preview (*p* = .44).

Preview Gap vs. Conjunction. Efficiency was analysed using a 2 (condition)) x 2 (display size) ANOVA. Condition (preview gap x conjunction) and display size (4 x 6) were both within-subjects factors. Search was significantly more efficient in the preview gap condition, *F*(1,14) = 37.53, *p* < .001, partial η^2 = .73. Efficiency decreased as display size increased, *F*(1,14) = 58.50, *p* < .001, partial η^2 = .81. This was the same for both conditions, reflected by a non-significant Condition x Display interaction, *F*(1,14) = 4.19, *p* = .060, partial η^2 = .23. The search slope for preview gap was 53.26 msec/item.

Preview Gap vs. Single-feature. Efficiency was analysed using a 2 (condition)) x 2 (display size) ANOVA. Condition (preview gap x single-feature) and display size (4 x 6) were both within-subjects factors. Search was significantly more efficient in the single-feature condition, *F*(1,14) = 8.19, *p* < .05, partial η^2 = .37. Efficiency decreased as display size increased, *F*(1,14) = 73.33, *p* < .001, partial η^2 = .84. There was a significant Condition x Display interaction, *F*(1,14) = 7.38, *p* < .05, partial η^2 = .35. Post-hoc comparisons using the Bonferroni correction showed significant differences between the display sizes for both single-feature (*p* < .001) and preview gap (*p* < .001). Compared to single-feature (*M* = 50.57, *SD* = 24.37), the preview gap condition (*M* = 106.51, *SD* = 71.48) had a significantly larger mean difference between the two display sizes, *t*(14) = 2.72, *p* = .017.

Preview Gap vs. Preview. Efficiency was analysed using a 2 (condition)) x 2 (display size) ANOVA. Condition (preview gap x preview) and display size (4 x 6) were both within-subjects factors. The main effect of condition failed to reach significance, *F*(1,14) = 3.05, *p* = .10, partial η^2 = .37. Efficiency decreased as display size increased, *F*(1,14) = 24.12, *p* < .001, partial η^2 = .63. There was a significant Condition x Display interaction, *F*(1,14) = 37.54, *p* < .001, partial η^2 = .73. Post-hoc comparisons using the Bonferroni correction showed significant differences between the display sizes for preview gap (*p* < .001); however, there was no significant difference between display sizes in preview (*p* = .44).

The efficiency slopes for the simulated low Conners 3AI group can be seen in Figure 3.6. The results show that, for the low Conners 3AI group, search is fast and efficient in single-feature and then becomes significantly less efficient in the conjunction condition. The fast and efficient search of single-feature is then re-gained in the preview condition, confirming that this group is capable of generating a preview benefit. Finally, when the gap display interrupts the continuous presence of preview items, the preview benefit is lost, and search becomes inefficient again compared to preview. This data indeed matches the human data obtained in the behavioural study of this chapter. Next, a parameter search is conducted to identify the changes that best characterise search performance in the high Conners 3AI group.

Parameter Search and Changes. The results of the behavioural study showed that the level of ADHD was significantly related to the magnitude of benefit in the preview gap condition. Furthermore, the behavioural exploratory analysis showed that children with high Conners 3AI scores do not lose the preview benefit in the preview gap condition like their low Conners 3AI score peers. Rather, the high Conners 3AI group generated a search benefit in the preview gap condition that’s similar to the benefit in the standard preview condition. Therefore, it was hypothesized that children with high levels of ADHD traits have differences in temporal binding. This notion is also supported by literature that children with ADHD demonstrate differences in connectivity and neural efficiency (Gonen-Yaacovi et al., 2016; Pertermann et al., 2019; Wu et al., 2023), which are critical to the temporal binding function (Singer, 2015, 2021). Accordingly, the parameter in the b-sSoTS model that implements temporal binding, *wbind*, was selected for changes.

The *wbind* parameter in the b-sSoTS model reflects the fact that, in the brain, early visual areas are able to recognise onsets (Gray et al., 1989; Singer & Gray, 1995), and this results in excitatory signals being sent forth to higher-level areas containing feature and saliency maps (Singer, 2015, 2021). In the model, when a particular location becomes activated in *both* feature maps (e.g., left top location in the “green” map and left top location in the “H” map simultaneously activate, see Figure 2.7), their common onset elicits extra activation in the saliency (location) map, such that items becomes even more salient. This occurs as a result of the *wbind* parameter, which increases the connection between feature and location maps through an increase in the feed-backward weight (Mavritsaki & Humphreys, 2016).

To determine which value of the *wbind* parameter should be used to simulate the high ADHD group, a parameter search was conducted. The *wbind* parameter was reduced by four steps of 25% so that efficiencies (see Table 3.10) and efficiency slopes (see Table 3.11) could be inspected at each step. The behavioural results showed that, in the low Conners 3AI group, the preview gap slope was nearly double that of the preview slope (preview slope was ~ 19 msec/item; preview gap slope was ~37 msec/item), similar to a classic pattern of efficient-to-inefficient seen in single-feature versus conjunction (Treisman & Gelade, 1980; Wolfe, 2020). In the high Conners 3AI group, however, preview and preview gap slopes were much closer (preview slope was ~29 msec/item; preview gap slope was ~33 msec/item). In the simulated low Conners 3AI group, there was also a very clear difference between preview and preview gap slopes (preview slope was ~ 3 msec/item; preview gap slope was ~53 msec/item). Accordingly, at each reduction step, these slopes were inspected to determine whether reducing the *wbind* parameter would give rise to closer preview and preview gap slopes, thus matching data of the high Conners 3AI group.

Table 3.10

Mean Efficiencies for Each Condition and Display Size at Each Reduction Step

Condition	100% TB		-25% TB		-50% TB		-75% TB		-100% TB	
	M	SD	M	SD	M	SD	M	SD	M	SD
Single-feature 4	300.02	15.41	300.87	15.21	304.25	14.76	303.72	12.63	304.07	12.76
Single-feature 6	350.60	19.57	353.41	17.91	355.73	21.33	359.75	20.79	359.27	22.47
Conjunction 4	409.24	34.55	413.50	34.43	430.97	64.86	424.43	34.98	443.57	67.20
Conjunction 6	609.53	136.88	646.76	182.96	633.93	156.81	638.26	137.65	657.23	138.20
Preview 4	338.19	25.93	348.32	36.62	324.18	21.08	326.51	29.68	322.45	11.86
Preview 6	344.14	18.21	368.26	33.71	350.32	23.70	347.71	19.56	354.11	19.03
Preview Gap 4	307.22	26.34	295.63	24.31	304.81	32.69	296.65	33.87	302.52	37.46
Preview Gap 6	413.73	73.95	417.47	60.73	397.52	47.20	390.94	63.83	369.66	41.28

Note. TB = Temporal Binding.

Table 3.11

Slope Statistics for the Four Conditions at Each Reduction Step

Condition	100% TB	-25% TB	-50% TB	-75% TB	-100% TB
Single-feature	25.29	26.27	25.74	28.01	27.60
Conjunction	100.14	116.63	101.48	106.92	106.83
Preview	2.98	9.97	13.07	10.60	15.83
Preview Gap	53.26	60.92	46.36	47.14	33.57

Note. Slopes calculated with the two display sizes, 4 and 6; TB = Temporal Binding.

Next, efficiencies were analysed using a 4 (group) x 4 (condition) x 2 (display) mixed ANOVA. Group (-25% temporal binding, 50% temporal binding, -75% temporal binding and -100% temporal binding) was a between-subjects factor. Condition (single-feature, conjunction, preview and preview gap) and display size (4 and 6) were both within-subjects factors. Levene's test indicated that the assumption of homogeneity of variance had been violated for efficiencies in the preview condition at display size 4, $F(3, 56) = 3.85$, $p < .05$. However, this assumption was met for all other variables. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Condition, $\chi^2(5) = 114.51$, $p < .001$, and for the Condition x Display interaction, $\chi^2(5) = 140.98$, $p < .001$. Accordingly, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .509$ and $\varepsilon = .436$, respectively). There were no significant differences between groups, $F(3, 56) = 0.26$, $p = .85$, partial $\eta^2 = .01$. The main effect of Condition was significant, $F(1.53, 85.53) = 348.77$, $p < .001$, partial $\eta^2 = .86$, as was the main effect of Display, $F(1, 56) = 253.11$, $p < .001$, partial $\eta^2 = .82$. In addition, the interaction between condition and display was significant, $F(1.31, 73.18) = 45.15$, $p < .001$, partial $\eta^2 = .45$. Group did not interact with condition, $F(9, 168) = 0.75$, $p = .67$, partial $\eta^2 = .04$, or with display, $F(3, 56) = 0.31$, $p = .82$, partial $\eta^2 = .02$. Finally, the

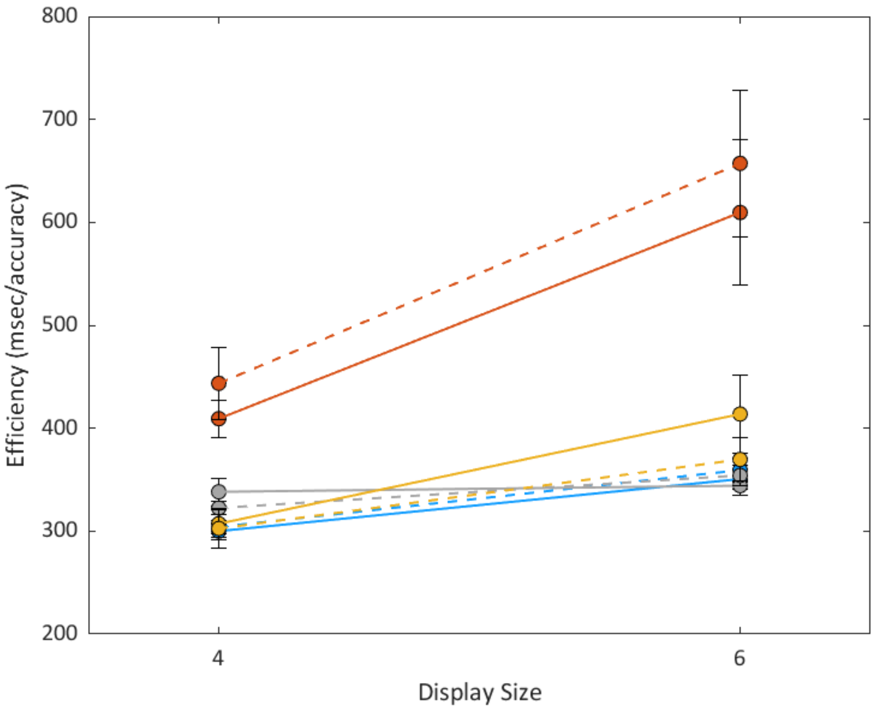
Group x Condition x Display interaction failed to reach significance, *F*(9, 168) = 0.27, *p* = .98, partial η^2 = .01.

Since there was no significant difference between the group's slopes, the efficiencies and efficiency slopes were visually inspected to determine which reduction level had the closest preview and preview gap slopes, as this was the overall aim. At the -25% reduction level, there was quite a large difference between these slopes, with preview slopes at ~10 msec/item and preview gap slopes at ~61 msec/item. Comparatively, at -100% binding reduction, slopes became much closer, with preview slopes at ~16 msec/item and preview gap slopes at ~34 msec/item. As such, this level of -100% temporal binding was chosen. Therefore, while the low Conners 3AI group was simulated by a 4.17% reduction in synaptic strength, the high Conners 3AI group was simulated by both a 4.17% reduction in synaptic strength and 100% reduction in temporal binding.

Simulated Low Conners 3AI vs. Simulated High Conners 3AI. Lastly, efficiencies were analysed using a 2 (group) x 4 (condition) x 2 (display) mixed ANOVA. Group (simulated low Conners 3AI x simulated high Conners 3AI) were between-subjects factors. Condition (single-feature x conjunction x preview x preview gap) and display size (4 x 6) were within-subjects factors. Levene's test indicated that the assumption of homogeneity of variance had been violated for efficiencies in preview at display size 4, *F*(1, 28) = 9.72, *p* < .01. However, this assumption was met for all other variables. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Condition, $\chi^2(5)$ = 57.52, *p* < .001, and for the Condition x Display interaction, $\chi^2(5)$ = 80.97, *p* < .001. Accordingly, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = .491 and ε = .432, respectively). Efficiency did not significantly differ between groups, *F*(1, 28) = 0.60, *p* = .45, partial η^2 = .02. However, efficiencies did differ significantly between conditions, *F*(1.47, 41.23) = 167.81, *p* < .001, partial η^2 = .86. Furthermore, there was a significant interaction between group and condition, *F*(3, 84) = 3.38, *p* < .05, partial η^2 = .11. Efficiency decreased as display size increased, $F(1, 28) = 154.30$, $p < .001$, partial $\eta^2 = .85$. The Condition x Display interaction was significant, $F(1.30, 36.32) = 24.84$, $p < .001$, partial $\eta^2 = .47$. Group did not interact with display, $F(1, 28) = 0.01$, $p = .94$, partial $\eta^2 = .00$. Finally, the Group x Condition x Display interaction failed to reach significance, $F(3, 84) = 0.74$, $p = .53$, partial $\eta^2 = .03$.The mean efficiencies for both groups are shown in Figure 3.7

Figure 3.7

Mean Efficiencies for Each Condition and Display Size for Simulated Low and High Conners 3AI Groups



Note. Simulated low Conners 3AI = solid lines; simulated high Conners 3AI = dashed lines. Blue = single-feature; orange = conjunction; grey = preview; yellow = preview gap. Error bars represent ±2 SE.

3.2.4 Computational Modelling Discussion

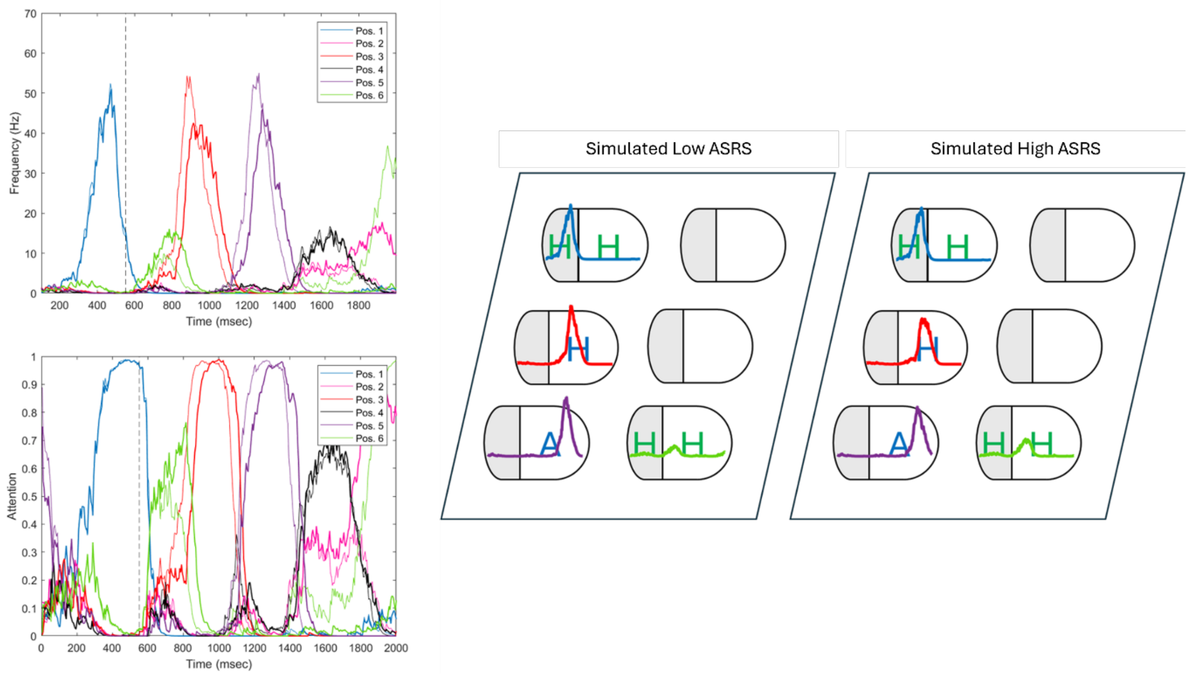
The aim of the present study was to use a neurocomputational model to test whether temporal binding differences could account for visual search performance in children with high levels of ADHD symptoms. This prediction was first derived from the behavioural study reported in the beginning of this chapter. In the simulated low Conners 3AI children, preview slopes were close to zero (~ 3 msec/item), indicating highly efficient search. In the preview gap condition, however, slopes became very inefficient (~53 msec/item). This loss of the preview benefit provides a qualitative match for performance observed in the low Conners 3AI group, as well as in previous reports of healthy adults (Watson & Humphreys, 1997). In the simulated high Conners 3AI children, where temporal binding was eliminated from the model, these two slopes grew much closer together. Slopes in the preview condition became higher (~ 16 msec/item) and slopes in the preview gap condition became lower (~ 34 msec/item). Accordingly, removing temporal binding in the b-sSoTS-c model provides a qualitative match for the visual search performance demonstrated by the high Conners 3AI group in the behavioural study.

One of the key benefits of using neurocomputational models is their ability to provide invaluable insights into why certain patterns of behaviour arise. Here, the effect of temporal binding can be explored and understood through the spiking activity of the model. As previously discussed, the first result that came about from the removal temporal binding was the increase in preview slopes. Figure 3.8 shows spiking activity in the preview condition. In the simulated low Conners 3AI group, when the final display appears, there's additional activation to the newer items, which share a common onset. Because old items don't share this onset here, these items end up competing less, leading to more efficient search slopes. In the simulated high Conners 3AI group, the additional activation from temporal binding is gone, and thus old items continue to compete at a higher level in the final display, leading to less efficient search slopes. An example of how this change in temporal binding affects old preview items can be seen in the activity of the preview item at position six in Figure 3.8.

In addition to increased preview efficiency, there was also a decrease in preview gap efficiency. Figure 3.9 shows the spiking activity in the preview gap condition. Here, in the simulated low Conners 3AI group, old preview items and new items receive additional activation at the final display as a result of their common onset after the gap display. For this group, the temporal binding that occurs at the final display allows all items to compete fully again, thus making search in this condition less efficient. In the simulated high Conners 3AI group, however, since old items do not receive any additional activation in the final display, they become suppressed, and therefore compete less. This lack of temporal binding therefore results in more efficient preview gap search. An example of how temporal binding affects the activity of old preview items in the preview gap search can be seen clearly in the activity of the preview item at position one in Figure 3.9.

Figure 3.8

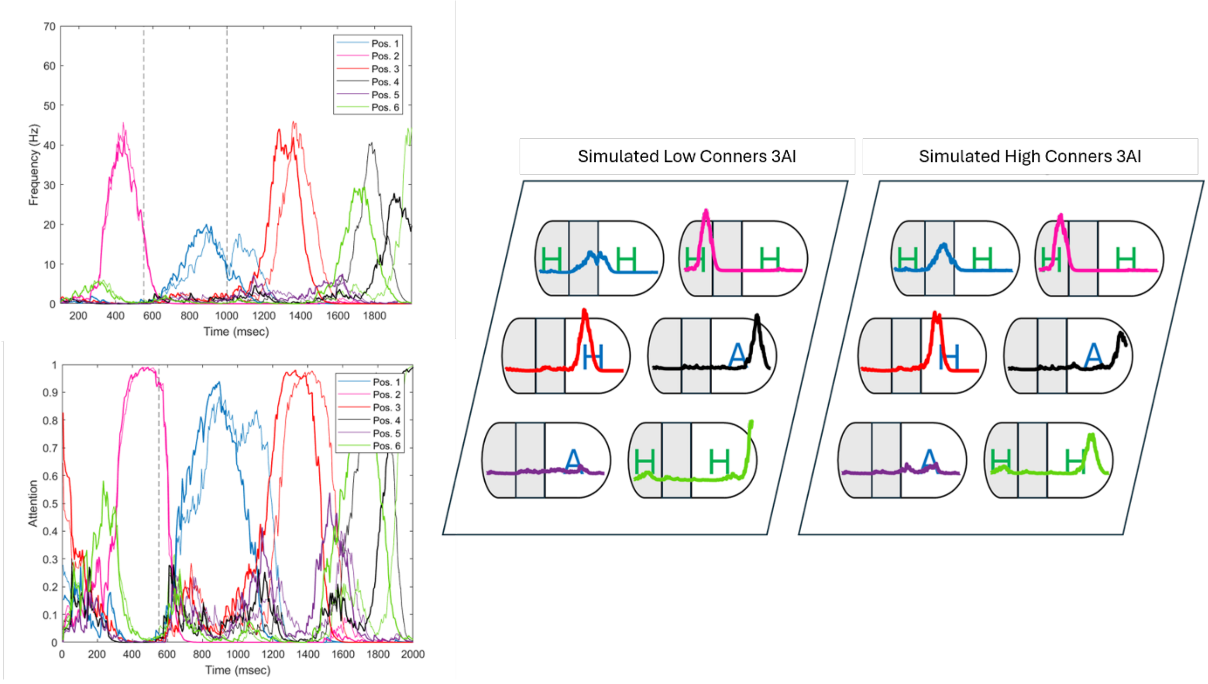
Spiking Activity in the Pools of the Location Map in the Preview Condition for Simulated Low and High Conners 3AI Groups



Note. On the right side, firing rates for each pool within the location map are shown. The grey portion of the circle represents the time of the preview display, while the white portion represents the final display. At the top on the left, firing rates for all positions are combined into a single graph. The graph at the bottom on the left depicts “attention” to each item, computed by the contrast between the attended item and other positions. Simulated low Conners 3AI = thin lines; simulated high Conners 3AI = thick lines.

Figure 3.9

Spiking Activity in the Pools of the Location Map in the Preview Gap Condition for Simulated Low and High Conners 3AI Groups



Note. On the right side, firing rates for each pool within the location map are shown. The first grey portion of the circle represents the time of the preview display. The second grey portion represents the gap display. Finally, the white portion represents the final display. At the top on the left, firing rates for all positions are combined into a single graph. The graph at the bottom on the left depicts "attention" to each item, computed by the contrast between the attended item and other positions. Simulated low Conners 3AI = thin lines; simulated high Conners 3AI = thick lines.

Taken together, these results indeed support the hypothesis of reduced temporal binding in ADHD. There has been very limited research on temporal binding in ADHD. Despite this, the results here are consistent with a previous study by Alderson et al. (2022), who demonstrated that children with ADHD performed worse in a working memory task when the colour-shape binding of stimuli was required, leading the authors to propose binding difficulties in ADHD (Alderson et al., 2022). However, using a similar paradigm, Ortega et al. (2020) found that children with ADHD had no differences in colour-shape binding (Ortega et al., 2020). In the present study, temporal binding refers to the binding of two separable features - both of which are in the visual domain. Other types of temporal binding can occur when features from different modalities (e.g., visual and auditory) occur simultaneously. Recent work by Schulze et al. (2021) found that individuals with ADHD had more audio-visual binding failures compared to healthy controls (Schulze et al., 2021). A follow-up diffusion MRI study by these authors subsequently found that percentage of successful cross-modal binding in individuals with ADHD was associated with differences in structural connectivity (Schulze et al., 2023). Finally, gamma-band oscillations have been linked to the binding of visual features using single-cell recoding studies, EEG, and even behavioural techniques (Csibra et al., 2000; Elliot & Müller, 2000; Gray et al., 1989; Herrmann & Mecklinger, 2000; Singer & Gray, 1995). Although activity in the gamma band is one of the lesser studied frequency bands in ADHD research (Michelini, Salmastyan, et al., 2022), the limited reports show that gamma band responses in ADHD are indeed often atypical (Barry et al., 2010; Lenz et al., 2010; Tombor et al., 2019; Wilson et al., 2012; Yordanova et al., 2001).

3.3 General Discussion

The aim of the present chapter was to use both behavioural and computational modelling methods to explore differences in time-based attention in ADHD. In the behavioural study of this chapter, preview and preview gap search were used to examine visual marking and temporal binding in both children with low and high levels of ADHD traits. It was hypothesized that children with high levels of ADHD traits (as determined by their Conners 3AI score) would demonstrate differences in both visual marking and temporal binding. Contrary to this prediction, children with high Conners 3AI scores were able to generate a preview benefit similar to their low-Conners-3AI-score peers, suggesting intact visual marking for both groups. Furthermore, both low and high Conners 3AI groups lost the preview benefit in the preview gap condition. However, a regression showed that the magnitude of the preview gap benefit was significantly related to level of ADHD trait. Guided by this and the a priori hypothesis, an exploratory analysis was conducted specifically into the preview gap condition between groups. This ultimately demonstrated that, while the preview benefit is lost in the low Conners 3AI group, the benefit is actually maintained in the high Conners 3AI group. This led to the hypothesis that temporal binding may be affected in individuals with high levels of ADHD traits, which was then tested in the second part of this chapter.

The second part of this chapter was the computational modelling study to test the hypothesis posited in the behavioural study. Here, the b-sSoTS-c model was used to simulate visual search performance in the low and high Conners 3AI groups. Then, the mechanisms underlying this performance were analysed by examining activity at the spiking level. The change in synaptic strength from the previous chapter was used to simulate the low Conners 3AI group, as these children were regarded as youth in the general population (compared to youth with ADHD). For the high Conners 3AI group, in addition to the synaptic strength reductions, temporal binding was also reduced. First, to identify the relevant value for the *wbind* parameter, a parameter search was conducted, where simulations were run and examined at reductions increasing by 25% (i.e., -25%, -50%, -75%, -100%). There was no statistically significant difference between these variations. However, when there was no temporal binding in the model, preview slopes became less efficient (from ~3 msec/item to ~16 msec/item) and preview gap slopes became more efficient (from ~53 msec/item to ~ 34 msec/item). Thus, the removal of temporal binding in the b-sSoTS model provides a good qualitative account of visual search performance in ADHD. Taken together, these two studies indeed provide compelling evidence that reduced temporal binding may affect allocation of spatiotemporal attention in ADHD.

The outcomes of the present study are significant as it demonstrates two important characterisations of time-based attention in ADHD. Firstly, despite the widely prevalent differences in top-down attention in ADHD (Hokken et al., 2023; Mullane & Klein, 2008; Onandia-Hinchado et al., 2021; Wang et al., 2016), visual marking appears to be intact. One reason for this intact mechanism may be that visual marking also relies on a passive inhibition mechanism alongside the active inhibition (Mavritsaki et al., 2006, 2011). The b-sSoTS model shows how this process unfolds. When preview items first appear, the neurons encoding for these stimuli increase their firing as attention is directed to these items. As a result of this high level of firing, a relatively large amount of calcium enters the cell. As calcium enters, the frequency of firing progressively lessens until the cells become fully saturated and unable to fire again. At the behavioural level, this equates to these items become less visibly salient until they can be ignored completely. While the preview benefit relies on both passive and active inhibition, and these interact dynamically, it may be that, because this passive mechanism works alongside the active inhibition, top-down attention is not taxed to the level necessary to generate behavioural differences (Bellgrove et al., 2013; Mukherjee et al., 2021). This is, however, speculative. Future research could potentially use neuroimaging methods like EEG to determine whether this visual marking is indeed intact or whether differences are not observable at the behavioural level.

The second outcome here is also significant as it demonstrates ADHD-related differences in a more bottom up functions of perception and attention - temporal binding. While bottom-up attention difficulties have indeed been reported in ADHD (Guo et al., 2023; Wang et al., 2016, 2017), they are often less prevalent (or less frequently discussed) than those of top-down control. However, it's important to consider where differences may originate within the cortical hierarchy. An example of how these differences may be obscured can be seen in a task that requires stimuli to be matched to an attentional template to determine its candidacy as a target. If a stimulus in the visual field is a target, but there's weak representation of the item in working memory (i.e., a top-down issue), this will affect performance. There is another situation to consider, however. If a stimulus is a target, and the target is represented strongly in working memory, but the perceptual construction of the stimulus is weak or noisy (i.e., a bottom-up issue), this may lead to identical difficulties at the behavioural level. Indeed, although bottom-up and top-down attention are often treated like distinct mechanisms, they interact dynamically, so that an issue in one will undoubtedly affect the other (Anderson & Kim, 2019; Awh et al., 2012; Vecera et al., 2014). Accordingly, it can be difficult to parse these apart. This difficulty can be quite effectively addressed by using neurocomputational models that can examine the effects of different mechanisms both independently and together.

Here, although reduced temporal binding lead to worse performance in the preview condition, they actually give rise to improved performance under the slightly different task conditions of preview gap. Importantly, the simulations with the b-sSoTS model show that this very subtle, low-level temporal binding process can actually produce observable and somewhat paradoxical results at the behavioural level. As previously mentioned, there is extremely limited research that considers temporal binding in ADHD. Here, however, it is shown that this process could potentially contribute to differences in this disorder and therefore should be considered in tasks that examine time-based attention in ADHD. Furthermore, the outcome of this reduced temporal binding relies heavily on the conditions of the task, and it should be studied further how reduced temporal binding might present behaviourally.

An important point to remember is that, in the behavioural study, the ANOVA showed no significant differences between groups. However, there was a significant relationship between ADHD trait and PGB. The PB and PGB are calculated from the slopes in each condition (see section 2.1.3). One aspect of the PG and PGB to consider is the number of outliers that are contributing to a high amount of variability, both in the high Conners 3AI group and in the preview gap benefit. This variability can be clearly seen in Figure 3.4. For instance, for the high group's preview gap benefit, the mean of 0.8093 suggests that this group was able to suppress around 81% of items. However, the confidence interval indicates that, in 95% of samples, the population mean will fall between 0.471 (~ 47% of items) and 1.147 (~115% of items). There was also a large 95% confidence interval for the significant Kendall's tau b value showing a significant relationship between ADHD trait and PGB. Accordingly, this relationship should be interpreted with caution, and further research is needed to confirm these results. Nevertheless, the present chapter still serves as an intriguing foundation for considering how bottom-up attention functions may contribute to ADHD-related differences in performance. Finally, the increased variability in the high ADHD group seen is indeed consistent with extensive research showing that variability in performance is commonly observed in ADHD (Arnett et al., 2023; Gonen-Yaacovi et al., 2016; Mowinckel et al., 2017), with some suggesting that this serves as one of the only consistent characteristics among all individuals with ADHD (Bellgrove et al., 2005; Karalunas et al., 2014). Accordingly, noisy performance in ADHD could be a further point of study for future research, particularly through computational modelling (Hauser et al., 2016b).

Although there are certainly cases of "pure" ADHD, there is also a very high rate of comorbidity in children with ADHD. Conduct disorder (CD) and oppositional defiant disorder (ODD) are two of the most common comorbidities with ADHD, with a reported prevalence of 27% to 55% (Barkley, 2006). In children with comorbid CD and ADHD, neurocognitive impairments are often more severe (Banaschewski et al., 2003; Hobson et al., 2011). Furthermore, studies report that CD is more closely associated with high levels of impulsivity and risk-taking (Hobson et al., 2011) that likely contributes to their behavioural profile of antisocial symptoms (e.g., increased aggression, fighting, stealing, etc.; Bari & Robbins, 2013). Ultimately, the additional/exacerbated symptoms in these individuals could contribute to differences in responding to salient stimuli and ignoring irrelevant information. For example, while ADHD has been associated with low levels of arousal (Mayer et al., 2016; Strauß et al., 2018), studies have shown that individuals with conduct disorder often demonstrate the opposite - increased levels of arousal and activation in response to stimuli (Lijffijt et al., 2017; Zhang et al., 2015). In the present study, comorbidities were not screened for in the high Conners 3AI group. Therefore, future work should address this limitation.

Overall, the present study adds to our current knowledge of how selection differences arise and present in ADHD (Hauser et al., 2016b; Mueller et al., 2017). Research that aims to uncover the nature of differences in ADHD and bring to light their underlying mechanisms contributes to an important foundation in identifying potential cognitive or biological markers for the disorder (Chen et al., 2023; Michelini, Norman, et al., 2022; Pagán, Huizar, & Schmidt, 2023). Developing more objective measures of ADHD will support our collective effort to effectively identify, accommodate, and treat affected individuals (Sonuga-Barke et al., 2023)

3.4 Chapter Summary

Much of the existing research in ADHD has examined top-down differences in these individuals. However, much less attention has been afforded to potential bottom-up differences. As these two types of attention interact dynamically to produce efficient and flexible performance at the behaviour level, much can be gained from developing a better understanding of what kinds of differences arise in ADHD, and how these impact (nearby) functions. In the present chapter, a behavioural study was first conducted to examine time-based attention between children with low and high levels of ADHD traits (as determined by their Conners 3AI score) using preview and preview gap search. Due to previously reported differences in the neural mechanisms that support attention, it was hypothesized that children with high levels of ADHD traits would demonstrate differences in visual marking, a top-down distractor suppression mechanism, and in temporal binding, a bottom-up saliency mechanism. Children with high levels of ADHD traits did not show any differences in visual marking, illustrated by a benefit in the preview condition similar to their low ADHD-trait peers. However, evidence of temporal binding differences were shown through a significant relationship between level of ADHD trait and preview gap benefit. Furthermore, an exploratory analysis showed that, unlike low ADHD-trait children, children with high levels of ADHD-traits were able to maintain the preview benefit in the preview gap condition. This led to the hypothesis of reduced temporal binding in children with high ADHD-traits. This hypothesis was then tested in the next part of this chapter, the computational modelling study. Here, the removal of temporal binding in the b-sSoTS-c model led to a qualitative match to the behavioural results for high Conners 3AI children, thus supporting the notion of reduced temporal binding in ADHD. Spiking data showed that the temporal binding impacts the level to which preview items compete for selection in the final display. In the next chapter, preview and preview gap search are examined in adults with high ADHD traits to determine whether this reduced temporal binding might also exist after development.

Chapter 4: Exploring Time-Based Attention in Adult ADHD

In the previous chapter, findings showed some evidence of reduced temporal binding in children with high levels of ADHD compared to their age- and IQ-matched low ADHD peers. While ADHD first arises in early childhood, symptoms and/or impairments very often continue into adulthood (Biederman et al., 2000; Breda et al., 2021; Faraone et al., 2006; Sibley et al., 2022). Previous literature has demonstrated that ADHD in adulthood is associated with continued difficulty in the ability to allocate attention both across space and over time (Cross-Villasana et al., 2015; Gmehlin et al., 2016; Guo et al., 2022; Guo et al., 2023; Mukherjee et al., 2021; Salomone et al., 2020; Somogyi et al., 2023). Cognitive and functional impairments have been shown to extend to subclinical cases of ADHD in adulthood (Sibley et al., 2022) and can worsen when comorbid mental disorders are present (Bartoli et al., 2023; Torres et al., 2017). Although subclinical, clinical and comorbid cases of ADHD all demonstrate differences in selective attention (Arat Çelık et al., 2021; Biederman et al., 2018; Lundervold et al., 2011; Marchetta et al., 2008; Pagán, Huizar, & Schmidt, 2023; Torres et al., 2017), more research is required to uncover the subtle commonalities and distinctions between these subgroups. Therefore, in the present chapter, the investigation of time-based attention is extended to adults with varying levels of ADHD. In a first behavioural study, adults with either low, borderline, or high levels of ADHD traits are compared in preview and preview gap search. The face-to-face data collection for this initial study was disrupted due to the COVID-19 lockdowns, however. Accordingly, a second behavioural study was conducted whereby, these groups, plus an additional group with high levels of ADHD and high levels of impulsiveness are compared on these tasks in a fully online format. This chapter begins with a brief review of the selective visual attention literature in adults with ADHD. The outcomes of these studies provide evidence that, at least in adulthood, time-based attention differences may not be specific to ADHD.

4.1 Comparing Low, Borderline and High ADHD

4.1.1 Background

ADHD has traditionally been characterised as a neurodevelopmental disorder that first emerges in childhood (APA, 2013; Posner et al., 2020; Sonuga-Barke et al., 2023). Indeed, ADHD can be reliably diagnosed as early as preschool (Joseph et al., 2023; Shephard et al., 2022; Tobarra-Sanchez et al., 2022) and age of first diagnosis typically occurs in children's school-aged years (Rocco et al., 2021; Visser et al., 2014). While remission occurs in some, symptoms and/or impairments often continue into adulthood for many (Biederman et al., 2000; Breda et al., 2021; Faraone et al., 2006; Sibley et al., 2022). Recently, research has shown that ADHD can also be a late-onset condition (Asherson & Agnew-Blais, 2019), thus challenging the traditional characterisation of this disorder (Sonuga-Barke et al., 2023). Whether childhood- or late-onset, ADHD affects approximately 6.76% of adults worldwide, which translates to about 366.33 million affected individuals across the globe (Song et al., 2021). ADHD-related symptoms and impairments in adulthood are associated with a wide range of adverse outcomes, including underemployment (Gjervan et al., 2012), difficulty establishing/maintaining relationships (Harpin et al., 2016; Wozniak, 2022), and lower overall quality of life (Gjervan et al., 2014; Orm et al., 2023; Quintero et al., 2019). As such, there exists a distinct need to continue developing a deeper understanding of ADHD and how impairments may present differently in adulthood.

In cases where ADHD persists into adulthood, symptoms and impairments typically undergo fluctuations and changes (Biederman et al., 2000; Cheung et al., 2015; Ginapp et al., 2023; Larsson et al., 2011; Sibley et al., 2022; Willcutt, 2012). For example, while inattentive symptoms typically persistent, hyperactive/impulsive symptoms generally improve over the course of development (Biederman et al., 2000; Cheung et al., 2016; Larsson et al., 2011). Despite these changes in symptoms, at the neural level, the PFC continues to serve as a main neural mechanism underlying difficulties. Similar to children and adolescents with ADHD, adults with ADHD show structural and functional differences in prefrontal areas (Almeida et al., 2010; Chen et al., 2015; Hart et al., 2013; Yang et al., 2019). Furthermore, in cases where remission occurs, there is normalisation of prefrontal structures (Shaw et al., 2006, 2013). PFC differences in adults with ADHD are also apparent at the behavioural level, as these individuals show impairment in neurocognitive domains associated with this area, such as WM (Torgalsbøen et al., 2021) interference control (Pazvantoğlu et al., 2012) and set shifting (Luna-Rodriguez et al., 2018). Recent fMRI research shows that poorer behavioural performance in measures of top-down control in adults with persistent ADHD is associated with lower functional activation in prefrontal and parietal regions, while performance and functional activation in remitted ADHD more closely resembles healthy controls (Schulz et al., 2017). Taken together, these findings support the notion that, similar to children with ADHD, adults with ADHD are likely to experience difficulty particularly in tasks that rely on PFC involvement, such as selective visual attention.

Indeed, similar to children with ADHD, adults with ADHD often demonstrate differences in selective attention (Onandia-Hinchado et al., 2021; Pagán, Huizar, & Schmidt, 2023; Pievsky & McGrath, 2018). For example, adults with ADHD often perform worse than controls when faced with interference from distractors that appear nearby in space (Cross-Villasana et al., 2015; Fuermaier et al., 2015, 2017; Gmehlin et al., 2016; Guo et al., 2022; Mehren et al., 2019; Tucha et al., 2017). These findings at the behavioural level are further supported by neuroimaging methods, such as EEG and fMRI, which show that differences in behavioural performance on attention tasks are accompanied by differences in neural activity (Cross-Villasana et al., 2015; Hsieh et al., 2022; Schulz et al., 2017). For instance, in one of the limited studies that use traditional visual search to examine selective attention in adult ADHD, Cross-Villasana et al. (2015) found that these individuals demonstrate shorter N2pc latency when required to locate a target in a single-feature search, reflective of differences in allocating sufficient attentional resources to a location in space that contains a target item (Eimer, 2014; Stoletniy et al., 2022).

Although it has been demonstrated that the ability to effectively allocate attention across space is impaired in adult ADHD (Cross-Villasana et al., 2015; Fuermaier et al., 2015, 2017; Gmehlin et al., 2016; Guo et al., 2022; Mehren et al., 2019; Tucha et al., 2017), considerably less research has investigated how ADHD in adults affects the ability to allocate attention over time. Indeed, while it has been shown that time-based attention functions like visual marking are largely intact in childhood ADHD (Mason et al., 2003, 2004), it has yet to be confirmed whether this ability continues to be unaffected in adults with ADHD. Interestingly, some previous research indicates the ability to actively suppress distractor items may be affected in adults with ADHD. This evidence comes from an EEG study by Cross-Villasana et al. (2015), in which adults with ADHD completed a visual search task that contained a singleton target (Cross-Villasana et al., 2015). Although not analysed by the authors, Wang et al. (2016) later pointed out that, for adults with ADHD, target-evoked N2pc component faded away with no subsequent contralateral positivity (Wang et al., 2016). This contralateral positivity, which reflects the active termination of attention after selection (Jannati et al., 2003), is also known as the P_D component, which is present during the active suppression of distractors (Sawaki et al., 2012). This P_D component has also been shown to be present during the preview period, thought to reflect the presence of visual marking (Berggren & Eimer, 2018). Accordingly, the lack of a P_D component in Cross-Villasana's study (although here after the target presentation) may indicate differences in this active suppression mechanism in adults with ADHD.

A second time-based attention function, temporal binding, has also yet to be investigated in adult ADHD. Temporal binding - the binding of separable visual feature through common onset, relies on fast and efficient neural communication within- and between- neural regions (Singer, 2015, 2021). Similar to children with ADHD, adults with ADHD have been shown to have altered white matter tract properties between the frontal and parietal regions of important attention networks, as well as between cortical and subcortical regions (Chiang et al., 2022; Gehricke et al., 2017; Konrad et al., 2012; Onnink et al., 2015; Tolonen et al., 2023). Indeed, these alterations in white matter in adults with ADHD contribute to disruptions in overall structural connectivity and reduced efficiency in the transfer of information across the brain (Bu et al., 2021; Ohnishi et al., 2023). Accordingly, these ADHD-related differences in structure and connectivity may contribute to disrupted functions like temporal binding.

Aims of Study. The present study aims to further explore visual marking and/or temporal binding differences by comparing search performance in the preview and preview gap conditions between adults with high, borderline and low ADHD symptoms (as determined by their ASRS scores). The recent acknowledgement of late-onset ADHD in adulthood (Asherson et al., 2016; Asherson & Agnew-Blais, 2019; Breda et al., 2021; Sonuga-Barke et al., 2023) has led to an increased need for research in this population, especially with the accompanying rise in the use of psychostimulant medications for treatment (Sibley et al., 2023). The diagnostic criterion for ADHD is arbitrary, and diagnosed individuals represent extreme cases of a continuum of behaviour present in the general population (Asherson & Trzaskowski, 2015; Larsson et al., 2012). Accordingly, the Adult ADHD Self Report Scale (ASRS) Screener (Kessler et al., 2005) is used here to determine these three groups in a sample of adults.

While previous research of adult ADHD has shown that these individuals demonstrate differences in selective visual attention (Cross-Villasana et al., 2015; Guo et al., 2022; Guo, Fuermaier, Koerts, Tucha, Scherbaum, & Müller, 2023; Salomone et al., 2020; Wang et al., 2016), others have found no significant differences (Roberts et al., 2018). These inconsistencies in ADHD literature may arise as a result of the prevalent use of medication in this disorder, which has shown to normalize ADHD-related brain differences (Rubia et al., 2014; Rubinson et al., 2019; Schweren et al., 2013; Silk et al., 2014). Contrary to the widespread evidence within the ADHD literature to support the notion of top-down selective visual attention difficulties in ADHD, the results of the previous chapter showed that top-down attention, at least in the form of top-down attentional suppression of distractors over time (i.e., visual marking) is intact in children with ADHD. While these results are supported by previous behavioural studies examining visual marking in childhood ADHD (Mason et al., 2003, 2004), this has yet to be investigated in adults with ADHD. While some evidence indicates differences in active distractor suppression/visual marking may be present in adult ADHD (Cross-Villasana et al., 2015; Wang et al., 2016), it is hypothesized here that, similar to children with high ADHD symptoms, adults with high ADHD symptoms will also likely demonstrate this pattern of no behavioural differences in visual marking, apparent through a preview benefit similar to adults with low and borderline ADHD symptoms.

Although individuals with ADHD may be able to generate a preview benefit, they may have difficulty in the more bottom-up time-based attention mechanism, temporal binding. Indeed, in the previous chapter, there was some evidence that children with high ADHD symptoms experience difficulty in this function. This reduced temporal binding thus may also affect adults with high ADHD symptoms. Accordingly, it is hypothesized that, search patterns in the low ASRS group will show a strong preview benefit in the preview condition, as well as a loss of the preview benefit in the preview gap condition. While the high ASRS group may also be able to generate a preview benefit similar to that in the low ASRS group, it is hypothesized that performance in the preview gap condition for the high ASRS group will be significantly more efficient than the low ASRS group, indicative of reduced temporal binding. Finally, the borderline ASRS group's preview gap benefit will be between that of the low and high ASRS groups.

4.1.2 Method

Participants. A total of 76 participants were recruited for the study. The high ASRS group consisted of 27 participants (*M* = 22.00 years, *SD* = 5.23), with 9 (33.3%) males and 18 (66.7%) females. In the borderline ASRS group, there were 30 participants (*M* = 20.87 years, *SD* = 4.48), with 4 (13.3%) males and 26 (86.7%) females. The low ASRS group consisted of 19 participants (*M* = 23.11 years, *SD* = 5.49), with 4 (21.1%) males and 15 (78.9%) females. Group assignment was decided according to the participant's Adult ADHD Self-Report Scale (ASRS) Screener score, which is described in detail below. All participants were recruited through Birmingham City University's RPS. Those interested in participating in the study were required to read the participant information sheet (see Appendix A) and provide written informed consent online (see Appendix B). Exclusionary criteria included a history or serious mental or physical health condition, such as epilepsy. Other exclusionary criteria included a diagnosis of ADHD and/or a history of treatment for ADHD. One individual reported medication used for a diagnosis of ADHD and was therefore excluded from the analysis. All participants reported having normal or corrected-to-normal vision. Individuals received course credit in exchange for their participation. Every experiment took place at the Department of Psychology, Birmingham City University and received ethical approval by the Business, Law, and Social Sciences Faculty Academic Ethics Committee (reference: Klein /3199 /R(A) /2019 /Mar /BLSS FAEC; see Appendix D)

A one-way ANOVA was conducted to confirm there were no significant differences in age or intelligence (see below) at different levels of ADHD traits (as determined by ASRS score). For age, there was no significant effect of ASRS score, *F*(2, 73) = 1.18, *p* = .312, η^2 = .03. Similarly, there was no effect of ASRS score on intelligence, *F*(2, 73) = 0.71, *p* = .495, η^2 = .03. Lastly, a one-way ANOVA was also conducted to confirm the groups did differ significantly on their ASRS screener scores (see below). Indeed, there was a significant effect of ADHD-trait on ASRS screener score, *F*(2, 73) =

133.28, $p < .001$, $\eta^2 = .79$. Post-hoc comparisons showed that the low ASRS group differed significantly from the borderline and high groups (both at $p < .001$) and the borderline and high group also differed significantly (at p < .001). Thus, groups differed significantly on ADHD symptom level but were matched in terms of age and intelligence. Table 4.1 shows these results.

Table 4.1

Means and Standard Deviations on Age, Intelligence, and ADHD Symptoms in Groups

Measure	Low ASRS	Borderline ASRS	High ASRS	*p*
Age (in years)	23.11 (5.49)	20.87 (4.48)	22.00 (5.23)	.312
WASI-II FSIQ-4	109.50 (10.27)	106.72 (9.90)	110.71 (10.12)	.495
ASRS Screener	7.00 (2.00)	10.90 (0.92)	17.00 (2.96)	< .001

Note. WASI-II FSIQ = Weschler's Adult Scale of Intelligence, 2nd Edition Full Scale Intelligence Quotient; ASRS = ADHD Self-Report Scale; Standard deviations are presented in parentheses.

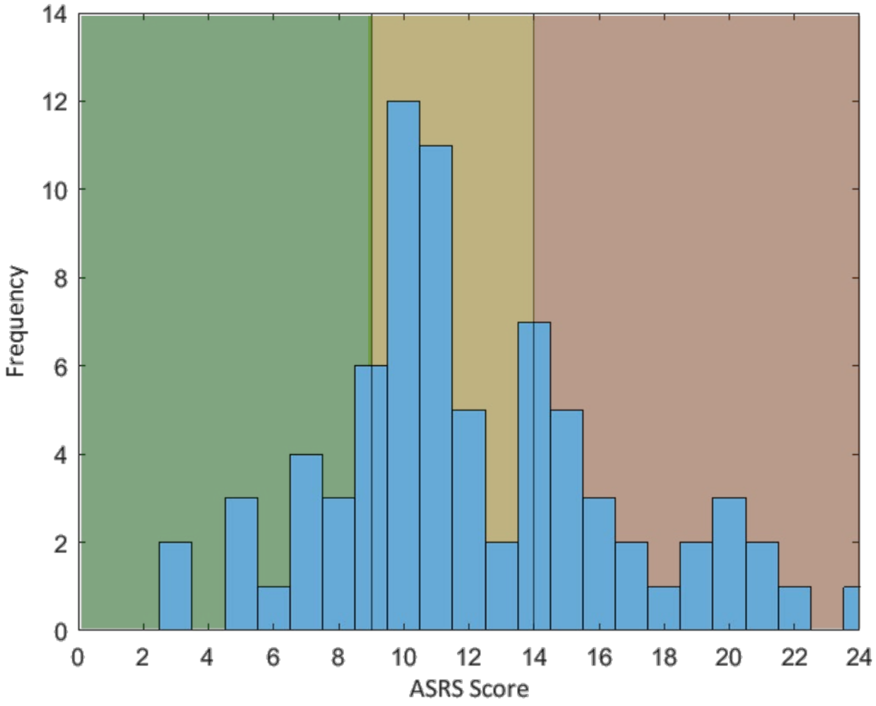
Materials. ***Weschler's Abbreviated Scale of Intelligence, 2nd Edition***. Each participant was tested using Weschler's Abbreviated Scale of Intelligence, 2nd Edition (WASI-II; Wechsler, 2011) to provide an estimate of intelligence. This intelligence scale is comprised of four subtests: Block Design, Vocabulary, Matrix Reasoning and Similarities. For each subtest, the sum of the raw scores were converted into a standardised score that were matched to the Full-Scale Intelligence Quotient (FSIQ-4) based on the participant's age. Overall results for the adult sample indicate good (.83) to excellent (.94) stability coefficients for the subtests and excellent (.90-.96) coefficients for the composites.

Adult ADHD Self-Report Scale Screener. Participants were asked to complete the Adult ADHD Self-Report Scale (ASRS) screener (Kessler et al., 2005, 2007) in order to provide a current rating of ADHD symptom severity. The ASRS screener is comprised of six items that correspond to DSM-IV diagnostic criteria for ADHD (see Appendix M). This short screener was derived from a longer, 18-item ASRS; however, it has been shown that the screener version's adequate sensitivity (68.7%), excellent specificity (99.5%), excellent classification accuracy (97.9%) outperformed the original 18-item ASRS (Kessler et al., 2005, 2007). Furthermore, the ASRS screener has shown good internal consistency and test-retest reliability (Kessler et al., 2007; Lewczuk et al., 2024; Lovett et al., 2021; Matza et al., 2011).

For each item on the ASRS screener, participants indicate how well the symptom describes occurrence of symptoms on a five-point response scale of never (0), rarely (1), sometimes (2), often (3) and very often (4). This yields a total score with a range from 0 to 24. Previous research has shown that, from this 0-24 scoring approach, a four-stratum classification scheme can be derived. In a large representative sample of health plan members, Kessler et al. (2007) showed that none (0.0%) of clinician-defined cases of ADHD had screener scores in the range of 0 to 9, while 58.8% of clinician-defined non-cases had screener scale scores in this range. Accordingly, in the present study, individuals with screener scale scores in this range were classified as "Low ASRS." In the second group (scores between 10 and 13), there were 35.1% of clinician-defined cases and 35.1% of clinician-defined non-cases. Here, this is defined as the "Borderline ASRS" group. In the last two groups (14-17 and 18-24), there were higher proportions of cases than non-cases; thus, individuals in either of these groups were classified as "High ASRS." The distribution of ASRS screener scores are shown in Figure 4.1.

Figure 4.1

Distribution of Scores on the Adult ADHD Self-Report Scale (ASRS) Screener



Note. Individuals with *s*cores between 0-9 are considered to have a low ASRS scores (green background); individuals with scores between 10 and 14 are considered to have a borderline ASRS scores (yellow background); individuals with scores between 15 and 24 are considered to have a high ASRS scores (orange background). Additional details about grouping procedure in text (see section 4.1.2).

Stimuli and Equipment. The stimuli and equipment used in the present study were the same as those used in the previous behavioural studies in chapters 2 and 3. The experiments were created using OpenSesame version 3.3 (Mathôt et al., 2012) and run on a Lenovo ThinkPad Yoga 12 laptop computer with an Intel Core i5 graphics card. In all experimental conditions, the target item was a blue [RGB = 0, 0, 225] letter H. Distractor items were green [RGB = 0, 128, 0] letter Hs and blue letter

As**.** Stimuli were displayed on a 12.5” digitized LCD screen 1920 x 1080 pixels running at 60 Hz. Stimuli were viewed from approximately 50 cm.

Design. The design of the present study was a 3 (group) x 4 (condition) x 3 (display size) mixed design. Group was a between-subjects factor with three levels (low ASRS x borderline ASRS x high ASRS). Condition and display size were both within-subjects factors. Condition had four levels (single-feature x conjunction x preview x preview gap) and display size had three levels (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction, preview and preview gap). Mean RTs and accuracies were calculated for each participant, condition and display size.

Procedure. Participants signed up for the experiment using the university’s online research participation scheme (RPS) platform (bcu.sona-systems.com). Those interested were directed to the study’s webpage. Here, participants were exposed to the study’s participant information sheet (see Appendix A). Once they familiarised themselves with the details of the study, it was confirmed then that potential participants were 18 years or older. Consent to participate was obtained on this online platform (see Appendix B). After consent was obtained, participants were then required to fill out their responses on the ASRS screener (see Appendix M). Once completed, participants were contacted by the researcher to schedule a date and time to meet to complete the visual search task and intelligence testing. Testing took place in a quiet room with a table and chairs, located at Birmingham City University’s City Centre campus. The search task and intelligence testing were administered in a single session, typically lasting 60 to 75 minutes. The visual search task was always completed first. The procedure for the visual search task was identical to that described in previous chapters (see section 2.1.2). Participants were debriefed upon completion of the study (see Appendix E).

Data Analysis. In cases where Mauchley’s test had indicated that the assumption of sphericity was violated, the Greenhouse-Geisser correction was used when estimates of sphericity were less than 0.75. When estimates of sphericity were greater than 0.75, the Huynh-Feldt correction was used. Similar to the behavioural studies in the previous chapters, RTs were sorted for each participant, condition, and display size, and these are shown in Table 4.2. Responses were excluded from analysis if they met one of the following criteria: (1) response incorrectly identified the location of the target; (2) response below 200 msec; (3) response more than 3 standard deviations above or below the participant's mean for a given condition and display size (see Mason et al., 2003). Accuracy (i.e., percentage of correct responses) was also calculated for each participant, condition and display size, and the mean accuracies for each group are shown in **Table 4.3**. Slopes of the RT-display size function were calculated using display sizes 4, 8 and 16 for all conditions (see Watson & Humphreys, 1997). Slope statistics are shown in Table 4.4.

Table 4.2

Mean RTs for Groups in Each Condition and Display Size

Condition	Low ASRS		Borderline ASRS		High ASRS	
	Mean	*SD*	Mean	*SD*	Mean	*SD*
Single-feature 2	508.47	62.98	546.28	127.89	550.32	88.26
Single-feature 4	569.61	108.39	590.80	141.54	619.68	113.32
Single-feature 8	630.70	102.10	653.72	124.26	662.22	100.28
Conjunction 4	608.97	80.72	646.57	113.01	663.17	110.57
Conjunction 8	734.44	129.13	757.09	170.43	797.75	148.89
Conjunction 16	984.23	228.28	974.83	212.96	1079.56	269.01
Preview 4	531.39	83.15	581.11	133.35	609.67	147.44
Preview 8	600.27	78.16	626.87	126.15	681.72	186.57
Preview 16	720.87	124.50	758.84	165.24	799.11	203.36
Preview gap 4	561.30	84.66	585.04	105.73	607.52	95.00
Preview gap 8	689.78	125.76	704.43	126.10	727.35	138.50
Preview gap 16	898.80	195.33	857.68	163.58	949.88	207.19

Table 4.3

Mean Accuracy Rates for Groups in Each Condition and Display Size

Condition	Low ASRS		Borderline ASRS		High ASRS	
	Mean	*SD*	Mean	*SD*	Mean	*SD*
Single-feature 2	97.11	3.03	97.83	2.84	94.26	4.74
Single-feature 4	95.26	4.24	96.00	4.62	96.30	3.82
Single-feature 8	96.58	4.73	97.00	4.07	95.00	3.67
Conjunction 4	98.16	2.48	96.83	4.04	94.26	5.32
Conjunction 8	97.63	2.56	97.33	4.50	97.04	3.74
Conjunction 16	94.74	5.89	96.00	4.62	96.67	5.72
Preview 4	95.00	5.53	96.33	3.70	96.85	3.96
Preview 8	96.32	4.03	95.00	5.25	96.11	4.67
Preview 16	97.89	3.84	96.00	5.48	96.67	3.67
Preview gap 4	97.37	2.56	96.33	4.14	97.04	3.99
Preview gap 8	96.05	4.27	96.00	5.32	94.26	5.67
Preview gap 16	96.58	4.43	96.83	4.04	95.74	6.00

Note. Percentages are shown.

Table 4.4

Slope Statistics for Groups

Group/Statistic	SF	CJ	PV	PVG
Low ASRS				
Slope	9.82	31.27	15.69	27.84
Intercept	477.92	484.07	471.09	456.79
Linearity (%)	98.19%	100.00%	99.94%	99.86%
Borderline ASRS				
Slope	8.80	27.34	15.05	22.21
Intercept	514.82	537.70	515.12	508.41
Linearity (%)	99.58%	100.00%	99.66%	99.30%
High ASRS				
Slope	8.75	34.77	15.63	28.43
Intercept	529.05	522.27	550.98	496.25
Linearity (%)	94.68%	99.99%	99.86%	99.98%

Note. SF = single-feature; CJ = conjunction; PV = preview; PVG = preview gap.

4.1.3 Results

Relationship Between Level of ADHD and Search Benefit. The relationship between level of ADHD symptoms and search benefit was first examined. The level of ADHD was reflected by a participant's score on the ASRS screener, with a possible range from 0 to 24. While in the comparisons below, participants are separated into three groups, it's also important to consider that ADHD traits are continuously distributed in the general population (Asherson & Trzaskowski, 2015; Sonuga-Barke et al., 2023). The continuous nature of this disorder makes it particularly difficult to be certain where to distinguish non-ADHD from ADHD. Accordingly, it may be beneficial for research to treat ADHD as a continuous variable. In the present study, the mean ASRS score for the entire sample (*N* = 76) was 12.09 (*SE* = 0.52, 95% CI [11.07, 13.12]), with a minimum score of 3 and maximum score of 24.

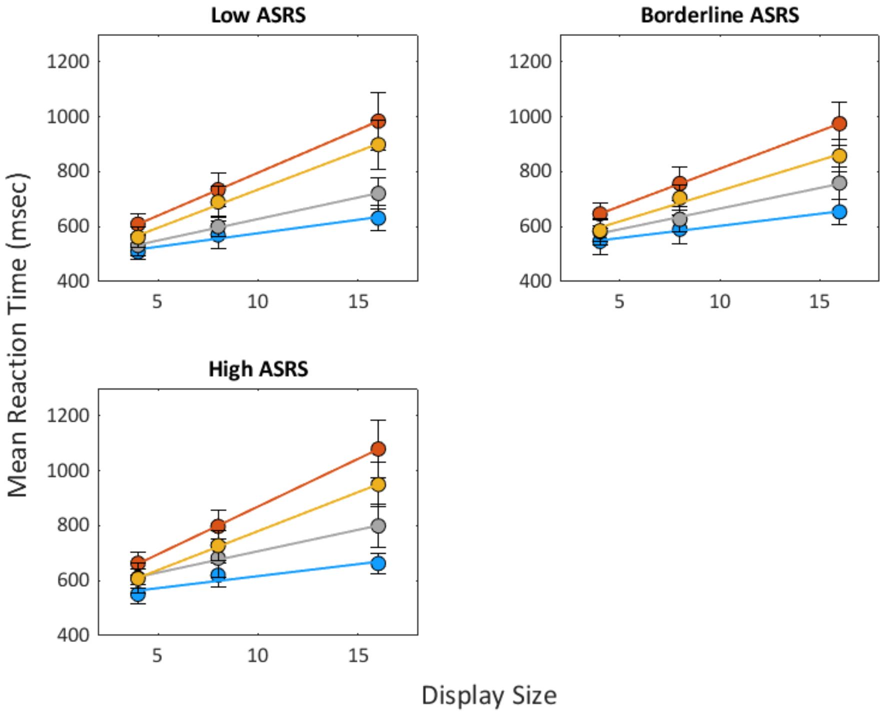
In the present study, search benefit is represented by the preview benefit and preview gap benefit index values (see section 2.1.3). These provide a measure of the benefit to search that arises from the previewing of items and from the offsetting of preview items (i.e., the gap display). Index values are computed using Equations 1 and 2, and the resulting value falls between 0 and 1. The PB is associated with values closer to 1, as this represents a higher percentage of items suppressed by visual marking, with a value of 1 reflecting 100% suppression of old preview items. In the present study, the mean PB index value was 0.62 (*SE* = 0.08, 95% CI [0.47, 0.77]). The PGB is associated with values closer to 0, as this indicates failure to suppress old items, with a value of 0 reflecting none of the preview items being suppressed. Here, the mean PGB index value was 0.04 (*SE* = 0.10, 95% CI [-0.17, 0.24]).

ASRS screener scores, $W = 0.967$, $p < .05$, PB index values, $W = 0.786$, $p < .001$, and PGB index values, $W = 0.847$, $p < .001$, were all non-normal. Accordingly, a Kendall's tau b correlation analysis was used to investigate the relationship between variables. ASRS screener score was not significantly related to either PB index value, $\tau = 0.63$, $p = .438$, or PGB index value, $\tau = .001$, $p = .986$.

Omnibus 3 x 4 x 3 ANOVA – RTs. All statistics for omnibus ANOVAs can be found in Appendix Table N.1. Correct mean RTs were analysed using a mixed 3 (group) x 4 (condition) x 3 (display) ANOVA. Group (low ASRS x borderline ASRS x high ASRS) was a between-subjects factor, and condition (single-feature x conjunction x preview x preview gap) and display (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction, preview, and preview gap) were within-subjects factors. Levene's test revealed that variances were homogeneous for all levels of the repeated measure variables (all *p*s ≥ .08). Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 45.21$, $p < .001$, and for the Condition x Display interaction, $\chi^2(20) = 125.46$, $p < .001$. Accordingly, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .682$ and $\varepsilon = .597$, respectively). Mean RTs did not differ significantly between groups, $F(2, 73) = 1.49$, $p = .23$, partial $\eta^2 = .04$. There was a significant main effect of Condition, $F(3, 219) = 136.82$, $p < .001$, partial $\eta^2 = .65$, and a main effect of Display, $F(1.36, 99.57) = 433.39$, $p < .001$, partial $\eta^2 = .86$. There was also a significant Condition x Display interaction, $F(3.58, 261.66) = 69.75$, $p < .001$, partial $\eta^2 = .49$. This significant interaction is explored further below. None of the other interactions, including the three-way interaction, reached significance. The mean RTs for groups in each condition and display size can be seen in Figure 4.2.

Figure 4.2

Mean RTs for Each Condition and Display Size in Low, Borderline and High ASRS Groups



Note. Single-feature = blue; conjunction = orange; preview = grey; preview gap = yellow. Error bars represent ±2 *SE*s.

Follow-Up 3 x 2 x 3 ANOVAs – RTs. All statistics for the follow-up ANOVAs comparing mean RTs can be found in Appendix Table N.2.

***Single-feature vs. Conjunction*.** Mean RTs from correct trials were analysed using a 2 x 3 ANOVA where condition (single-feature x conjunction) and display size (2 x 4 x 8 for single-feature and 4 x 8 x 16 for conjunction) were both within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 30.94$, $p < .001$, and for the Condition x Display interaction, $\chi^2(2) = 34.67$, $p < .001$. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity for the main effect of display (ε = .745) and for the interaction between condition and display (ε = .740). RTs were significantly faster in the single-feature condition, $F(1, 75) = 354.36$, $p < .001$, partial $\eta^2 = .83$, and increased with display size, $F(1.49, 111.80) = 314.33$, $p < .001$, partial $\eta^2 = .81$. There was a significant Condition x Display interaction, $F(1.46, 109.16) = 141.31$, $p < .001$, partial $\eta^2 = .66$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for single-feature (all $p < .001$s) and for conjunction (all $p < .001$s). Compared to single-feature ($M = 57.50$, $SD = 63.74$), the conjunction condition ($M = 122.80$, $SD = 84.97$) had a significantly larger mean difference between the two lower display sizes, $t(75) = -6.54$, $p < .001$. Between the larger two display sizes, the conjunction condition ($M = 248.52$, $SD = 151.77$) also had a significantly larger mean difference compared to single-feature ($M = 55.22$, $SD = 55.94$), $t(75) = -10.72$, $p < .001$. Conjunction search was significantly less efficient than single-feature.

***Conjunction vs. Preview*.** In order to determine whether a preview benefit occurred, mean RTs for correct trials were analysed using a 2 (condition) x 3 (display size) ANOVA. Condition (conjunction x preview) and display size (4 x 8 x 16) were both within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 42.00$, $p < .001$, and for the Condition x Display interaction, $\chi^2(2) = 31.78$, $p < .001$. Accordingly, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = .698 and ε = .741, respectively). Overall, RTs were significantly faster in the preview condition, $F(1, 75) = 209.37$, $p < .001$, partial $\eta^2 = .74$, and increased with display size, $F(1.40, 104.67) = 356.25$, $p < .001$, partial $\eta^2 = .83$. There was a significant Condition x Display interaction, $F(1.48, 111.19) = 62.61$, $p < .001$, partial $\eta^2 = .46$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for conjunction (all $p < .001$s) and for preview (all $p < .001$s). Compared to preview ($M = 60.89$, $SD = 64.43$), the conjunction condition ($M = 122.80$, $SD = 84.97$) had a significantly larger mean difference between the two lower display sizes, $t(75) = -5.61$, $p < .001$. Between the larger two display sizes, the conjunction condition ($M = 248.52$, $SD = 151.77$)

also had a significantly larger mean difference compared to preview (*M* = 123.94, *SD* = 86.52), *t*(75) = -6.76, *p* < .001. The increase in RTs with display size occurred more so in the conjunction condition. This indicates that a benefit did occur, as search was more efficient in the preview condition compared to the conjunction condition.

Single-feature vs. Preview. Mean RTs for correct trials were analysed using a 2 (condition) x 3 (display) ANOVA, where condition (single-feature x preview) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 7.91$, *p* < .05, and for the Condition x Display interaction, $\chi^2(2) = 9.84$, *p* < .01. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity (ε = .929 and ε = .909, respectively). RTs were faster in single-feature, *F*(1, 75) = 37.16, *p* < .001, partial η^2 = .31, and increased with display size, *F*(1.86, 139.39) = 236.06, *p* < .001, partial η^2 = .76. The two-way interaction between condition and display was also significant, *F*(1.82, 136.41) = 31.26, *p* < .001, partial η^2 = .29. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for single-feature (all *p* < .001s) and for preview (all *p* < .001s). The single-feature (*M* = 57.50, *SD* = 63.74) and preview (*M* = 60.89, *SD* = 64.43) conditions did not differ significantly between the two lower display sizes, *t*(75) = -0.41, *p* = .686. Between the larger two display sizes, the preview condition (*M* = 123.94, *SD* = 86.52) had a significantly larger mean difference compared to single-feature (*M* = 55.22, *SD* = 55.94), *t*(75) = -6.37, *p* < .001. RTs increased with display size more so (i.e., slopes were steeper) in the preview condition.

Conjunction vs. Preview Gap**.** In order to determine how search in the preview gap condition compares to conjunction, mean RTs for correct trials were analysed using two-way ANOVA. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 65.86$, *p* < .001, and for the Condition x Display interaction, $\chi^2(20) = 14.92$, *p* < .001.

Accordingly, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity for the main effect of display ($\varepsilon = .629$) and Huynh-Feldt estimates for the interaction of condition and display ($\varepsilon = .863$). RTs were faster in the preview gap condition, $F(1, 75) = 48.31$, $p < .001$, partial $\eta^2 = .39$, and increased with display size, $F(1.26, 94.38) = 392.50$, $p < .001$, partial $\eta^2 = .84$. There was a significant Condition x Display interaction, $F(1.73, 129.44) = 7.70$, $p < .001$, partial $\eta^2 = .09$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for conjunction (all $p < .001$s) and for preview gap (all $p < .001$s). The conjunction ($M = 122.80$, $SD = 84.97$) and preview gap ($M = 121.82$, $SD = 81.67$) conditions did not differ significantly between the two lower display sizes, $t(75) = 0.08$, $p = .939$. Between the larger two display sizes, the conjunction condition ($M = 248.52$, $SD = 151.77$) had a significantly larger mean difference compared to preview gap ($M = 191.81$, $SD = 116.36$), $t(75) = 3.06$, $p = .003$. There was some benefit in the preview gap condition compared to the conjunction condition.

Single-feature vs. Preview Gap. Mean correct RTs were analysed using a 2 x 3 ANOVA with condition (single-feature x preview gap) and display (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction) as within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 25.92$, $p < .001$, and for the Condition x Display interaction, $\chi^2(2) = 14.78$, $p < .001$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .785$ and $\varepsilon = .864$, respectively). Overall, RTs were significantly faster in the single-feature condition, $F(1, 75) = 156.47$, $p < .001$, partial $\eta^2 = .68$, and RTs also increased with display size, $F(1.57, 117.75) = 356.44$, $p < .001$, partial $\eta^2 = .83$. There was a significant interaction between condition and display size, $F(1.73, 129.63) = 106.74$, $p < .001$, partial $\eta^2 = .56$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for single-feature (all $p < .001$s) and for preview gap (all $p < .001$s). Compared to single-feature ($M = 57.50$, $SD = 63.74$), the preview gap condition ($M = 121.82$, $SD = 81.67$) had a significantly larger mean difference between the two lower display sizes, $t(75) = -6.03$, p

< .001. Between the larger two display sizes, the preview gap condition (*M* = 191.81, *SD* = 116.36) also had a significantly larger mean difference compared to single-feature (*M* = 55.22, *SD* = 55.94), *t*(75) = -8.99, *p* < .001. RTs increased with display size more so in the preview gap condition.

Preview vs. Preview Gap. Mean RTs for correct trials were analysed using a mixed 2 x 3 ANOVA. Condition (preview x preview gap) and display size (4 x 8 x 16) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 34.64$, *p* < .001, and for the Condition x Display interaction, $\chi^2(2) = 9.54$, *p* < .01. Accordingly, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity for the main effect of display (ε = .728) and Huynh-Feldt estimates of sphericity for the Condition x Display interaction (ε = .912). RTs were faster in the preview condition, *F*(1, 75) = 39.88, *p* < .001, partial $\eta^2 = .35$, and also increased significantly with display size, *F*(1.46, 109.19) = 298.31, *p* < .001, partial $\eta^2 = .80$. There was a significant Condition x Display interaction, *F*(1.83, 136.86) = 63.72, *p* < .001, partial $\eta^2 = .46$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for preview (all *p* < .001s) and for preview gap (all *p* < .001s). Compared to preview (*M* = 60.89, *SD* = 64.43), the preview gap condition (*M* = 121.82, *SD* = 81.67) had a significantly larger mean difference between the two lower display sizes, *t*(75) = -6.56, *p* < .001. Between the larger two display sizes, the preview gap condition (*M* = 191.81, *SD* = 116.36) also had a significantly larger mean difference compared to preview (*M* = 123.94, *SD* = 86.52), *t*(75) = -5.68, *p* < .001. The search benefit associated with the preview condition was indeed lost in the preview gap condition.

Preview and Preview Gap Benefit Indices. Adults with low, borderline and high ASRS scores were compared on PB and PGB index values. These indices provide a non-biased measure of the performance benefit generated from the temporal elements of the preview and preview gap conditions. How these indices are calculated and interpreted are discussed in previous chapters (see section 2.1.3). The PB and PGB index values are shown in Table 4.5.

Table 4.5

Preview and Preview Gap Benefit Index Value Means, Standard Deviations, and One-Way ANOVA Statistics

Index	Low ASRS	Borderline ASRS	High ASRS	F(2, 73)	η^2
Preview Benefit	0.62 (0.46)	0.62 (0.70)	0.63 (0.75)	0.01 (n.s.)	.00
Preview Gap Benefit	0.03 (0.63)	0.02 (1.09)	0.07 (0.84)	0.02 (n.s.)	.00

Note. Standard deviations are in parentheses. Groups did not differ significantly from one another on either the preview benefit or the preview gap benefit. The index values can be interpreted as the percentage of old preview items suppressed at the final display; n.s. = not significant

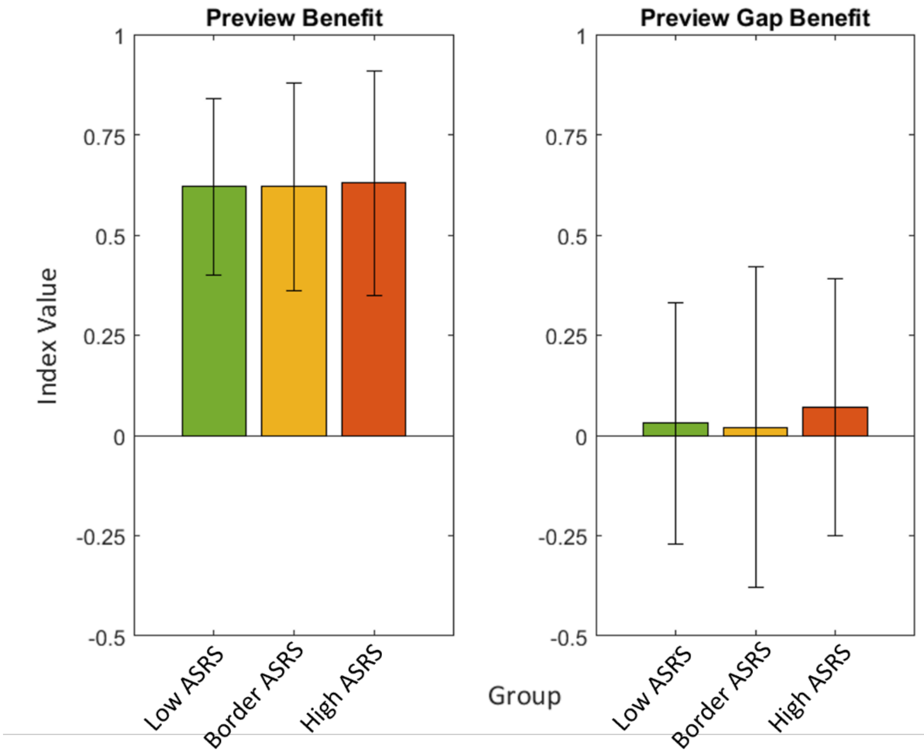
The value of the PB indices were very similar for all three groups. For the low ASRS group, the PB index was 0.622 (*SE* = 0.105), for the borderline ASRS it was 0.634 (*SE* = 0.143) and for the high ASRS group it was 0.616 (*SE* = 0.127). A one-way ANOVA was conducted to determine if there were any significant differences between groups on the PB index value. Levene's test indicated that the assumption of homogeneity of variance had been met, $F(2, 73) = 0.41$, $p = .664$. There was no significant difference between the three groups, $F(2, 73) = 0.01$, $p = .995$, $\eta^2 = .00$. PB index values were non-normal in the low ASRS group, $W = 0.848$, $p < .01$, the borderline ASRS group, $W = 0.577$, $p < .001$, and in the high ASRS group, $W = 0.894$, $p < .01$. For the low ASRS group, the PB contained 1 outlier at the low end of the scale with values equal to or less than -0.80. For the borderline ASRS group, the PB contained 2 outliers at the high end of the scale with values equal to or greater than

2.10 and 3 outliers at the low end of the scale with values equal to or less than -0.50. Finally, for the high ASRS group, the PB contained 4 outliers at the low end of the scale with values less than or equal to 0.18.

The values of the PGB indices were also very similar for the groups. For the low ASRS group, the PGB index was 0.028 (*SE* = 0.144). For the borderline ASRS group, the PGB index was 0.020 (*SE* = 0.199). Finally, for the high ASRS group, the PGB index was 0.067 (*SE* = 0.161). A one-way ANOVA was conducted to test for significant differences between groups. Levene's test indicated that the assumption of homogeneity of variance had been met, $F(2, 73) = 1.20$, $p = .308$. There was no significant difference between the three groups, $F(2, 73) = 0.02$, $p = .979$, $\eta^2 = .00$. PGB index values were non-normal in the low ASRS group, $W = 0.871$, $p < .05$, the borderline ASRS group, $W = 0.882$, $p < .01$, and in the high ASRS group, $W = 0.730$, $p < .01$. There were no outliers in the low ASRS group. In the borderline ASRS group, the PGB contained 1 outlier at the high end of the scale with values greater than or equal to 1.9 and 4 outliers at the lower end of the scale with values less than or equal to -1.7. The high ASRS group contained 4 outliers at the lower end of the scale with values less than or equal to -0.7. PB and PGB index values for each group are shown in Figure 4.3.

Figure 4.3

PB and PGB Index Values for the Low, Borderline and High ASRS Groups



Note. Index values range from 0 to 1. Values of 0 indicate no benefit – none of the old items could be sufficiently suppressed in the competition for selection, and therefore search was as inefficient as if all items had been presented simultaneously. Values of 1 indicate the maximum benefit – all old items were sufficiently suppressed, and therefore competition for selection occurred amongst only the new items. Values between 0 and 1 represent partial suppression of old items (e.g., a value of 0.5 indicates approximately 50% of old items were suppressed). While PB values typically trend more toward 1, PGB values tend more toward 0. Error bars represent ± 2*SE*.

Omnibus 3 x 4 x 3 ANOVA – Accuracy. Accuracy was analysed using a 3 (group) x 4 (condition) x 3 (display) ANOVA. Group (low ASRS x borderline ASRS x high ASRS) was a between-subjects factor, and condition (single-feature x conjunction x preview x preview gap) and display (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction, preview, and preview gap) were within-subjects factors. Levene's test was significant for accuracy in single-feature at display size 2, F(2, 73) = 4.30, *p* < .05, and single-feature at display size 4, F(2, 73) = 4.38, *p* < .05, indicating unequal variances at these levels. For all other condition/display sizes, there was no significant differences between variances. Mauchley's test indicated that the assumption of sphericity had been met for the main effects of condition, display, as well as for the Condition x Display interaction. Accuracy did not differ significantly between groups, *F*(2, 73) = 0.80, *p* = .46, η^2 = .02. Neither the main effect of Condition nor the main effect of Display reached significance. The Condition x Display interaction, however, was significant, *F*(6, 438) = 2.18, *p* < .05, η^2 = .03. Neither the Group x Condition interaction nor the Group x Display interaction reached significance. Finally, the Group x Condition x Display interaction was significant, *F*(12, 38) = 2.22, *p* < .05, η^2 = .06. This significant interaction is explored further below. All statistics for the accuracy follow-up ANOVAs can be found in Appendix Table N.3.

Follow-Up 2 x 3 ANOVAs: Low ASRS Group Accuracy. ***Single-feature vs. Conjunction***. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (single-feature x conjunction) and display (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction) as within-subjects factors. Neither the main effects nor their interaction reached significance.

Conjunction vs. Preview. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (conjunction x preview) and display (4 x 8 x 16) as within-subjects factors. Neither of the main effects reached significance. However, the Condition x Display interaction was significant, *F*(2, 36) = 6.66, *p* < .01, partial η^2 = .27. While accuracy increased with display size in the preview condition, it decreased with display size in conjunction.

Single-feature vs. Preview. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (single-feature x preview) and display (2 x 4 x 8 for single-feature; 4 x 8 x 16 for preview) as within-subjects factors. Neither the main effects nor their interaction reached significance.

Conjunction vs. Preview Gap. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (conjunction x preview gap) and display (4 x 8 x 16) as within-subjects factors. Neither of the main effects reached significance. Similarly, the Condition x Display interaction also failed to reach significance.

Single-feature vs. Preview Gap. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (single-feature x preview gap) and display (2 x 4 x 8 for single-feature; 4 x 8 x 16 for preview gap) as within-subjects factors. Again, neither of the main effects nor their interaction reached significance.

Preview vs. Preview Gap. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (preview x preview gap) and display (4 x 8 x 16) as within-subjects factors. Neither of the main effects of condition or display reached significance. The Condition x Display interaction also failed to reach significance.

Follow-Up 2 x 3 ANOVAs: Borderline ASRS Group Accuracy. ***Single-feature vs. Conjunction***. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (single-feature x conjunction) and display (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction) as within-subjects factors. Neither of the main effects were significant. Similarly, the interaction of condition and display also failed to reach significance.

Conjunction vs. Preview. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (conjunction x preview) and display (4 x 8 x 16) as within-subjects factors. The main effect of condition reached significance, $F(1, 29) = 4.27$, $p < .05$, partial $\eta^2 = .13$, as there was lower accuracy in the preview condition ($M = 95.80$, $SE = 0.006$) compared to conjunction ($M = 96.70$, $SE = 0.006$). The main effect of display and the Condition x Display interaction failed to reach significance.

Single-feature vs. Preview. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (single-feature x preview) and display (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction) as within-subjects factors. The main effect of Condition reached significance, *F*(1, 29) = 4.27, $p < .05$, partial $\eta^2 = .13$, as there was lower accuracy in the preview condition compared to single-feature (*M* = 96.90, *SE* = 0.004). The effect of Display and the interaction between condition and display failed to reach significance.

Conjunction vs. Preview Gap. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (conjunction x preview gap) and display (4 x 8 x 16) as within-subjects factors. Neither the main effects nor the Condition x Display interaction reached significance.

Single-feature vs. Preview Gap. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (single-feature x preview gap) and display (2 x 4 x 8 for single-feature; 4 x 8 x 16 for preview gap) as within-subjects factors. Neither of the main effects nor their interaction reached significance.

Preview vs. Preview Gap. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (preview x preview gap) and display (4 x 8 x 16) as within-subjects factors. Neither of the main effects of condition or display reached significance. The Condition x Display interaction also failed to reach significance.

Follow-Up 2 x 3 ANOVAs: High ASRS Group Accuracy. ***Single-feature vs. Conjunction***. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (single-feature x conjunction) and display (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction) as within-subjects factors. The main effect of Condition failed to reach significance. There was a significant main effect of Display, *F*(1, 52) = 4.77, $p < .05$, partial $\eta^2 = .16$. The interaction between condition and display also failed to reach significance.

Conjunction vs. Preview. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (conjunction x preview) and display (4 x 8 x 16) as within-subjects factors. Neither the main effects nor their interaction reached significance.

Single-feature vs. Preview. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (single-feature x preview) and display (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction) as within-subjects factors. Neither of the main effects of condition or display reached significance. The Condition x Display interaction also failed to reach significance.

Conjunction vs. Preview Gap. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (conjunction x preview gap) and display (4 x 8 x 16) as within-subjects factors. Neither Condition nor Display reached significance. However, there was a significant Condition x Display interaction, $F(2, 52) = 8.21$, $p < .01$, partial $\eta^2 = .24$. Accuracy increased with display size in the conjunction condition. In contrast, accuracy decreased as display size increased in the preview gap condition.

Single-feature vs. Preview Gap. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (single-feature x preview gap) and display (2 x 4 x 8 for single-feature; 4 x 8 x 16 for preview gap) as within-subjects factors. Neither of the main effects reach significance. The Condition x Display interaction, however, was significant, $F(2, 52) = 3.59$, $p < .05$, partial $\eta^2 = .12$. Accuracy increased with display size in the single-feature condition but decreased as display size increased in the preview gap condition.

Preview vs. Preview Gap. Accuracy was analysed using a 2 (condition) x 3 (display) ANOVA with condition (preview x preview gap) and display (4 x 8 x 16) as within-subjects factors. Neither of the main effects of Condition or Display reached significance. The Condition x Display interaction also failed to reach significance.

4.1.4 Discussion

The present study compared visual search performance in the preview and preview gap conditions between adults with low, borderline and high levels of ADHD to determine whether time-based attention is affected in this disorder. In preview search, old distractors are visually marked (i.e., actively suppressed) through top-down attentional inhibition in order to prioritise the selection of new items (Berggren & Eimer, 2018; Olivers et al., 2006; Watson & Humphreys, 1997; Yamauchi & Kawahara, 2020). Individuals with ADHD often perform worse on measures that require top-down attention in general (Mullane & Klein, 2008; O'Conaill et al., 2015; Skalski et al., 2021), as well as in distractor suppression specifically (Wang et al., 2016; Zhu et al., 2023). However, in the previous chapter, it was shown that children with high levels of ADHD symptoms were capable of generating a preview benefit similar to their low-ADHD-symptom peers. This finding indicates visual marking of old items may be intact in ADHD - at least in childhood. Similar result have also been reported in previous work examining preview search in childhood ADHD (Mason et al., 2003, 2004). Accordingly, it was hypothesized that this ability would also be unaffected (at the behavioural level, at least) by ADHD in adulthood, thus allowing for adults with either borderline or high levels of ADHD symptoms to perform similarly in the preview condition compared to healthy controls. This was indeed the case. For all three groups, the slopes of the RT function in the preview condition were approximately 15 msec (see Table 4.4). Furthermore, the PB index for all three groups was roughly the same: 0.62 for low, 0.62 for borderline, and 0.63 for high (see Table 4.5). This indicates that for all groups, roughly 60% of old items were visually marked over the course of the preview display.

These results, although not statistically significant, do have some important implications. As previously stated, the top-down suppression of non-relevant information is very often implicated in both children and adults with ADHD (Hokken et al., 2023; Mullane & Klein, 2008; Onandia-Hinchado et al., 2021). This is the case at the empirical level using neuropsychological testing (Bouzabou et al., 2021; Coll-Martín et al., 2021; Gmehlin et al., 2016; Hokken et al., 2023; Salomone et al., 2020; Somogyi et al., 2023) and at the behavioural level, with symptoms such as "easily distracted" and "has difficulty sustaining attention on tasks or play activities" for children and "starts tasks, but quickly loses focus and is easily side-tracked" in adults (American Psychiatric Association, 2013; Asherson et al., 2016; Thapar & Cooper, 2016). Previous work provides substantial evidence that the ability to generate a preview benefit does indeed require the application of top-down attentional inhibition to old preview items (Berggren & Eimer, 2018; Braithwaite et al., 2005; Watson & Humphreys, 2000; Yamauchi & Kawahara, 2020), as well as top-down expectancy for the target item's features (Braithwaite & Humphreys, 2003). Indeed, visual marking is an active process that requires top-down control (Mavritsaki et al., 2011; Watson et al., 2003). As such, it's interesting that this process appears to be unaffected by ADHD.

One reason for the conservation of this ability may lie in the role of neuronal adaptation providing a "passive" inhibitory mechanism (see section 3.3 for more discussion on this topic). A particularly important point to note here is the specificity of the beneficial temporal element here. Neuronal adaptation refers to the reduction in the activity of neurons firing for specific stimuli within the visual field (while they're physically present), and the time course of this process is approximately 500 to 1000 msec long (Mavritsaki et al., 2006). As such, this time-based mechanism is markedly different from what is typically considered "sustained attention," a process that has been shown to be affected in ADHD (Bellgrove et al., 2005; Coll-Martín et al., 2021; Gmehlin et al., 2016; Huang-Pollock et al., 2012; Pagán, Huizar, & Schmidt, 2023; Thomson et al., 2022; Tsal et al., 2005). Indeed, outside the time window of neuronal adaptation, it is unclear how individuals might differ from controls. Therefore, in preview search, the intact ability to visually mark old items in ADHD appears to arise from the benefit that all items don't appear together at once, and that there's no required sustained maintenance of suppression. Future research could investigate how to utilise this specific presentation of information to make more ADHD-friendly learning materials in schools.

Other than visual marking, temporal binding also contributes to efficient time-based attention (Kunar et al., 2003; Mavritsaki & Humphreys, 2016). Although temporal binding is considered to be a more bottom-up function of attention, this is a complex mechanism that requires the precise coordination of intricate within- and between-region neural connections (Singer, 2015, 2021), which are commonly found to be atypical in ADHD (Bouziane et al., 2018; Mazaheri et al., 2010; Schulze et al., 2021; Thomson et al., 2022). The ability to temporally bind items also has been linked to activity in the posterior parietal cortex (Battelli et al., 2007; Mavritsaki & Humphreys, 2016; Olivers & Humphreys, 2004), which has also been implicated in ADHD (Dipnall et al., 2023; Hoogman et al., 2019; O'Conaill et al., 2015; Schulz et al., 2017; Zhu et al., 2023). Furthermore, in the previous chapter, the behavioural study showed a significant relationship between the level of ADHD symptoms and benefit in the preview gap condition. As intact temporal binding leads to the absence of any search benefit in the preview gap condition (Mavritsaki & Humphreys, 2016), it was proposed that temporal binding might be reduced in ADHD. This hypothesis was further examined and confirmed through the computational modelling study. Accordingly, it was hypothesized that adults with ADHD may exhibit reduced temporal binding compared to healthy controls, and that these this reduction would be proportional to their level of ADHD symptom. However, this was not found to be the case in the present study. First, there was no relationship between level of ADHD and PGB. Furthermore, slopes in the preview gap condition did not differ significantly between groups (~28 for low; ~ 22 for borderline; ~ 28 for high; see Table 4.4). PGB values were also similar between groups: 0.03 for low, 0.02 for borderline, and 0.07% for high. This indicates that only 3%, 2% and 7% of preview items were suppressed in the final display in the low, borderline and high groups (respectively). These results indicate intact temporal binding in adult ADHD.

Although there were no significant differences between groups on the search slopes for the visual search conditions, and there was no relationship between level of ADHD trait and search benefit, there are a few other findings to note here. For one, there was some increased variability in the high ASRS group for the preview condition RTs (see Table 4.2). Increased RT variability is a very common finding in ADHD (Bellgrove et al., 2005; Gmehlin et al., 2016; Karalunas et al., 2014; Moses et al., 2022; Pievsky & McGrath, 2018) and has been linked to differences in white matter microstructure (Thomson et al., 2022) as well as to differences in the dopamine transporter genotype (Bellgrove et al., 2005). Here, this increased variability may reflect difficulty in consistently visually marking old items. However, further research should be undertaken to explore this. Other than RT variability, there was also an interesting pattern in the accuracies of the high ASRS group. In the conjunction condition for the low ASRS group, accuracy decreased as display size increased, as is commonly the case (Wolfe, 2015b). However, in the high ASRS group, accuracy actually increased with display size. Additionally, for the ADHD group, accuracy decreased as display size increased only the preview gap condition. This is an interesting result because, as the slopes show, the competition in these two conditions is essentially the same (i.e., all distractor items compete at an equal level in the final display). Despite this, it appears that the added temporal (gap) element in the preview gap condition affects the accuracy of responses. In a previous literature review on visual search in ADHD, Mullane and Klein (2008) hypothesized that individuals with ADHD may perform best at intermediate levels of difficulty, rather than at levels of difficulty that are either too low or high (Mullane & Klein, 2008). Here, it may be that conjunction represents that intermediate level, while the added preview and gap displays contribute to increasing the level of difficulty, so that accuracy is affected here. Future research is needed here to explore this possibility.

One key limitation to the behavioural study presented here is the lack of screening individuals, particularly with high levels of ADHD, for any co-morbid disorders, which may affect performance (Lijffijt et al., 2017; Nigg, 2001; Oosterlaan et al., 1998; S. Zhang et al., 2015). The high rate of co-morbidity in adult ADHD may contribute to inconsistencies in the ADHD literature (Nigg et al., 2020). These topics are addressed in the next behavioural study, where these three groups, plus a fourth group of individuals with both high levels of ADHD and high levels of impulsiveness are included to represent those with comorbid impulse disorders.

4.2 Comparing Low, Borderline, High and High + High Impulsiveness

4.2.1 Background

As previously discussed, adults with ADHD demonstrate differences across a wide variety of neurocognitive domains (Holst & Thorell, 2020; Onandia-Hinchado et al., 2021). Adults with ADHD often perform worse on measures of attention (Guo et al., 2022; Salomone et al., 2020; Guo et al., 2023; Somogyi et al., 2023), arousal/vigilance (Coll-Martín et al., 2021; Strauß et al., 2018), "cool" executive functions like working memory (Fossum et al., 2021; Torgalsbøen et al., 2021), response inhibition (Mehren et al., 2019; Duval et al., 2021; Shang et al., 2018) and set-shifting (Luna-Rodriguez et al., 2018), as well as "hot" executive functions like delay discounting (Dai et al., 2016; Marx et al., 2021). This can make it particularly difficult to reliably identify a set criteria of differences specific to this disorder, and thus presents difficulty in diagnosis (Nigg et al., 2020; Sonuga-Barke et al., 2023).

Other than the inherent heterogeneity of this disorder, the high rate of co-morbidity in ADHD may also presents challenges for accurate identification (Asherson et al., 2014; Grogan et al., 2018; Udal et al., 2014). ADHD in adulthood often co-occurs with other common mental health disorders, including generalised anxiety disorder (GAD; Hartman et al., 2023; Koyuncu et al., 2022), depression (Chen et al., 2016; Powell et al., 2021), bipolar disorder (Schiweck et al., 2021) and substance use disorders (Luderer et al., 2021; Oliva et al., 2021). Furthermore, there is a great deal of overlap in symptoms and impairments between these conditions, which can make it difficult to properly diagnose and treat (Asherson et al., 2016; Katzman et al., 2017; Sonuga-Barke et al., 2023). For example, constant worrying, feelings of restlessness and excessive mind-wandering are common to both ADHD and GAD (Grogan et al., 2018; Koyuncu et al., 2022). Other ADHD symptoms like emotional instability and impulsive behaviour are also characteristic of bipolar disorder and depression (Asherson et al., 2014; Kitsune et al., 2016). Accordingly, it is important that research aims to distinguish individuals with ADHD, individuals with co-morbid ADHD and differential diagnoses, as these groups - although possibly demonstrating similar or identical symptoms - could reflect distinct neural mechanisms.

While "pure" ADHD and comorbid ADHD can share some similarities in neurocognitive difficulties (e.g., attention, executive function; Lau-Zhu et al., 2019; Michelini et al., 2018), comorbid groups can show distinct patterns of difficulties compared to ADHD alone (Bartoli et al., 2023; Lundervold et al., 2011; Marchetta et al., 2008; Torres et al., 2017). For example, Torres et al. (2017) found that adults with comorbid ADHD and bipolar disorder performed worse compared to adults with pure ADHD on neurocognitive tests of executive function. However, those with pure ADHD performed worse than their co-morbid peers on measures of selective attention (Torres et al., 2017). Sometimes very similar elements of mental illness, such as attention and impulsivity, can even have opposite effects. For example, while ADHD has been associated with low levels of arousal (Mayer et al., 2016; Strauß et al., 2018), studies have shown that individuals with other impulse disorder often demonstrate the opposite - increased levels of arousal and activation in response to stimuli (Lijffijt et al., 2017; S. Zhang et al., 2015). As ADHD and impulse disorders can appear to be very similar at the symptomatic level (Asherson et al., 2016) or can be co-morbid (Asherson et al., 2014; Dai et al., 2016; Hartman et al., 2023), it is important to aim to distinguish these in ADHD research.

Aims of Study. The aim of the present study is to examine differences in visual marking and/or temporal binding between four groups: adults with low ADHD symptoms, adults with borderline ADHD symptoms, adults with high ADHD symptoms and adults with both high ADHD symptoms and high impulsiveness. Previous research has shown that adults with ADHD have normal levels of impulsiveness (as measured by the Barratt Impulsiveness Scale; Chamberlain et al., 2021), while other, often co-occurring disorders demonstrate higher levels of impulsiveness (Crisp & Grant, 2024). Therefore, the Barratt Impulsiveness Scale – Brief (BIS-B; Steinberg et al., 2013) was used to distinguish adults with high ADHD levels (but normal impulsiveness) and adults with high levels of ADHD *and* high levels of impulsiveness.

As adults with ADHD often display difficulties in attention (Onandia-Hinchado et al., 2021), the high ASRS group could demonstrate reduced temporal binding, similar to the children with high ADHD symptoms in the previous chapter. This would be evident by more efficient search (i.e., flatter slopes) in the preview gap condition. Furthermore, as subclinical cases of ADHD often demonstrate similar symptoms as clinical cases (Hirata et al., 2023; Zendarski et al., 2022), the borderline ASRS group may show similar difficulties as the high ASRS group. Finally, as cases of comorbid ADHD often experience more severe symptoms and outcomes (Bartoli et al., 2023; Torres et al., 2017), it is hypothesized that the high ASRS + BIS-B group will perform worse than the high ASRS (normal impulsiveness) group.

4.2.2 Method

Participants. A total of 92 participants were recruited using two online participant recruitment platforms: the Research Participation Scheme (RPS) at Birmingham City University (bcu.sona-systems.com) and Prolific (www.prolific.com). There were 23 participants in the low ASRS group with a mean age of 25.09 years (*SD* = 6.68). Five (21.70%) were male, 18 (78.30%) were female. There were 23 participants in the borderline ASRS group with a mean age of 28.04 years (*SD* = 13.86). Three (13.00%) were male and 20 (87.00%) were female. There were 23 participants in the high ASRS group with a mean age of 25.00 years (*SD* = 10.70). Three (13.00%) were male and 20 (87.00%) were female. Finally, there were 23 participants in the high ASRS + BIS-B group, with a mean age of 21.83 years (*SD* = 5.77). In this group, 5 (21.70%) were male and 18 (78.30%) were female. Those interested in participating in the study were required to read the participant information sheet (see Appendix A) and provide written informed consent online (see Appendix B). Exclusionary criteria included a history or serious mental or physical health condition, such as epilepsy. Other exclusionary criteria included a diagnosis of ADHD and/or a history of treatment for ADHD. Three participants were excluded from the study for having a previous history of undergoing treatment for ADHD. All participants reported having normal or corrected-to-normal vision. University students who were recruited via RPS received course credit in exchange for their participation. Individuals who were recruited via Prolific received a total of £4.10 for their participation in the study.

A one-way ANOVA was conducted to determine whether there were significant differences between groups on age, ASRS score and BIS-B score (see below). Levene's test showed that the assumption of homogeneity of variance was violated for age ($p < .001$), ASRS score ($p = .002$), and BIS-B score ($p = .009$). For age, there was no significant difference between groups, $F(3, 88) = 1.53$, $p = .211$, $\eta^2 = .05$. Groups differed significantly on ASRS score, $F(3, 88) = 185.84$, $p < .001$, $\eta^2 = .86$. Planned contrasts showed that each of the groups differed significantly from one another (all *p*s < .001). There was a significant difference between groups on BIS-B score, $F(3, 88) = 69.29$, $p < .001$, $\eta^2 = .70$. Planned contrasts showed that the low ASRS group differed from the other three groups (all *p*s < .001), and the ASRS ADHD + impulsive group differed significantly from all other three groups (all *p*s < .001). However, there was no significant difference between the borderline ASRS and high ASRS groups ($p = .293$). These statistics describing participant characteristics are shown in Table 4.6.

Table 4.6

Means and Standard Deviations on Age, ASRS Screener Score and BIS-B Score in the Four Groups

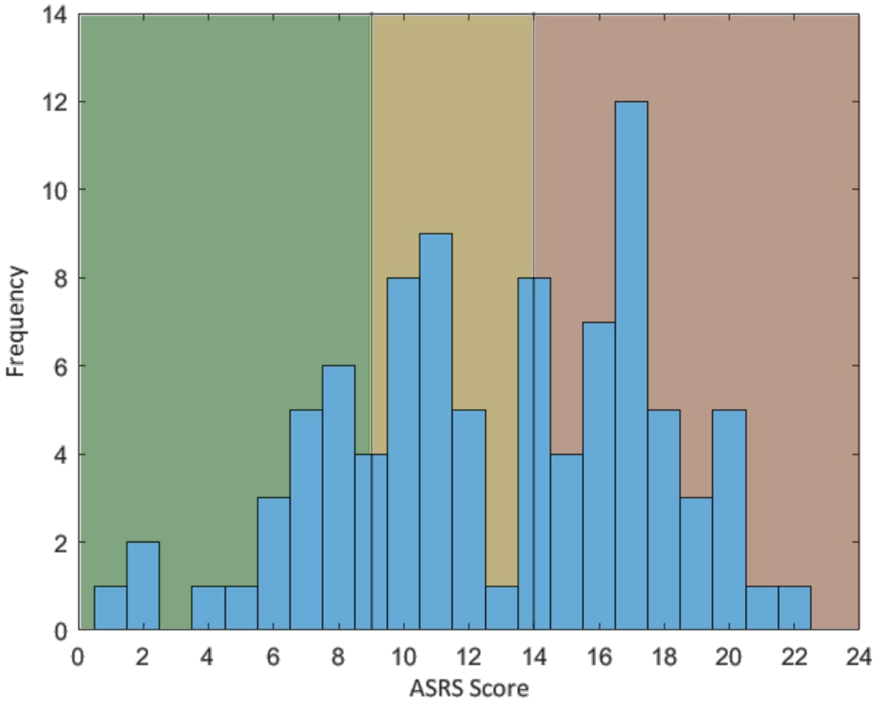
Measure	Low ASRS	Border ASRS	High ASRS	High ASRS + BIS-B	*p*
Age (in years)	25.09 (*6.68*)	28.04 (*13.86*)	25.00 (*10.70*)	21.83 (*5.77*)	.312
ASRS Screener	6.57 (*2.32*)	10.96 (*0.88*)	15.87 (*1.52*)	17.96 (*2.10*)	<.001
BIS-B Score	13.26 (*2.93*)	16.04 (*2.18*)	16.70 (*1.96*)	23.78 (*3.07*)	< .001

Note. ASRS = Adult ADHD Self Report Scale; BIS-B = Barratt Impulsiveness Scale Brief; n.s. = not significant; standard deviations are presented in parentheses.

Materials. ***Adult ADHD Self-Report Scale (ASRS) Screener*.** Similar to the first behavioural study in this chapter, participants were required to complete the Adult ADHD Self-Report Scale (ASRS) Screener (Kessler et al., 2005, 2007; see Appendix M) in order to provide a current rating of ADHD symptom severity. Additional details regarding the content of this scale screener, as well as its validity and reliability, are discussed in section 4.1.2. The method of grouping here using the ASRS scores was the same as that described in the previous chapter. However, here, the low, borderline and high ASRS score groups were also required to have a BIS-B score that reflected normal levels of impulsiveness (see below). The distribution of ASRS screener scores for participants is shown in Figure 4.4.

Figure 4.4

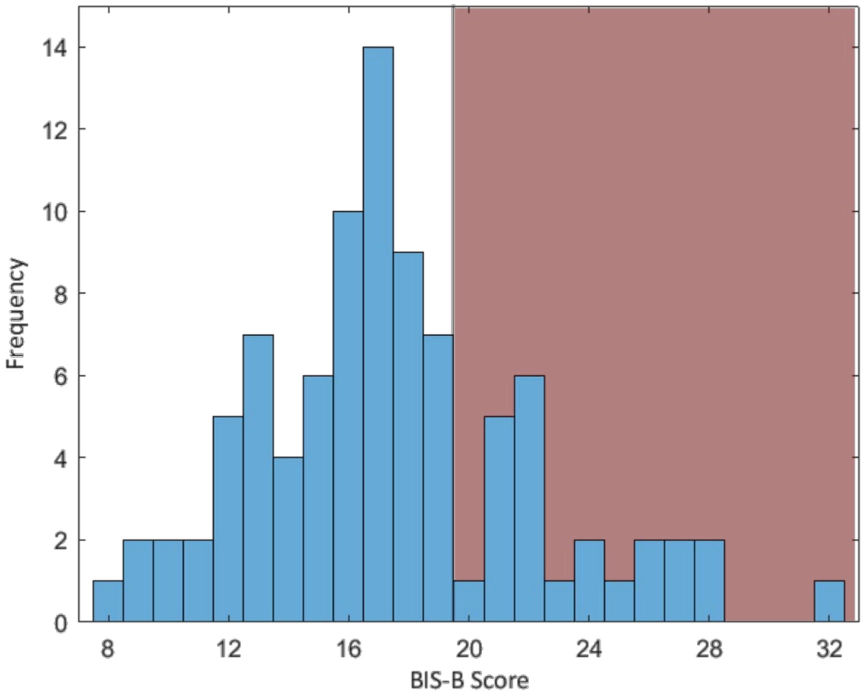
Distribution of Scores on the Adult ADHD Self-Report Scale (ASRS) Screener



Note. Individuals with *s*cores between 0-9 are considered to have a low probability of ADHD (green background); individuals with scores between 10 and 14 are considered to have a borderline probability of ADHD (yellow background); individuals with scores between 15 and 24 are considered to have a high probability of ADHD (orange background). Additional details about grouping procedure in 4.1.2.

Figure 4.5

Distribution of Scores on the Barratt Impulsiveness Scale - Brief (BIS-B)



Note. Individuals with a score below 20 were considered to have low/average levels of impulsiveness (white background). Individuals with scores equal to or above 20 were considered to have high levels of impulsiveness (red background).

Barratt Impulsiveness Scale – Brief (BIS-B). Participants were also required to complete the Barratt Impulsiveness Scale – Brief (BIS-B) to provide a measure of participants' level of impulsivity (see Appendix O). The BIS-B is a shortened version of the Barratt Impulsiveness Scale (BIS-11), a 30-item self-report measure commonly used assess the construct of impulsiveness (Patton et al., 1995; Steinberg et al., 2013). The BIS-B uses items from the BIS-11 to create a an 8-item questionnaire that measures a single dimension of impulsivity (Morean et al., 2014). Participants indicate the frequency with which they engage in impulsive (e.g., I act on the spur of the moment) or non-impulsive (e.g., I am self-controlled) behaviours. Each item is rated on a 4-point Likert scale, from 1 (Rarely/Never) to 4 (Almost Always/Always). Some items (indicating non-impulsiveness) are reverse scored. All responses are summed to create an overall score ranging from 8 to 32, with a higher score reflecting higher levels of impulsiveness. The BIS-B has good internal consistency (Cronbach's αs = .73-83; Steinberg et al., 2013) as well as good test-retest reliability (Mathias et al., 2018). Furthermore, this measure correlates well with other established measures impulsivity (Charles et al., 2021; Fields et al., 2015; Morean et al., 2014; Steinberg et al., 2013). The cutoff to determine whether a score was considered "high" here was a score equal to or higher than 20, as this was in line previous research (Charles et al., 2021; Fields et al., 2015; Mathias et al., 2018; Steinberg et al., 2013).

Stimuli and Equipment. The experiment was programmed in PsychoPy (Peirce et al., 2019) and run online via Pavlovia (Peirce & Macaskill, 2018). Before search displays appeared, a black central fixation cross was displayed in the centre of the screen. In all displays, the target was a blue [RGB = 0, 0, 225] letter H. In the single-feature condition, the target blue letter H was surrounded by blue [RGB = 0, 0, 225] letter A distractors. In the conjunction, preview and preview gap conditions, the target blue letter H was surrounded by green [RGB = 0, 128, 0] letter H and blue letter A distractors. All stimuli were presented on a white background.

Design. For the present experiment, there were two within-participant factors and one between-participant factor: condition (within: single feature x conjunction x preview x preview gap), display (within: 2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction, preview and preview gap) and group (between: low ASRS x borderline ASRS x high ASRS x high ASRS + BIS-B). Mean RTs and accuracies were calculated for each participant, condition and display size. Additional details regarding the design of this study are discussed in the first behavioural study of this chapter (see section 4.1).

Procedure. Over the RPS, a number of university-run studies were advertised to current students, and this study was among them. Interested individuals were re-directed to the study's website, where they were required to read through the participant information sheet (see Appendix A), confirm that they were over 18 years old, and provide their consent to participate (see Appendix B). After consent was obtained, the participant was asked to complete the 6-item ASRS screener (Kessler et al., 2005; see Appendix M), followed by the 8-item BIS-B (Steinberg et al., 2013; see Appendix O). Participants were then contacted by the experimenter to schedule a date and time to complete the visual search experiment. At the agreed time/date participants met with the researcher over Microsoft Teams. Participants were asked to share the screen, so that the experimenter was able to see the visual search task on the participant's computer as it was being completed. This was done to ensure the experimental conditions (e.g., on a computer in quiet room) were met and the participant completed search task without any interruptions. After the experiment was complete, the participant received credits over RPS.

Over the Prolific platform, the study was separated into two. A first study was available to all potential participants on the Prolific platform. Once individuals provided their consent to participate over the Prolific website, they were re-directed to the study's website, where they were asked to complete the ASRS screener and BIS-B. A total of 134 participants completed this initial study and were awarded £1.00 for their participation. From this pool of 134, the experimenter then invited 32 participants to participate in the visual search experiment based on their responses in the first study, so that each of the four groups of this study had an equal number of participants (*n* = 23). Of these 38 potential participants, 20 agreed to participate the visual search task. Once consent was provided for this second study, participants were re-directed to the study's Calendly page, where they chose an available date and time to meet with the researcher. Once chosen, a Microsoft Teams link for the meeting was sent to their Prolific account. Here also, participants were required to share their screen with the experimenter to ensure the RTs were valid. After completing the visual search task, participants were rewarded £3.10 to their account on Prolific.

Data Analysis. The data analysis for this study was identical to the other behavioural studies reported in the present thesis. RTs were sorted for each participant, condition, and display size (see Table 4.7). Accuracy was also calculated for each participant, condition and display size (see Table 4.8). Finally, slopes were calculated using display sizes 4, 8 and 16 for all conditions (see Table 4.9).

Table 4.7

Mean RTs for Each Condition and Display Size in Each of the Four Groups

Condition	Low ASRS		Borderline ASRS		High ASRS		High ASRS + BIS-B	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Single-feature 2	508.47	62.98	546.28	127.89	550.32	88.26	546.26	146.96
Single-feature 4	569.61	108.39	590.80	141.54	619.68	113.32	598.11	170.60
Single-feature 8	630.70	102.10	653.72	124.26	662.22	100.28	676.60	186.87
Conjunction 4	608.97	80.72	646.57	113.01	663.17	110.57	713.40	220.31
Conjunction 8	734.44	129.13	757.09	170.43	797.75	148.89	832.59	260.21
Conjunction 16	984.23	228.28	974.83	212.96	1079.56	269.01	1142.51	379.97
Preview 4	531.39	83.15	581.11	133.35	609.67	147.44	635.61	223.06
Preview 8	600.27	78.16	626.87	126.15	681.72	186.57	752.41	236.34
Preview 16	720.87	124.50	758.84	165.24	799.11	203.36	900.48	298.12
Preview gap 4	561.30	84.66	585.04	105.73	607.52	95.00	580.47	115.68
Preview gap 8	689.78	125.76	704.43	126.10	727.35	138.50	746.49	178.40
Preview gap 16	898.80	195.33	857.68	163.58	949.88	207.19	898.04	249.17

Table 4.8

Mean Accuracy Rates for Each Condition and Display Size in Each of the Four Groups

Condition	Low ASRS		Borderline ASRS		High ASRS		High ASRS + BIS-B	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Single-feature 2	96.09	3.00	95.22	3.84	96.30	3.44	93.91	4.76
Single-feature 4	93.26	4.42	93.48	4.11	93.70	5.48	92.83	6.37
Single-feature 8	95.65	5.29	94.13	5.15	95.65	4.60	95.87	4.17
Conjunction 4	95.87	4.43	97.39	3.33	96.09	4.51	95.22	5.74
Conjunction 8	95.00	3.69	97.83	2.95	96.52	5.53	95.65	4.34
Conjunction 16	94.57	6.01	95.65	3.47	96.09	5.21	95.87	4.43
Preview 4	97.39	3.95	96.30	4.58	98.70	2.24	96.74	4.91
Preview 8	95.00	5.22	95.65	3.47	95.22	4.12	95.22	5.33
Preview 16	94.78	5.74	96.30	3.44	96.09	4.25	97.17	4.73
Preview gap 4	95.87	4.17	96.52	5.53	98.26	2.43	96.30	3.76
Preview gap 8	94.35	5.90	96.52	3.82	94.78	4.64	95.65	5.50
Preview gap 16	95.65	4.84	97.39	3.33	96.74	3.88	95.22	5.53

Table 4.9

Slope Statistics for Each of the Four Groups

Group/Statistic	SF	CJ	PV	PVG
Low ASRS				
Slope	9.73	25.92	14.26	18.92
Intercept	474.14	494.24	487.16	473.26
Linearity (%)	99.97	99.99	99.97	99.63
Borderline ASRS				
Slope	8.48	31.31	21.71	24.80
Intercept	483.17	478.24	461.72	464.70
Linearity (%)	98.66	99.96	99.93	0.9939
High ASRS				
Slope	8.92	27.61	18.68	24.38
Intercept	483.96	508.84	487.63	457.85
Linearity (%)	99.28	100	99.01	99.63
High ASRS + BIS-B				
Slope	10.71	36.18	21.56	25.39
Intercept	507.02	558.44	561.58	504.69
Linearity (%)	99.74	99.81	99.26	97.67

Note. SF = single-feature; CJ = conjunction; PV = preview; PVG = preview gap.

4.2.3 Results

Relationship Between Level of ADHD, Level of Impulsiveness and Search Benefit. The relationship between ADHD, impulsiveness and search benefit were examined. As is explained in the previous behavioural study, the level of ADHD was reflected by a participant's score on the ASRS screener, with a possible range from 0 to 24. In the present study, the mean ASRS score for the entire sample (*N* = 92) was 12.84 (*SE* = 0.50, 95% CI [11.85, 13.83]), with a minimum score of 1 and maximum score of 22.

Previous research has shown that adults with ADHD actually demonstrate normative levels of trait impulsivity as determined by the Barratt Impulsiveness Scale (Chamberlain et al., 2021). As such, individuals with high levels of ADHD *and* higher than average levels of impulsivity may represent a population distinct from those with a sole diagnosis of adult ADHD. As high scores on the BIS are seen in bipolar disorder and impulse disorders (Charles et al., 2021; Mathias et al., 2018; Steinberg et al., 2013), this high ADHD + high impulsivity group may represent those with co-morbidities. As impulsiveness is also a continuously distributed trait in the general population, this too can be considered a continuous variable. The BIS-B was used in the present study, which has a possible range from 8 to 32. The mean BIS-B score was 17.45 (*SE* = 0.49, 95% CI [16.48, 18.41]), with a minimum score of 8 and a maximum score of 32.

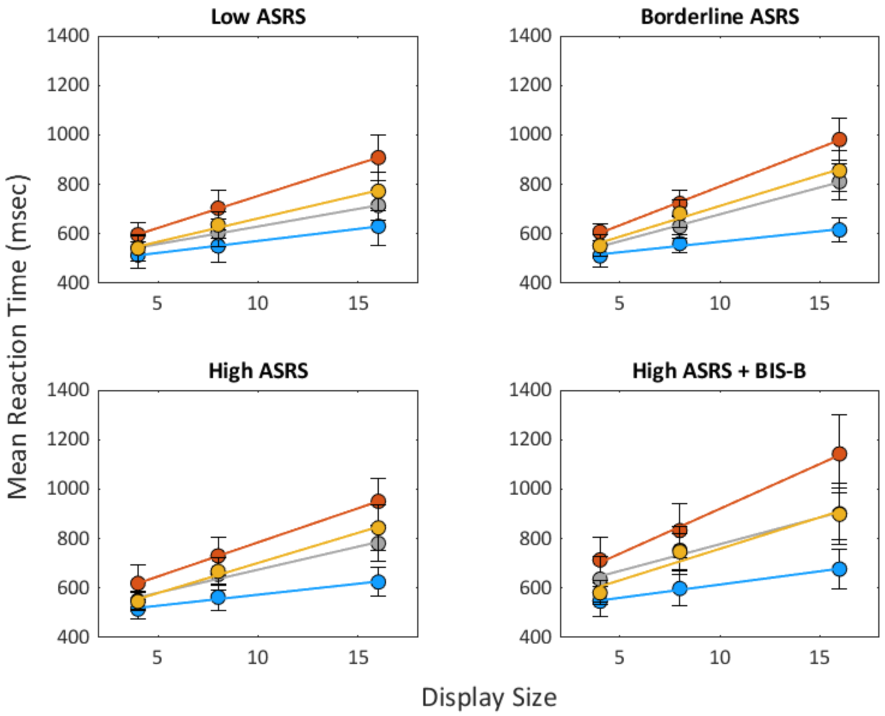
In the present study, search benefit is represented by the preview benefit and preview gap benefit index values (see section 2.1.3 and Equations 1 and 2). These provide a measure of the benefit to search that arises from the previewing of items and from the offsetting of preview items (i.e., the gap display). In the present study, the mean PB index value was 0.49 (*SE* = 0.07, 95% CI [0.35, 0.63]). The PGB is associated with values closer to 0, as this indicates failure to suppress old items, with a value of 0 reflecting none of the preview items being suppressed. Here, the mean PGB index value was 0.27 (*SE* = 0.12, 95% CI [0.04, 0.50]).

ASRS screener scores, $W = 0.971$, $p < .05$, BIS-B scores, $W = 0.968$, $p < .05$, PB index values, $W = 0.945$, $p < .001$, and PGB index values, $W = 0.768$, $p < .001$, were all non-normal. Accordingly, a Kendall's tau b correlation analysis was used to investigate the relationship between variables. ASRS score was not significantly related to either PB index value, $\tau = - .014$, $p = 0.852$, or PGB index value, $\tau = - .020$, $p = .784$. Similarly, BIS-B score was not related to PB value, $\tau = .037$, $p = .614$, or PGB value, $\tau = .037$, $p = .609$.

Omnibus 4 x 4 x 3 ANOVA – RTs. The mean RTs for each condition and display size for the four groups are shown in Figure 4.6 and Figure 4.7. Correct mean RTs were analysed using a 4 (group) x 4 (condition) x 3 (display) mixed ANOVA. Group (low ASRS x borderline ASRS x high ASRS x high ASRS + BIS-B) was a between-subjects factor. Condition (single-feature x conjunction x preview x preview gap) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction, preview and preview gap) were within-subjects factors. Levene's test was significant for preview at display size 8, F(2, 88) = 2.85, $p < .05$, indicating unequal variances at this level. For all other condition/display sizes, there was no significant differences between variances. Mauchley's test indicated that the assumption of sphericity had been violated for the main effects of Condition, $\chi^2(5) = 34.76$, $p < .00$, and display, $\chi^2(2) = 69.81$, $p < .001$, as well as for the Condition x Display interaction, $\chi^2(20) = 117.45$, $p < .001$. For the main effect of condition, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .894$). For the main effect of display and the Condition x Display interaction, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .644$ and $\varepsilon = .668$, respectively). Mean RTs did not differ significantly between groups, $F(3, 88) = 2.31$, $p = .08$, partial $\eta^2 = .07$. RTs were significantly different between conditions, $F(2.68, 236.04) = 133.68$, $p < .001$, partial $\eta^2 = .60$, and there was a significant Condition x Group interaction, $F(9, 264) = 2.47$, $p < .05$, partial $\eta^2 = .08$. These are explored further in additional analyses below. RTs increased with display size, $F(1.29, 113.42) = 506.93$, $p < .001$, partial $\eta^2 = .85$. The Group x Display interaction was also significant, $F(6, 176) = 2.22$, $p < .05$, partial $\eta^2 = .07$, which is also explored below. There was a significant Condition x Display interaction, *F*(4.01, 352.86) = 2.31, *p* < .001, partial η^2 = .40, which is explored further below. The three-way interaction of Group x Condition x Display failed to reach significance, *F*(18, 528) = 1.33, *p* = .19, partial η^2 = .04. All statistics for the omnibus ANOVAs are shown in Appendix Table P.1.

Figure 4.6

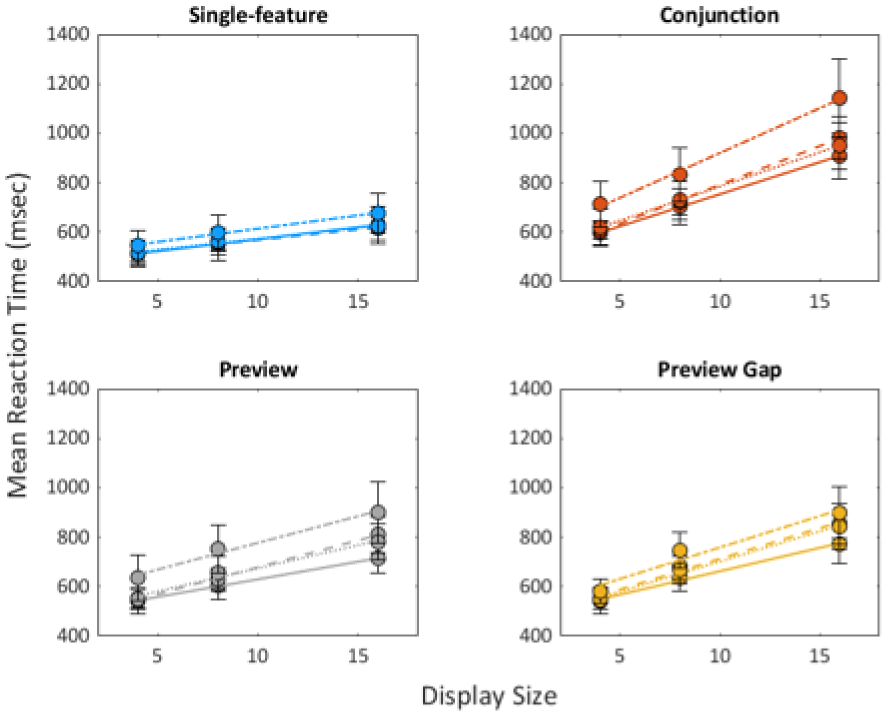
Mean RTs Separated by Group



Note. Single-feature = blue; conjunction = orange; preview = grey; preview gap = yellow. Error bars represent ±2 *SE*s.

Figure 4.7

Mean RTs Separated by Condition



Note. Low ASRS = solid line; borderline ASRS = dashed line; high ASRS = dotted line; high ASRS + BIS-B = dashed-dotted line. Error bars represent ±2 *SE*s.

Follow-Up 4 x 2 x 3 ANOVAs - RTs. All statistics for follow-up ANOVAs are listed in Appendix Table P.2.

Single-feature vs. Conjunction. Correct mean RTs were analysed using a 4 (group) x 2 (condition) x 3 (display) mixed ANOVA. Group (low ASRS x borderline ASRS x high ASRS x high ASRS + BIS-B) was a between-subjects factor. Condition (single-feature x conjunction) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 49.40$, $p < .001$, and for the Condition x Display interaction, $\chi^2(2) = 51.98$, $p < .001$. Accordingly, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = .698 and ε = .690, respectively). Mean RTs did not differ significantly between groups. RTs became significantly slower in the conjunction condition compared to single-feature, *F*(1, 88) = 307.65, *p* < .001, partial η^2 = .78. There was also a significant Group x Condition interaction, *F*(3, 88) = 4.19, *p* < .01, partial η^2 = .13. Post-hoc pairwise comparisons using the Bonferroni correction showed RTs were significantly slower in the conjunction condition in the high ASRS + BIS-B group compared to the low ASRS group (at *p* < .05) only. RTs increased significantly with display size, *F*(1.46, 122.80) = 400.79, *p* < .001, partial η^2 = .82. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences (at *p* < .001) between each of the display sizes. The Group x Display interaction failed to reach significance. There was a significant Condition x Display interaction, *F*(1.38, 121.40) = 133.85, *p* < .001, partial η^2 = .60. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for single-feature (all *p* < .001s) and for conjunction (all *p* < .001s). Compared to single-feature (*M* = 46.63, *SD* = 45.45), the conjunction condition (*M* = 113.02, *SD* = 83.87) had a significantly larger mean difference between the two lower display sizes, *t*(91) = -7.18, *p* < .001. Between the larger two display sizes, the conjunction condition (*M* = 248.45, *SD* = 157.17) also had a significantly larger mean difference compared to single-feature (*M* = 68.66, *SD* = 59.25), *t*(92) = -10.67, *p* < .001. Slopes were steeper in the conjunction condition. This pattern held for all four groups, reflected by the fact that the three-way interaction between group, condition and display failed to reach significance.

Conjunction vs. Preview. Correct mean RTs were analysed using a 4 (group) x 2 (condition) x 3 (display) mixed ANOVA. Group (low ASRS x borderline ASRS x high ASRS x high ASRS + BIS-B) was a between-subjects factor. Condition (conjunction x preview) and display size (4 x 8 x 16) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2)$ = 54.32, *p* < .001, and for the Condition x Display interaction, $\chi^2(2)$ = 21.01, *p* < .001. For the main effect of Display, degrees of freedom were corrected using

Greenhouse-Geisser estimates of sphericity ($\varepsilon = .683$). For the Condition x Display interaction, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .866$). There was a main effect of Group, $F(3, 88) = 3.25$, $p < .05$, partial $\eta^2 = .10$. Post-hoc pairwise comparisons using the Bonferroni correction showed that the high ASRS + BIS-B group was significantly slower than the low ASRS group (at $p < .05$) only. RTs became significantly faster in the preview condition compared to conjunction, $F(3, 88) = 211.10$, $p < .001$, partial $\eta^2 = .71$. Group did not interact with condition. RTs increased with display size, $F(1.37,120.19) = 390.68$, $p < .001$, partial $\eta^2 = .82$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences (at $p < .001$) between each of the display sizes. There was a significant Group x Display interaction, $F(6, 176) = 2.51$, $p < .05$, partial $\eta^2 = .08$. Post-hoc pairwise comparisons using the Bonferroni correction showed that mean RTs in the high ASRS + BIS-B group were significantly slower than the low ASRS group at display size 16 only (at $p < .05$). There was a significant Condition x Display interaction, $F(1.73, 152.35) = 38.95$, $p < .001$, partial $\eta^2 = .31$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for preview (all $p < .001$s) and for conjunction (all $p < .001$s). The preview ($M = 90.11$, $SD = 92.57$) and the conjunction condition ($M = 113.02$, $SD = 83.87$) did not differ significantly between the two lower display sizes, $t(91) = 1.99$, $p = .05$. Between the larger two display sizes, the conjunction condition ($M = 248.45$, $SD = 157.17$) had a significantly larger mean difference compared to preview ($M = 141.30$, $SD = 101.48$), $t(92) = 6.19$, $p < .001$. RTs increased with display size in the conjunction condition and this pattern held for all groups, indicated by a non-significant Group x Condition x Display interaction. All four groups demonstrated a preview benefit.

Single-feature vs. Preview Correct mean RTs were analysed using a 4 (group) x 2 (condition) x 3 (display) mixed ANOVA. Group (low ASRS x borderline ASRS x high ASRS x high ASRS + BIS-B) was a between-subjects factor. Condition (single-feature x preview) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for preview) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 27.41$, $p < .001$, and for the Condition x Display interaction, $\chi^2(2) = 14.67$, $p < .001$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .826$ and $\varepsilon = .909$, respectively). There was no significant difference between groups. RTs were significantly faster in the single-feature condition compared to preview, $F(3, 88) = 88.15$, $p < .001$, partial $\eta^2 = .50$. Group significantly interacted with condition, $F(3, 88) = 3.62$, $p < .005$, partial $\eta^2 = .11$. Post-hoc pairwise comparisons using the Bonferroni correction showed RTs were significantly slower in the preview condition in the high ASRS + BIS-B group compared to the low ASRS group (at $p < .05$). RTs increased significantly with display size, $F(1.65, 145.45) = 309.22$, $p < .001$, partial $\eta^2 = .78$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences (at $p < .001$) between each of the display sizes. Display did not interact with group. There was a significant Condition x Display interaction, $F(1.82, 160.03) = 49.82$, $p < .001$, partial $\eta^2 = .36$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for single-feature (all $p < .001$s) and for preview (all $p < .001$s). Compared to single-feature ($M = 46.63$, $SD = 45.45$), the preview condition ($M = 90.11$, $SD = 92.57$) had a significantly larger mean difference between the two lower display sizes, $t(91) = -4.46$, $p < .001$. Between the larger two display sizes, the preview condition ($M = 141.30$, $SD = 101.48$) also had a significantly larger mean difference compared to single-feature ($M = 68.66$, $SD = 59.25$), $t(92) = -6.15$, $p < .001$. RTs increased with display size more so in the preview condition. Finally, there was a significant Group x Condition x Display interaction, $F(5.18, 151.98) = 2.29$, $p < .05$, partial $\eta^2 = .07$.

Conjunction vs. Preview Gap. Correct mean RTs were analysed using a 4 (group) x 2 (condition) x 3 (display) mixed ANOVA. Group (low ASRS x borderline ASRS x high ASRS x high ASRS + BIS-B) was a between-subjects factor. Condition (conjunction x preview gap) and display size (4 x 8 x 16) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 65.11$, $p < .001$, and for the Condition x Display interaction, $\chi^2(2) = 26.39$, $p < .001$. For the main effect of Display, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .655$). For the Condition x Display interaction, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .832$). There was no significant difference between groups. RTs were significantly faster in the preview gap condition, $F(3, 88) = 72.73$, $p < .001$, partial $\eta^2 = .45$. Group did not interact with condition. RTs increased significantly with display size, $F(1.31,115.27) = 431.38$, $p < .001$, partial $\eta^2 = .83$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences (at $p < .001$) between each of the display sizes. Group did not interact with display. There was a significant Condition x Display interaction, $F(1.67, 146.48) = 17.79$, $p < .001$, partial $\eta^2 = .17$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for conjunction (all $p < .001$s) and for preview gap (all $p < .001$s). The preview gap (M = 128.35, SD = 82.88), the conjunction condition (M = 113.02, SD = 83.87) did not differ significantly between the two lower display sizes, $t(91) = -1.36$, $p = .176$. Between the larger two display sizes, the conjunction condition (M = 248.45, SD = 157.17) had a significantly larger mean difference compared to preview gap (M = 159.11, SD = 121.07), $t(92) = 4.98$, $p < .001$. RTs increased with display size more so in the conjunction condition, and this held for all groups, demonstrated by the lack of a significant Group x Condition x Display interaction. For all groups, search in the preview gap condition was significantly more efficient than search in the conjunction condition.

Single-feature vs. Preview Gap Correct mean RTs were analysed using a 4 (group) x 2 (condition) x 3 (display) mixed ANOVA. Group (low ASRS x borderline ASRS x high ASRS x high ASRS + BIS-B) was a between-subjects factor. Condition (single-feature x preview gap) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for preview gap) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 42.32$, $p < .001$, and for the Condition x Display interaction, $\chi^2(2) = 25.23$, $p < .001$. For the main effect of Display, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = .722). For the Condition x Display interaction, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity (ε = .839). RTs did not differ significantly between groups. RTs were significantly faster in the single-feature condition compared to preview gap, *F*(3, 88) = 86.81, $p < .001$, partial $\eta^2 = .50$. Group did not interact with condition. RTs increased with display size, *F*(1.44, 127.06) = 358.08, $p < .001$, partial $\eta^2 = .80$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences (at $p < .001$) between each of the display sizes. Group did not interact with display. There was a significant Condition x Display interaction, *F*(1.68, 147.68) = 98.34, $p < .001$, partial $\eta^2 = .53$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for single-feature (all *p* < .001s) and for preview gap (all *p* < .001s). Compared to single-feature (*M* = 46.63, *SD* = 45.45), the preview gap condition (*M* = 128.35, *SD* = 82.88) had a significantly larger mean difference between the two lower display sizes, *t*(91) = -9.26, $p < .001$. Between the larger two display sizes, the preview gap condition (*M* = 159.11, *SD* = 121.07) also had a significantly larger mean difference compared to single-feature (*M* = 68.66, *SD* = 59.25), *t*(92) = -6.72, $p < .001$. RTs increased with display size more so in the preview gap condition, and this pattern held for all groups, reflected by the lack of a significant three-way interaction. For all groups, search in preview gap was significantly less efficient than in single-feature.

Preview vs. Preview Gap. Correct mean RTs were analysed using a 4 (group) x 2 (condition) x 3 (display) mixed ANOVA. Group (low ADHD x borderline ASRS x high ASRS x high ASRS + BIS-B) was a between-subjects factor. Condition (preview x preview gap) and display size (4 x 8 x 16) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Display, $\chi^2(2) = 46.94$, $p < .001$. Accordingly, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = .706). There was no significant difference between groups. RTs did not significantly differ between conditions, and group did not interact with condition. RTs increased significantly with display size, *F*(1.41, 124.21) = 335.14, $p < .001$, partial $\eta^2 =$

.79. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences (at $p < .001$) between each of the display sizes. There was a significant interaction between group and display, $F(6, 176) = 2.30$, $p < .05$, partial $\eta^2 = .79$. Post-hoc pairwise comparisons using the Bonferroni correction showed that at display size 8, the high ASRS + BIS-B group's RTs were significantly slower compared to the low ASRS group (at $p < .05$). There was a significant Condition x Display interaction, $F(2, 176) = 10.96$, $p < .001$, partial $\eta^2 = .11$. Post-hoc comparisons using the Bonferroni correction showed significant differences at each of the three display sizes for preview (all $p < .001$s) and for preview gap (all $p < .001$s). Compared to preview ($M = 90.11$, $SD = 92.57$), the preview gap condition ($M = 128.35$, $SD = 82.88$) had a significantly larger mean difference between the two lower display sizes, $t(91) = -3.58$, $p < .001$. Between the larger two display sizes, the preview gap ($M = 159.11$, $SD = 121.07$) and preview ($M = 141.30$, $SD = 101.48$) conditions did not significantly differ, $t(92) = -1.33$, $p = .188$.The three-way interaction between group, condition and display was not significant. For all groups, search in the preview gap condition was significantly less efficient than search in the preview condition.

Preview and Preview Gap Benedit Indices. The low ASRS, borderline ASRS, high ASRS and high ASRS + BIS-B groups were compared on PB and PGB index values. As discussed previously, these indices provide a non-biased measure of the search benefit obtained in the preview and preview gap conditions. The calculation and interpretation of these indices are discussed in previous sections (see section 2.1.3).

The PB index value for the low ASRS group was 0.561 ($SE = 0.125$), for the borderline ASRS group it was 0.383 ($SE = 0.157$), for the high ASRS group it was 0.585 ($SE = 0.141$) and for the high ASRS + BIS-B group it was 0.443 ($SE = 0.147$). A one-way ANOVA was conducted to determine whether groups differed significantly. Levene's test indicated the assumption of homogeneity of variance was met, $F(3, 88) = 0.25$, $p = 0.86$. Groups did not differ significantly, $F(3, 88) = 0.45$, $p = .72$,

$\eta^2 = .02$. PB index values in the high ASRS + BIS-B group were non-normal, $W = 0.871$, $p < .001$; however, they were normal in the low, borderline and high ASRS groups. For the low ASRS group, there were 2 outliers at the high end of the scale with values greater than or equal to 1.4 and 3 outliers at the low end of the scale with values less than or equal to -0.3. In the borderline ASRS group, there were 2 outliers at the high end of the scale with values greater than or equal to 2.0 and 2 outliers at the low end of the scale with values less than or equal to -1.0. In the high ASRS group, there were 2 outliers at the high end of the scale with values greater than or equal to 1.6 and 2 outliers at the low end of the scale with values less than or equal to -0.6. In the high ASRS + BIS-B group, there were 2 outliers at the lower end of the scale with values less than or equal to -1.0.

For the PGB index, the value for the low ASRS group was 0.402 ($SE = 0.317$). For the borderline ASRS group, this value was 0.093 ($SE = 0.227$), and for the high ASRS group it was 0.254 ($SE = 0.147$). Finally, for the high ASRS + impulsive group, the PGB index was 0.329 ($SE = 0.233$). Again, a one-way ANOVA was conducted identify the existence of group differences. Levene's test indicated the assumption of homogeneity of variance was met, $F(3, 88) = 0.24$, $p = 0.87$. Groups did not differ significantly, $F(3, 88) = 0.31$, $p = .82$, $\eta^2 = .01$. PGB index values were non-normal in the low ASRS group, $W = 0.706$, $p < .001$, the borderline ASRS group, $W = 0.605$, $p < .001$, and the high ASRS + BIS-B group, $W = 0.867$, $p < .01$; however, index values were normal in the high ASRS group, $W = 0.952$, $p = .32$. For the low ASRS group, there was 1 outlier at the high end of the scale with a value of 5.3 and 3 outliers at the low end of the scale with values less than or equal to -1.1. In the borderline ASRS group, there were 3 outliers at the low end of the scale with values less than or equal to -0.-7. In the high ASRS group, there was 1 outlier at the high end of the scale with a value of 2.2. In the high ASRS + BIS-B group, there was 1 outlier at the lower end of the scale with a values less of -3.1 and 1 outlier at the high end of the scale with a value of 3.4. The PB and PGB index values are shown in Table 4.10 and Figure 4.8.

Table 4.10

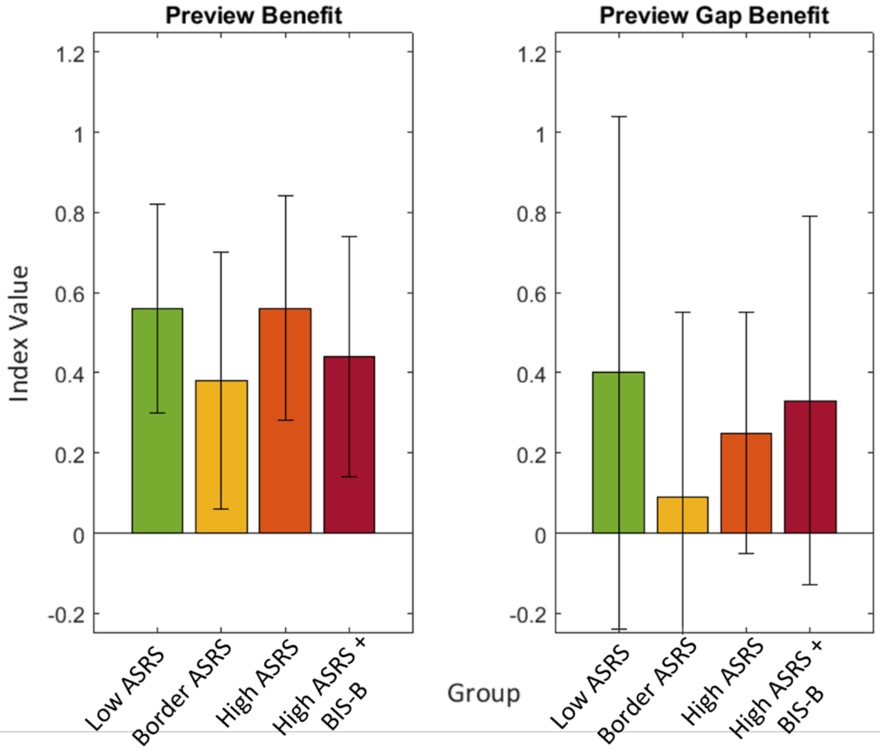
PB and PGB Index Means, Standard Deviations and One-Way ANOVA Statistics

Index	Low ASRS	Border ASRS	High ASRS	High ASRS + BIS-B	F(2, 88)
PB	0.56 (0.60)	0.38 (0.75)	0.59 (0.68)	0.44 (0.71)	0.45 (n.s.)
PGB	0.40 (1.52)	0.09 (1.09)	0.25 (0.71)	0.33 (1.12)	0.31 (n.s.)

Note. PB = preview benefit. PGB = preview gap benefit. Standard deviations are in parentheses. Groups did not differ significantly from one another on either the preview benefit or the preview gap benefit. There is a high amount of variability in both the PB and PGB index values for all groups. The index values can be interpreted as the percentage of old preview items suppressed at the final display.

Figure 4.8

PB and PGB Index Values for the Four Groups



Note. Index values range from 0 to 1. Values of 0 indicate no benefit – none of the old items could be sufficiently suppressed in the competition for selection, and therefore search was as inefficient as if all items had been presented simultaneously. Values of 1 indicate the maximum benefit – all old items were sufficiently suppressed, and therefore competition for selection occurred amongst only the new items. Values between 0 and 1 represent partial suppression of old items (e.g., a value of 0.5 indicates approximately 50% of old items were suppressed). While PB values typically trend more toward 1, PGB values tend more toward 0. Error bars represent ±2 *SE*.

Omnibus 4 x 4 x 3 ANOVA – Accuracy. Accuracies were analysed using a 4 (group) x 2 (condition) x 3 (display) mixed ANOVA. Group (low ASRS x borderline ASRS x high ASRS x high ASRS + BIS-B) was a between-subjects factor. Condition (single-feature x conjunction) and display size (2 x 4 x 8 for single-feature; 4 x 8 x 16 for conjunction) were within-subjects factors. Mauchley's test indicated that the assumption of sphericity had been violated for the main effect of Condition, $\chi^2(5) = 15.39$, $p < .01$, and for the Condition x Display interaction, $\chi^2(20) = 32.67$, $p < .05$. Accordingly, degrees of freedom were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = .968$ and $\varepsilon = .989$, respectively). Levene's test was significant for single-feature at display size 4, F(3, 88) = 3.45, $p < .05$, and for preview at display size 4, $F(3, 88) = 3.26$, $p < .05$, indicating unequal variances at these levels. For all other condition/display sizes, there was no significant differences between variances. There was no significant differences between groups, $F(3, 88) = 0.633$, $p = .596$, partial $\eta^2 = .02$. Accuracy differed significantly between conditions, $F(2.90, 255.55) = 8.48$, $p < .001$, partial $\eta^2 = .09$. Group did not interact with condition, $F(9, 264) = 1.13$, $p = .34$, partial $\eta^2 = .04$. There was a main effect of Display, $F(2, 176) = 10.72$, $p < .001$, partial $\eta^2 = .11$. Post-hoc pairwise comparisons using the Bonferroni correction showed significant differences between display sizes 4 and 8 (at $p < .001$) and display sizes 8 and 16 (at $p < .05$), but there no significant difference between display size 4 and 16 ($p = .176$). Display did not interact with group, $F(2, 176) = 1.65$, $p = .14$, partial $\eta^2 = .05$. There was a significant Condition x Display interaction, $F(5.94, 522.37) = 2.66$, $p < .05$, partial $\eta^2 = .03$. However, the three-way interaction failed to reach significance, $F(18, 528) = 0.79$, $p = .70$, partial $\eta^2 = .03$.

4.2.4 Discussion

In the present study, four groups with varying levels of ADHD symptoms and impulsivity were compared in preview and preview gap search to determine whether groups differ in their ability to visually mark and/or temporally bind items. The first group, which is referred to as the low ASRS group, consists of individuals who did not have elevated levels of ADHD symptoms or impulsiveness, and thus reflect healthy controls. Those in the borderline and high ASRS groups indicated elevated levels of ADHD symptoms on the ASRS screener (Kessler et al., 2005, 2007), indicative of either subclinical or clinical cases of ADHD, respectively. Furthermore, in the borderline and high ADHD groups, individuals demonstrated normal levels of impulsiveness, as measured by the BIS-B (Steinberg et al., 2013). Finally, a fourth group, the high ASRS and BIS-B group, consisted of individuals that showed both elevated levels of ADHD and elevated levels of impulsiveness. As research shows adults with ADHD typically demonstrate normal levels of impulsiveness (as measured by the Barratt Impulsivity Scale; Chamberlain et al., 2021; Stanford et al., 2009), this fourth group is aimed to be representative of individuals who have co-morbid ADHD. In previous research (Mason et al., 2003, 2004), it has been shown that children with ADHD are able to generate a preview benefit similar to their TD peers, indicative of sufficient visual marking (i.e., top-down suppression) of old distractor items. This was also reported in the previous chapter in children with high Conners 3AI scores. Accordingly, it was hypothesized here that the borderline and high ASRS groups would also demonstrate this ability through a preview benefit similar to their low ASRS peers. This was indeed the case in the present study, as well as in the first behavioural study reported in this chapter. For the low, borderline and high ASRS groups, preview slopes were significantly more efficient (i.e., flatter) than conjunction. Preview slopes were ~14 msec/item for the low ASRS group, ~22 msec/item for the borderline ASRS group, and ~19 msec/item for the high ASRS group (see Table 4.9). Furthermore, the preview benefit index values for these groups indicate that 56%, 38% and 59% of preview items were suppressed in the final display for the low, borderline and high ASRS groups, respectively (see Table 4.10).

For the high ASRS + BIS-B group, it was hypothesized that this co-morbidity would affect visual marking. Although the effect of impulsiveness has not yet been investigated with regard to visual marking specifically, previous research has indeed shown that those with co-morbid ADHD often perform worse non co-morbid peers on measures of top-down control (Salarvan et al., 2019;

Torres et al., 2017; Y. Zhang et al., 2024). Contrary to this hypothesis, however, the high ASRS + BIS-B impulsive group were able to generate a preview benefit similar to the other three groups. This indicates intact visual marking in this group as well. Preview slopes in this group were ~22 msec/item, and the PB index value for this group indicated 44% of preview items were successfully suppressed by the final display. Although this group was indeed able to generate a preview benefit, this group did perform differently than the low ASRS group in some respects. For instance, in the comparison between conjunction and preview, mean RTs became significantly slower at display sizes 8 and 16 more so in the high ASRS + BIS-B group compared to the low ADHD group. Furthermore, RTs became significantly slower in the preview condition compared to single-feature more so in high ASRS + BIS-B group compared to low ASRS group. These results perhaps indicate that the high ASRS + BIS-B group are indeed affected by the requirement to visually mark items, as it slows response times and is affected by display size. Despite this, however, they are still able to generate a preview benefit. Further research should explore these subtle differences in performance.

It is also important to note that, although mean RTs became significantly slower in the conjunction condition compared to single-feature for all groups, this occurred more so in the high ASRS + BIS-B group compared to the low ASRS group. This indicates some increased difficulty in the conjunction condition for this group. As conjunction search is associated with the allocation of effortful, top-down attention (Treisman & Gelade, 1980; Wolfe, 2020), this result aligns with previous literature of difficulty with top-down control in co-morbid ADHD groups (Miyauchi et al., 2023; Salarvan et al., 2019; Torres et al., 2017; Zhang et al., 2024). Given this apparent difficulty, it is interesting that this did not extend to weaker visual marking, which also requires top-down control (Humphreys et al., 2005; Watson & Humphreys, 2000; Yamauchi & Kawahara, 2020). Apparently, the temporal element of the preview condition is beneficial enough to offset both the top-down element of the conjunctive target (i.e., top-down expectancy for the target item) and the top-down element of the preview (i.e., visual marking).

Other than visual marking then, a second hypothesis predicted that temporal binding would become increasingly weaker according to ADHD symptom, with the weakest being the high ASRS + BIS-B group. Indeed, although temporal binding is considered a more bottom-up function of time-based attention, it requires complex coordination both within- and between-brain regions at very fast timescales (Singer, 2015, 2021). As the efficiency of neural signalling is implicated in ADHD (Gonen-Yaacovi et al., 2016; Pertermann et al., 2019) and there is substantial evidence of weakened connectivity (Mazaheri et al., 2010; Soman et al., 2023b; Wang et al., 2009; Wu et al., 2023) in ADHD, temporal binding may be at risk for problems in this disorder. In the previous chapter, behavioural and computational modelling methods were used to explore this function in children with high ADHD symptoms. It was found that there was a significant relationship between ADHD symptom level and preview gap benefit, and there was also (non-significant) evidence of slope differences between these groups. As previously mentioned, the magnitude of the benefit in the preview gap condition is associated with temporal binding - a reduced or absent benefit is indicative of intact temporal binding, while a continued benefit in this condition reflects weakened temporal binding (Kunar et al., 2003; Mavritsaki & Humphreys, 2016). Accordingly, it was hypothesized that the magnitude of the preview gap benefit would increase with level of ADHD (and impulsiveness), reflected both in the flattening of slopes across groups, and the increase in the PGB index values. However, this was not the case. There were no significant differences between the group's preview gap slopes. The slopes were ~19 msec/item for low ASRS, ~25 msec/item for borderline ASRS, ~ 24 msec/item for high ASRS, and ~25 msec for high ASRS + BIS-B - all of which were significantly steeper than the preview slopes (see Table 4.9). Accordingly, this indicates that temporal binding is likely to be intact in adults with borderline and high levels of ADHD and in adults with high levels of ADHD and impulsiveness.

A final aspect to note in the present results are the increased PGB index values (particularly in the low ASRS group) and variability for these values (see Table 4.10). As discussed previously, PB index values are usually higher (closer to 1), indicative of a high percentage of preview items being suppressed at the final display. In contrast, preview gap values tend to be lower (closer to 0), indicative of a low percentage of preview items being suppressed at the final display. This typical low PGB index value reflects the lack of any search benefit in this condition, as an index value of 0 would indicate search was as difficult as a standard conjunction search. As the existence of any benefit in this condition is associated with the strength of temporal binding (e.g., weak binding yielding more benefit; Mavritsaki & Humphreys, 2016), it was hypothesized that the magnitude of the benefit would increase across the groups, with the low ASRS group having the lowest PGB index scores and high ASRS + BIS-B group having the highest. However, the low ASRS group had the highest PGB index value at 0.40, indicating that 40% of preview items were suppressed at the final display. This value drops (although not significantly so) to 0.09 for the borderline ASRS group, then appears to climb back up to 0.33 for the high ASRS + BIS-B group. There is also a large amount of variability for the low ASRS group's PGB (see Figure 4.5). These two findings are unexpected, as they do not fit with the hypothesis, nor do they fit with previous findings in the literature of preview gap performance in healthy controls. One consideration here is that these results may have arisen as a result of conducting this experiment using an online platform. However, all sessions were monitored to ensure RTs were valid. Furthermore, these unexpected results occur only for the low ASRS group, rather than for all groups, who were tested in an identical manner. Ultimately, these results should be interpreted with caution, and further research should aim to rectify this inconsistency.

4.3 General Discussion

The present chapter presents two behavioural studies aimed to examine time-based attention in adults with varying levels of ADHD. In the first study, adults with low levels of ADHD symptoms (and are thus considered healthy controls) are compared to adults with borderline levels and high levels of ADHD symptoms on preview and preview gap search. Here, it was hypothesized that, similar to children with high levels of ADHD symptoms, adults with borderline and high levels of

ADHD symptoms would have intact visual marking and thus perform similarly to their low-ADHD-symptom peers in preview search. This was indeed the case, as all groups were able to generate a substantial preview benefit, whereby the previewing of distractor items resulted in slopes significantly more efficient than those seen in a standard conjunction search. The PB index values indicated about 60% of preview items were suppressed in all groups. A second hypothesis for this behavioural study concerned the strength of temporal binding in borderline and high ASRS groups. In the previous chapter, it was shown that the magnitude of preview gap benefit was significantly related to the level of ADHD symptoms in children. Furthermore, an exploratory analysis showed that children with high levels of ADHD symptoms maintained the preview benefit in the preview gap condition. As the loss of the preview benefit in this condition is indicative of strong temporal binding (Mavritsaki & Humphreys, 2016), it was proposed that temporal binding may be weaker in ADHD. A computational modelling study established this hypothesis was indeed biologically plausible. Accordingly, it was hypothesized here that the magnitude of preview gap benefit would be positively correlated with level of ADHD symptoms. It was also predicted that slopes in the preview gap condition would become significantly more efficient (i.e., flatter) between low and borderline, as well as between borderline and high. However, this was not the case. There was no relationship between level of ADHD and PGB. Furthermore, there was no significant difference between groups on preview gap slopes. Only between 2% and 7% of preview items were suppressed in the preview gap condition, according to PGB index values. These results indicate that temporal binding is intact in adults with borderline and high levels of ADHD symptoms.

A second behavioural study was then conducted in order to address a few limitations of the first study. First, data collection for this first behavioural study was interrupted due to COVID-19. Therefore, there are unequal sample sizes for the three groups, with only 17 participants in low ASRS group while the borderline and high ASRS groups had nearly twice this amount (30 in borderline and 27 in high). Unequal samples affects the assumption of equal variances, which is a key assumption in

ANOVA tests. Importantly, this can have a detrimental effect on statistical power (Rusticus & Lovato, 2014). A second issue with this first behavioural study is the sole use of the ASRS screener for ADHD identification. This measure is indeed commonly used (Lewczuk et al., 2024; Mattos et al., 2024; Vňuková et al., 2021) and initial research indicated both high sensitivity (68.7%) and specificity (99.5%) for the correct identification of ADHD in the general population (Kessler et al., 2005). However, more recently, Chamberlain et al. (2021) used the ASRS screener in two normative cohorts of young adults in the US and UK. They found that 86-90% of individuals that had been identified by this screener as having probable ADHD were actually unlikely to truly have the disorder. They estimated the positive predictive value was only about 11.5% (Chamberlain et al., 2021). Accordingly, in the second study, a second impulsiveness screener was used alongside the ASRS. This had two purposes: first, individuals who scored high on impulsiveness but low or borderline on ADHD symptoms were not included in the study to avoid a false ADHD identification in individuals more likely to have an impulse disorder. Secondly, the high ADHD individuals were separated by their impulsiveness level to represent "pure" ADHD and those more likely to have co-morbid ADHD and an impulse disorder. Ultimately, the second study was designed to correct the problems with statistical validity and the imprecision of measurement, as these issues in the first study are likely to have a sizeable impact on the reliability of the findings.

With equal sample sizes, and with the addition of the BIS-B, the second study was then conducted. A further change in the methodology here was that the experiment was conducted entirely online. Here, the hypotheses were essentially the same: the low, borderline and high ADHD groups were predicted to have intact visual marking, in line with previous research (Mason et al., 2003, 2004) and the results of chapter 3. Furthermore, as individuals with co-morbid ADHD generally experience more impairment (Miyauchi et al., 2023; Salarvan et al., 2019; Torres et al., 2017; Zhang et al., 2024), it was hypothesized that these individuals may possibly demonstrate difficulty in the preview condition, indicative of differences in visual marking. Additionally, it was hypothesized that weak temporal binding/increased preview gap benefit would be correlated with level of ADHD symptom. Finally, it was predicted that temporal binding weakness would be most prominent in this group compared to their low, borderline and high ADHD peers. Only the first of these predictions was met. Indeed, there was no significant difference between the low, borderline and high ASRS groups on preview slopes. However, this was also the case for the high ASRS + BIS-B group, implying intact visual marking for all groups. PB index values indicated that between 38-59% of preview items were suppressed. These values were lower than expected, as lowest PB index values in the previous behavioural studies was 0.61 (see section 3.1.2). Also contrary to hypothesis, there was no relationship between ADHD level, impulsiveness level and PGB. Preview gap slopes did not significantly differ between any of the four groups. PGB index values indicated that between 9-40% of preview items were suppressed in the preview gap condition. These values were also quite a bit higher (and had quite a bit more variability) than what was seen in the previous studies reported in the present thesis.

Other than visual marking and temporal binding, a few other results were of interest. In the first behavioural study, while accuracy decreased in the difficult conjunction condition for the low ASRS group, accuracy actually increased as display size increased for the high ASRS group. This could indicate that the conditions of the conjunction search are the “right” level of difficulty (i.e., not too easy but not too hard), allowing these individuals to be more efficient (Mullane & Klein, 2008). In the second study, the high ASRS + BIS-B group often had slower RTs compared to the low ASRS group in more difficult conditions (i.e., conjunction and preview) and at higher display sizes (i.e., 8 and 16). This is likely to reflect the more prominent differences in top-down functioning this group generally (Miyauchi et al., 2023; Salarvan et al., 2019; Torres et al., 2017; Zhang et al., 2024). However, despite this, this group demonstrated intact visual marking and temporal binding, indicating that time-based attention is likely unaffected by ADHD and impulsiveness.

Although this finding indeed supports the idea that the ability to visually mark items is not affected by ADHD, it may be that differences in visual marking do exist but are just not observable in the present study. For one, it may be that the task conditions here are not complex enough to elicit these differences. Indeed, previous work with conjunction search has shown that in children with attention difficulties, visual search performance differences were not apparent until very high display sizes of 32 items - twice that of the highest display size used here (Shalev & Tsal, 2003; Tsal et al., 2005). Another possibility is that ADHD-related differences in visual marking might be evident at the neural level instead of the behavioural level. Previous research has shown that, in visual search conditions that require active suppression of distractor items, individuals with ADHD have reduced amplitudes of the P_D component, as well as reduced functional activity in the IPL (Cross-Villasana et al., 2015; Wang et al., 2016; Zhu et al., 2023), both of which are associated with visual marking (Berggren & Eimer, 2018; Olivers & Humphreys, 2004; Pollmann et al., 2003; Reeder et al., 2017). This notion is also applicable to temporal binding. Previous research indicates that temporal binding relies on the fast and efficient communication between- and within-regions of the brain (Singer, 2015, 2021), and the neural efficiency and connectivity that gives rise to this communication is often weakened in ADHD (Brennan & Arnsten, 2008; Pertermann et al., 2019; Wang et al., 2009; Wu et al., 2023). Other work indicates the PPC is also an important region in the function of temporal binding (Mavritsaki & Humphreys, 2016; Olivers & Humphreys, 2004), which is a key area implicated in ADHD (Hoogman et al., 2019; Lin et al., 2015; Schulz et al., 2017). As such, future research may seek to confirm whether differences arise between ADHD and healthy control groups using neuroimaging techniques in additional to analysing behavioural performance.

While ADHD has traditionally been characterised as a categorical disorder, it is probably better understood as a dimensional disorder (Sonuga-Barke et al., 2023). Indeed, evidence shows that the common genetic variants associated with risk of clinical ADHD diagnosis also influence the distribution of inattention and hyperactivity/impulsivity traits present in the general population

(Martin et al., 2014; Stergiakouli et al., 2015). This supports the notion that an ADHD diagnosis represent extreme cases of a continuum of behaviour (Asherson & Trzaskowski, 2015; Larsson et al., 2012). High levels of ADHD-traits in non-diagnosed individuals has been linked to similar functional impairments, including technology addictions (Aydin et al., 2023; Panagiotidi & Overton, 2022), worse substance abuse outcomes (Yoshimura et al., 2022) as well as poor academic achievement (Gray et al., 2017; Zendarski et al., 2022). Furthermore, similar patterns of impairment are also shown in subthreshold ADHD cases (Hirata et al., 2023; Sibley et al., 2022). Accordingly, the studies in the present thesis use groups comprised of individuals who display varying levels of ADHD traits but have never been diagnosed or undergone treatment for ADHD. While this provides a more accurate and generalisable sample, it also means that the impairments in time-based attention might have been more pronounced if the groups were comprised of diagnosed individuals.

4.4 Chapter Summary

Although ADHD is traditionally characterised as a childhood disorder that resolves by adulthood, often times symptoms and impairments can continue to affect individuals in adulthood (Biederman et al., 2000; Breda et al., 2021; Faraone et al., 2006; Sibley et al., 2022). Recently, the existence of late-onset ADHD has been evidenced, whereby individuals who did not meet the criteria for ADHD in childhood begin to experience symptoms and impairments for the first time in adulthood (Asherson et al., 2016; Asherson & Agnew-Blais, 2019). As adult ADHD is becoming more recognised, it is important that research aim to characterise differences in these individuals to better understand how neurocognitive differences in this disorder present in adulthood (Lovett & Harrison, 2021; Sibley et al., 2018). The present chapter presented two behavioural studies aimed at exploring how time-based attention is affected by both borderline and high levels of ADHD symptoms. An additional group comprised of individuals demonstrating both high levels of ADHD and high levels of impulsiveness were included in the second study here to analyse how co-morbid individuals compare to groups with low, borderline and high levels of ADHD symptoms. Levels of ADHD symptoms were determined by Adult ADHD Self-Report Screener (ASRS) scores, while levels of impulsiveness were identified by Barratt Impulsiveness Scale-Brief (BIS-B) scores. These groups were compared on two measures of visual search tasks, preview and preview gap search, to specifically examine two time-based attention functions, namely visual marking and temporal binding. The results of these studies showed that similar to low ASRS score, those with borderline ASRS, high ASRS and high ASRS + BIS-B scores are able to efficiently use top-down attention in time to visually mark old preview items and generate a preview benefit. Similarly, all four of these groups demonstrated strong temporal binding in the preview gap condition, such that the benefit to search was lost under these search conditions. Despite this, the high ASRS + BIS-B group demonstrated some general difficulty compared to healthy controls in the more difficult search conditions and at higher display sizes. Overall, the results of this chapter indicate that time-based attention, particularly visual marking and temporal binding, are not affected by ADHD.

Chapter 5: Discussion

At any given moment, we are being bombarded by limitless information in the environment around us (Cowan et al., 2005; Tsotsos, 1990). In order to successfully interact with this environment and achieve our behavioural goals, we must selectively prioritise relevant information while simultaneously ignoring the irrelevant. This is the crucial process of selective attention (Buschman & Kastner, 2015; Chun et al., 2011; Desimone & Duncan, 1995; Krauzlis et al., 2023). In the visual domain, a large body of research has been dedicated to understanding how selective attention is effectively allocated to a particular location in space or moment in time, particularly in the adult brain (Buschman & Kastner, 2015; Carrasco, 2011; Long & Kuhl, 2018; Moore & Zirnsak, 2017; Stemmann & Freiwald, 2019). However, much less is known about how selective attention operates during development and how neurodevelopmental disorders like ADHD may affect these operations (Amso & Scerif, 2015; Kim & Kastner, 2019; Lynn & Amso, 2023). Accordingly, the overarching aim of the present thesis was to examine the age- and ADHD-related differences in selective attention in and explore the potential mechanisms underlying these differences. Specifically, time-based attention was examined using an interdisciplinary approach with both behavioural and computational modelling methods. Classic visual search tasks were employed in order to capture behavioural performance, and to draw conclusions based in psychological theories like FIT and GSM (Treisman & Gelade, 1980; Wolfe, 1994, 2021). These conclusions were then tested using a neurocomputational model, so that the plausibility of assumptions at the psychological level could be further scrutinized at the physiological level.

Consistent with the aim of the thesis, the studies presented here provide new insights into both age-related and ADHD-related differences in selective visual attention at both the behavioural and neural levels. Notably, the efficiency with which selective visual attention is allocated improves over development (Lynn et al., 2020, 2024; Merrill & Lookadoo, 2004; Zupan et al., 2018).

Furthermore, children with ADHD are likely to experience differences in time-based attention in addition to age-related differences (Mason et al., 2004, 2005). However, any ADHD-related difficulties in time-based attention appear to resolve by adulthood. Accordingly, the present thesis contributes significantly to the existing body of literature. Furthermore, it provides an original contribution to the literature on attention differences in ADHD by using an interdisciplinary approach. This chapter will provide an overall summary and evaluation of the findings presented in chapters 2, 3 and 4 and discuss how these findings align with the aims and objectives of the thesis. The theoretical and practical implications of this research will then be considered. Finally, the limitations and future directions of this research will be discussed.

5.1 Overview: Aims and Objectives

Items in the visual field compete for neural representation according to their level of behavioural relevance, as determined by the combined bottom-up (stimulus-driven) and top-down (goal-driven) signals (Boshra & Kastner, 2022; Buschman & Kastner, 2015; Desimone & Duncan, 1995; Fiebelkorn & Kastner, 2020). Accordingly, the ability to direct and focus our attention to what is important to our goals – as well as to ignore what might be distracting – relies on how priority is computed across both space and over time (Fecteau & Munoz, 2006; Peelen & Kastner, 2014; Yu et al., 2023). At the behavioural level, this ability is captured by the efficiency with which a pre-determined target can be located among distractors (Wolfe, 2020, 2021). Differences in this search efficiency in individuals ADHD would thus demonstrate a fundamental difference in selective visual attention. To this end, single-feature, conjunction, preview and preview gap search (Treisman & Gelade, 1980; Watson & Humphreys, 1997) were employed to investigate the mechanisms of attention across space and time. Furthermore, a neurocomputational model, the binding spiking-search over time and space (b-sSoTS) model (Mavritsaki et al., 2011; Mavritsaki & Humphreys, 2016), was used to simulate age- and ADHD-related differences at the behavioural level, so that the mechanisms underlying search, including top-down expectancy for target features, visual marking and temporal binding, could be further examined at the neural level.

The present thesis aimed to accomplish the following objectives: establishing a general pattern of search for the preview and preview gap conditions that is characteristic of late childhood (i.e., 7- to 12-years old), and examining how this pattern of search differs from that of adulthood (see Chapter 2.1); using the b-sSoTS model to test the synaptic strength and top-down expectancy as proposed mechanisms underlying the age-related differences in search and simulate children's visual search performance (see Chapter 2.2); investigating whether levels of ADHD-traits in children influences the efficiency of time-based attention in the preview and preview gap conditions (see Chapter 3.1); simulating ADHD visual search performance using b-sSoTS and exploring temporal binding as a potential mechanism implicated in the disorder (see Chapter 3.2); and lastly, examining whether differences in time-based attention arise in adults with ADHD (see Chapter 4.1), and whether these occur and/or differ in co-morbid ADHD and a suspected impulse disorder (Chapter 4.2). In the following section, the key findings of each research objective will be discussed further.

5.2 Key Findings

In chapter 2, children in late childhood (7- to 12-years olds) and adults were compared on four visual search conditions in order to establish the pattern of search slopes characteristic to each group, and to examine any differences between them. Children were significantly slower and less accurate compared to adults. Importantly, all participants – both children and adults - demonstrated intact basic mechanisms of search. Flat slopes in the single-feature condition indicated efficient detection of pop-out targets across varying numbers of surrounding distractors. Comparatively steeper slopes in the conjunction condition reflected the more inefficient search that occurs when more effortful, top-down attention is required (Treisman & Gelade, 1980; Wolfe, 2020). Notably, while both groups exhibited this classic slope pattern, children found it even more difficult than adults to identify the target in the conjunction condition. This difference between groups may be indicative of age-related differences in allocating top-down control, particularly under increasing interference from nearby distractors (Donnelly et al., 2007; Lynn et al., 2020; Merrill & Lookadoo, 2004). However, these difficulties in top-down attention did not appear to negatively affect search over time. Indeed, both children and adults demonstrated a benefit to search in the preview condition, indicative of intact visual marking of old “previewed” distractor items (Berggren & Eimer, 2018; Olivers et al., 2006; Osugi et al., 2016; Watson & Humphreys, 1997). Furthermore, both of these groups demonstrated a loss of the preview benefit in the preview gap condition, which points to sufficient temporal binding in children and adults (Kunar et al., 2003; Mavritsaki & Humphreys, 2016). Analysis of these time-based benefits using the preview and preview gap benefit index showed (non-significantly) larger benefits in both the preview and preview gap conditions in children. However, the lack of group differences between children and adults on performance in preview and preview gap search warrants further research to understand how time-based attention differs in childhood.

The behavioural results presented in chapter 2 were then further analysed using the b-sSoTS model, a neurocomputational model that employs biologically plausible activation functions (see section 2.2.2). The architecture and dynamics of the b-sSoTs model allows visual search to be simulated at both the behavioural level and neural level, ultimately providing unique insight into the potential mechanisms underlying behaviour. Here, hypotheses derived from the behavioural study were investigated using the b-sSoTS model to analyse the potential mechanisms underlying children’s visual search performance. Simulations showed that reducing synaptic strength in the model provided a good qualitative fit for children’s longer RTs, worse accuracy, and decreased efficiency in the conjunction condition. This synaptic strength reflects the strength to which neurons encoding for the same stimuli are coupled. This strength increases across development with experience and with neurotransmitter changes that occur in adolescence (Hashimoto et al., 2009;

Perica et al., 2022; Topchiy et al., 2024). Importantly, reduced synaptic strength provided a better account of the behavioural performance compared to the strength of top-down expectancy, both alone and combined with synaptic strength changes. Reducing synaptic strength also provided a qualitative account for the adult-like performance in preview and preview gap search. This revised "child" version of the model was named the b-sSoTS-c (where "c" stands for "child"). By analysing simulations of the b-sSoTS-c at the spiking level, it was shown that, in preview search, the reduced strength of distractors allowing them to become suppressed faster, thus reducing competition in the final display. In the preview gap condition, this meant that preview items could become more suppressed during the gap display. Then, when all items re-appeared after the gap, the reduced strength of items meant that temporal binding was not as strong, again reducing competition for the target item.

Chapter 3 presents an investigation into visual attention differences between children with low and high levels of ADHD symptoms (as determined by their Conners 3AI scores) using visual search. The results from this chapter contribute significantly to the overall thesis, as differences in preview gap search highlight potential differences in underlying mechanisms in time-based attention in children with high levels of ADHD symptoms. Search efficiency in the preview gap condition has been shown to uniquely tap into temporal binding, a more bottom-up mechanism of time-based attention (Kunar et al., 2003; Mavritsaki & Humphreys, 2016). The effects of temporal binding are not only important in and of itself in determining the competitive interactions among spatially distributed items, but also in the evolution of priority level for identical objects presented at distinct moments in time (Mavritsaki & Humphreys, 2016). As such, examining behavioural performance in preview gap or other visual search tasks can offer insight into the complex interactions underlying the emergence of attention. Indeed, this chapter showed a significant relationship between level of ADHD and search benefit experienced in the preview gap condition. An exploratory analysis showed that children with low Conners 3AI scores elicited a benefit to search in the preview condition; however, this benefit was lost in the preview gap condition – a pattern of results indicative of intact visual marking and temporal binding (Kunar et al., 2003; Mavritsaki & Humphreys, 2016; Watson & Humphreys, 1997). Importantly, while children with high Conners 3AI scores also demonstrated a preview benefit, this benefit was maintained in the preview gap condition, indicating reductions in temporal binding. Still, the lack of any significant differences between groups again warrants additional research into time-based attention in childhood ADHD.

In the second study of chapter 3, a computational modelling study was undertaken to investigate the biological plausibility of reduced temporal binding in children with high levels of ADHD symptoms. First, the b-sSoTS-c model was used to simulate the low Conners 3AI (i.e., general population) group's search performance. Next, to simulate the high Conners 3AI group, temporal binding was removed from the b-sSoTS-c model. Simulations showed that, in the preview condition, when items are not bound by their common onset, groups become less distinct from one another. When analysed at the spiking level, this means that old items compete with newer items more so when temporal binding is removed, resulting in a slight increase in competition. In contrast, preview gap search becomes much more efficient when temporal binding is absent. In the spiking level simulations, it was shown that this result occurs when the continued suppression of old items is not offset by the increased activation in all items at the final display implemented through temporal binding. As a result, there is less competition between items. Overall, when temporal binding was removed, preview and preview gap slopes become much closer, such that a significant search benefit is maintained in the preview gap condition. Accordingly, the removal of temporal binding in the model provided a good qualitative fit for the high Conners 3AI group's visual search performance.

Chapter 4 of the present thesis presented two related behavioural studies examining time-based attention in adult ADHD. Time-based attention, specifically preview and preview gap search, has not yet been studied in the field of adult ADHD research. As adult ADHD has only acknowledged in the past 30 years or so (APA, 1994; Lange et al., 2010), there is an increased need for research in this area. The aim here was to determine whether adults with ADHD would demonstrate intact visual marking but weakened temporal binding. In a first study, a low ASRS group (i.e., general population), a borderline ASRS group, and a high ASRS group were compared in preview and preview gap. Results demonstrated that all groups were able to generate a preview benefit, indicative of intact visual marking. Furthermore, this search benefit was lost in the preview gap condition, reflecting strong temporal binding. However, the in-person data collection for this study was disrupted by COVID-19 lockdowns, which ultimately led to issues with statistical validity due to unequal sample sizes in groups (Rusticus & Lovato, 2014). Accordingly, a second study was undertaken. In this second study, which was conducted completely online, four groups were compared: adults with low ASRS (i.e., general population), adults with borderline ASRS, adults with high ASRS and, lastly, adults with both high ASRS and high levels of impulsiveness. Impulsiveness, which was measured using the BIS-B (Steinberg et al., 2013), was a variable of interest here, as adults with ADHD have been shown to have normal levels of impulsiveness as measured by this scale (Chamberlain et al., 2021). Accordingly, it was ensured that the low, borderline and high ADHD groups all had normal BIS-B scores. In contrast, the high ASRS + impulsive group comprised of individuals with high ASRS scores and high BIS-B scores, aimed at representing a co-morbid ADHD group. This study produced similar results. All groups were able to generate a preview benefit, indicating that all groups were able to sufficiently mark old preview items. Similarly, this search benefit was lost in the preview gap condition, indicating all groups were able to temporally bind items. Despite this, the high ASRS + BIS-B group was overall slower in more difficult conditions (conjunction and preview) and at higher display sizes (6 and 18) compared to the low ASRS group. These results contribute significantly to the overall thesis, as they demonstrate that visual marking and temporal binding function normally in cases of adult ADHD. Furthermore, while individuals with high levels of ADHD and impulsiveness experience some difficulty in measures of attention, their ability to visually mark and temporally bind items appears to be intact.

5.3 Implications for Research

Although these conclusions warrant further research, the work presented here has yielded substantial new insights into attention and attention difficulties. First, the present thesis has added to the existing evidence of age-related differences in selective visual attention in the literature. Importantly, the computational modelling study has expanded on the potential mechanisms underlying these developmental differences by showing reduced synaptic strength provides a better account for the slower, less accurate, and less efficient performance in childhood over and above reduced top-down attention. Second, the present thesis has also presented novel evidence of how ADHD in childhood can contribute to differences in time-based attention, in addition to age-related difficulties. This outcome is particularly significant as it indicates weakness in bottom-up functions like temporal binding, rather than top-down functions like visual marking, better characterises ADHD. Finally, two behavioural studies in adults with and without ADHD showed that no differences in visual marking and temporal binding. The visual search tasks used – single-feature, conjunction, preview and preview gap – provided insight into the competitive mechanisms at the behavioural level, which can be understood by analysing slopes of the RT function. These tasks are backed by extensive literature, and are easy to implement in an experimental setting, thus offering a more consistent measure of attention in ADHD research (Eckstein, 2011; Nakayama & Martini, 2011; Wolfe, 2015b, 2020). Finally, the b-sSoTS model, a neurocomputational model with biologically plausible activation functions, provided a spiking-level account of search performance (Mavritsaki et al., 2006, 2011; Mavritsaki & Humphreys, 2016). Simulations of visual search in children and in ADHD provided a unique insight into the role of synaptic strength and temporal binding mechanisms in performance. Ultimately, the design and methodology used has revealed significant new insights into attention in typical development and in ADHD, which have substantial implications for both theory and practice.

5.3.1 Implications for Theory

From a theoretical perspective, approaching attention in development and ADHD using a combination of behavioural and computational modelling methods is highly advantageous in reducing the inconsistencies in research. When both the psychological and physiological levels of behaviour are taken into consideration, a more comprehensive account of human cognition can be achieved (Kriegeskorte & Douglas, 2018). Importantly, there is a grounding in psychological theory: FIT (Treisman & Gelade, 1980), GSM (Wolfe, 1994, 2021), similarity theory (Duncan & Humphreys, 1989) – these provide a solid foundation from which the topic can be approached. From this, theoretical assumptions can then be constrained by biological plausibility, and these constraints could also provide unique insight into mechanisms that aren't considered at the psychological level (Shine et al., 2021; Teufel & Fletcher, 2016).

The present thesis demonstrates that developmental differences in selective visual attention may arise not solely as a function of weaker top-down expectancy, but from reduced synaptic strength in the developing brain. Improvements in synaptic strength is one of a few crucial processes of maturation (Bourgeois et al., 2000), such as myelination (Barnea-Goraly et al., 2005; Lebel & Deoni, 2018; Scantlebury et al., 2014) and synaptic pruning (Gogtay et al., 2004; Petanjek et al., 2011). Together, these maturational processes allow the brain to develop the robust communication within- and between-networks that ultimately gives rise to the complex cognitive control in adulthood (Kolk & Rakic, 2022; Luna et al., 2015; Uhlhaas et al., 2010). These mechanisms work interdependently to achieve such complex cognition (Amso & Scerif, 2015; Parr et al., 2024), and thus, research in this area would benefit from using neuroimaging and computational modelling techniques to parse these processes apart to determine their independent and combined contributions to the formation of high level functioning. This could also provide critical insight into how development may go wrong, such as in disorders like ADHD (Kim & Kastner, 2019; Lynn & Amso, 2023).

Although the symptoms and indeed the name indicate an obvious attention “deficit” in ADHD, it has been difficult to consistently identify a precise attentional difficulty (Callan et al., 2024; Fried et al., 2021; Huang-Pollock et al., 2005; Salomone et al., 2020). Indeed, while there continues to be an abundance of studies that aim to examine attention in ADHD (Guo et al., 2023; Guo et al., 2022; Hokken et al., 2023; Skalski et al., 2021; Wang et al., 2016) the measures used are often inconsistent or insufficient, perhaps contributing to this difficulty (Hokken et al., 2023; Onandia-Hinchado et al., 2021; Wilding, 2005). There continues to be, however, a substantial theoretical interest in determining how attentional functions are affected in ADHD (Amso & Scerif, 2015; Kim & Kastner, 2019; Mueller et al., 2017). When attention is characterised in terms of competitive interactions that occur across the cortical hierarchy, a much more cohesive picture of differences could emerge (Lynn et al., 2020). For example, differences in arousal might affect selection at a more sensory level (e.g., reduced dopamine and/norepinephrine may affect a stimulus’ perceptual saliency; Dönmez et al., 2020), whereas differences in executive function may arise from selection of irrelevant information that is then passed on and acted upon at higher levels (Markant & Amso, 2014; Ortega et al., 2020). Alternatively, selection of representations such as rules might also yield the EF difficulties observed in ADHD. Ultimately, all of these can be understood in terms of biased competition computations that give rise to selection (Lynn & Amso, 2023).

The thesis presented here indeed demonstrates that selective visual attention, particularly in the temporal domain, may be affected by ADHD. Moreover, the results indicate that, while visual marking (a top-down function) is intact in individuals with high levels of ADHD symptoms, temporal binding (a bottom-up function) may be affected in this disorder. There is large body of neuroimaging literature implicating the PFC in ADHD (Almeida et al., 2010; Arnsten, 2009; Rubia et al., 1999; Schulz et al., 2017; Seidman et al., 2006; Zhang et al., 2023, 2024) as well as behavioural literature implicating top-down functioning (Fried et al., 2021; Luna-Rodriguez et al., 2018; Mohamed et al., 2021; Pievsky & McGrath, 2018; Willcutt et al., 2005). However, these results support the idea that ADHD-related differences also affect the more "basic" bottom-up functions, which are oftentimes be overlooked. Some literature has proposed that ADHD-related differences do indeed originate at lower-level functions, and these in turn impair higher-level functions (e.g., CEM; Sergeant et al., 1999, 2003). However, the results here indicate that differences in more low-level functions (like temporal binding) do not necessarily affect higher-level, top-down functions (like visual marking).

Overall, little theoretical work has examined time-based attention functions in ADHD. Neuroimaging methods such as EEG and fMRI are particularly important in providing insight into these functions in ADHD (Cheung et al., 2016; Li et al., 2022; McLoughlin et al., 2022). Furthermore, neurocomputational models of ADHD, particularly ones that consider neurotransmitter differences (such as DA and NE), are equally essential in characterising how these time-based attention differences may arise (Hauser et al., 2016a; Rolls et al., 2021). As such, advancing research in this domain by using a combination of behavioural, neuroimaging, and computational modelling methods would contribute substantially to theoretical evidence, as well as have important implications for practice.

5.3.2 Implications for Practice

The findings of the present thesis illustrate that selective visual attention emerges as a result of multiple mechanisms that interact in a dynamic manner across space and over time (Buschman & Kastner, 2015; Fiebelkorn & Kastner, 2020). It also provides evidence that both the competitive computations that subserve this emergence are implicated in both typical development and in ADHD. Furthermore, it indicates that children with ADHD may experience additional difficulties in selection in addition to those attributed to development. Finally, it illustrates that some attention differences in childhood ADHD may resolve by adulthood, despite a continued experience of ADHD symptoms.

Generally, the study of what and how children attend to information is critical. Indeed, information that is selected by attention often continues on to subsequent stages of processing, including action, learning and memory (Markant et al., 2015; Markant & Amso, 2014). Ultimately, what is attended is the information that is interacted with, and this interaction in turn contributes significantly to the furtherance of the development of the brain and its connections (Astle et al., 2023; Mareschal et al., 2007; Westermann et al., 2007). Accordingly, the quality and quantity of the information interacted with represents an important aspect to consider in the field of attention research. One prominent example of this is the increasing exposure children and adolescents have to different types of media during screen-time. While some screen content can be beneficial to children's development (Linebarger & Walker, 2005), it has also been shown that, in the wrong context, screen time can impair attention and other executive functions (McHarg et al., 2020). Furthermore, unsupervised/excessive access to social media platforms in childhood and adolescence has been linked mental health problems such as depression and anxiety (McCrae et al., 2017; Riehm et al., 2019). Ultimately, further research in this domain could reveal the ways in which they are able to experience and interact with the surrounding environment, and how this contributes to their abilities and trajectory of development (Amso & Scerif, 2015; Lynn & Amso, 2023).

In ADHD, where selective attention is affected, individuals are at a higher risk for adverse outcomes (Fleming et al., 2017; Harpin et al., 2016; Klein et al., 2012). Indeed, in ADHD, there are differences in the PFC, which is likely to contribute to reduced control over behaviour and increased susceptibility to risky behaviours (Arnsten, 2006; Blankenstein et al., 2024; Brennan & Arnsten, 2008; Dekkers et al., 2016). Accordingly, the quantity and quality of information these individuals interact with is even more essential. Recent literature has shown that there is a reciprocal relationship between ADHD symptoms and problematic digital media use (Thorell et al., 2024). Indeed, children with ADHD are more likely to develop internet and/or gaming addictions (Ferguson & Ceranoglu, 2014; Wartberg et al., 2019, 2020). Additionally, these digital media addictions predict higher levels of ADHD symptoms in the future (Boer et al., 2020; Hygen et al., 2020; Wartberg et al., 2019). Further research in this domain could explore the complex relationship between the distinct ways in which diagnosed individuals experience and interact with the surrounding environment and how this contributes to symptoms and impairments, and vice versa (Amso & Scerif, 2015; Kim & Kastner, 2019). Indeed, the prioritisation of salient information is important in countless everyday activities, such as driving and commuting (Peelen & Kastner, 2014; Wolfe, 2020). Accordingly, research in this domain could ultimately translate into the development of technology aimed at accommodating these impairments.

In an educational context, understanding how selective visual attention differs in ADHD could allow for educators and aides to develop new methods to introduce and pace material to ensure equal learning opportunities for affected individuals (Alkahtani, 2024; Cerezo et al., 2024). Related research could also potentially develop computerised cognitive training programmes aimed to develop increased control over behaviour (Westwood et al., 2023). Indeed, a recent meta-analysis of computerised programme interventions found that both specialised and general training of executive functioning resulted in a reduction of ADHD symptoms (Wu et al., 2023). This may be particularly effective for borderline cases where medication may not be necessary or may lead to greater improvements in addition to medication.

Finally, the results of the present thesis characterise the selective visual attention differences in ADHD that may be useful in potentially distinguishing it from other neurodevelopmental disorders like autism, dyslexia and schizophrenia. These, as well as other, neurodevelopmental disorders often overlap in their symptoms, profile of cognitive abilities, and neurobiological mechanisms (Duan et al., 2024; Lau-Zhu et al., 2019; Park et al., 2018; Riglin et al., 2022; Vidyasagar, 1999). Accordingly, it is important to consider how other neurodevelopmental disorders may or may not differ in their visual search performance.

For example, while children and adults with ADHD often perform worse in visual search tasks than their non-ADHD peers (Guo et al., 2023; Karatekin & Asarnow, 1998; Mason et al., 2003; Skalski et al., 2021; Tsal et al., 2005; Wang et al., 2016, 2017), children and adults with autism have consistently shown enhanced visual search abilities, particularly under difficult search conditions (Keehn & Joseph, 2016; O'Riordan et al., 2001; O'Riordan, 2004; Shirama et al., 2017). Children with dyslexia perform similar to children with ADHD in visual search tasks; they are often slower and less accurate (Huang & Wang, 2009; Liu et al., 2019; Wang & Yang, 2020). However, accuracy in children with dyslexia is worse specifically when linguistic stimuli is used (Hokken et al., 2023). Individuals with schizophrenia also demonstrate slower and less accurate search, particularly in the more difficult conjunction search (Gold et al., 2007; Mori et al., 1996; Tanaka et al., 2007). However, differences have also been evidenced in single-feature search (Karatekin & Asarnow, 1998). A recent study by Canu et al. (2022) compared individuals with ADHD, with schizophrenia, with autism spectrum disorder, and typically developing controls on a difficult visual search task. Compared to TD controls, those with schizophrenia demonstrated the most severe impairments in search, followed by individuals with ADHD, while those with autism had enhanced search performance. The authors suggested that these results demonstrate a continuum of impairment in these neurodevelopmental disorders (Canu et al., 2022).

At present, preview and preview gap search have not yet been examined in any other neurodevelopmental disorder other than ADHD. Future research could use these search tasks to investigate visual marking and temporal binding in other disorders, possibly highlighting unique characteristics that may be able to distinguish one disorder from another.

5.4 Limitations and Future Directions

Previous research has established that ADHD affects selective attention – that is, the ability to selectively process relevant information while ignoring irrelevant, potentially distracting information (Hokken et al., 2023; Mullane & Klein, 2008; Onandia-Hinchado et al., 2021). The present thesis contributes additional knowledge to this research domain within the context of time-based selective visual attention. Indeed, in children with ADHD, the ability to effectively allocate attention to a particular moment in time so that information is bound by their common onset is affected. Temporal binding relies on fast and efficient communication between distinct areas in the brain that are encoding to-be-bound information (Singer, 2015, 2021; Singer & Gray, 1995). Previous research has demonstrated differences in connectivity between areas within the brain and, more specifically, within the attention network (Hoogman et al., 2019; Silk et al., 2016; Thomson et al., 2022). Furthermore, reductions in important catecholamines DA and NE are likely to affect the efficiency of neural signals (Arnsten & Pliszka, 2011; Berridge & Arnsten, 2015). Bellgrove et al. (2006) proposed that genetic variations in a catecholamine-related gene, DBH, results in selective attention differences in both spatial and temporal domains. Hence, ADHD-related impairments affect the dynamic manner in which top-down and bottom-up mechanisms contribute to selective attention. This is also demonstrated in the research presented here. However, some limitations must be considered and examined in future research.

5.4.1 Limitations

One limitation of the present thesis arises from the use of subjective self-report questionnaires like the Conners 3AI, ASRS, and BIS-B to establish groups comprised of individuals with low or high (or borderline) levels of ADHD symptoms. Indeed, research has shown that the ability of these self-report screener methods to accurately identify symptoms that are positively attributed to ADHD is less than ideal. For example, while the ASRS originally had a positive predictive value (PPV) of 88% (at 5% prevalence; Harrison & Edwards, 2023; Kessler et al., 2005), subsequent work shows this PPV is much lower, at values of between 6-12% (Chamberlain et al., 2021; Dunlop et al., 2018; Pettersson et al., 2018; van de Glind et al., 2013). These results indicate that using the ASRS in particular may not be able to accurately identify symptoms as positively belonging to ADHD, rather than other, similar mental disorders like depression or anxiety.

Ultimately, it is inherently difficult to distinguish ADHD symptoms from those of other common disorders that can mimic these symptoms and impairments. In childhood, it is easier to rule out differential diagnoses (e.g., oppositional defiant disorder, conduct disorder, mood disorders, etc.; Sibley et al., 2018). However, in adulthood, it becomes increasingly difficult to tease apart ADHD from other disorders (Asherson et al., 2016). While motor hyperactivity tends to decline with age in ADHD (Biederman et al., 2000; Larsson et al., 2011), this hyperactivity appears to shift to feelings of restlessness and unfocused mental activity, similar to that typically also observed in anxiety and bipolar disorder (Grogan et al., 2018; Koyuncu et al., 2022). The problems with emotional regulation and sleep in ADHD also present in depression (Joormann & Stanton, 2016; Steiger & Pawlowski, 2019). In recent years, the COVID-19 pandemic has caused increased stress, anxiety and depression (Ferwana & Varshney, 2024; González-Alonso et al., 2024; Ramos-Vera et al., 2024) and this decline in mental health has led to ADHD-like difficulty in concentration and in academic performance (Giusti et al., 2021; Jaywant et al., 2024). As the pandemic occurred during the course of this thesis, the effects of COVID-19 may have potentially impacted how adults rated their ADHD-like behaviours in the online study, compared to how they would have rated these behaviours prior to the pandemic.

A second limitation here arises from the impact of the COVID-19 pandemic. Indeed, the government-mandated lock-downs disrupted data collection for the first behavioural study presented in chapter 4 (see section 4.1). As a result of this disruption, it was not possible to ensure each of the three groups had an identical number of participants. Indeed, for this study, there are only 17 participants in low ASRS group, while the borderline and high ASRS groups had nearly twice this amount (30 in borderline and 27 in high). Unequal samples affects the assumption of equal variances, which is a key assumption in ANOVA tests, and this can have a detrimental effect on statistical power (Rusticus & Lovato, 2014). Accordingly, the results for this study should be interpreted with caution.

In response to the COVID-19 lockdowns, the visual search tasks were implemented through an entirely online platform. Since the main variable of interest here was mean RTs, every effort was made to ensure that RTs during the experiment were valid. This included requiring the visual search portion of the experiment to be completed over MS Teams, so as to ensure that participants were sitting at a table in a quiet room, with minimal distractions, and that they were engaged in the task from start to finish. Recent research has demonstrated that this method of online data collection is indeed reliable (Leong et al., 2022). However, there are still imitations as to how well controlled this method can be. Outside distractions, such as others unexpectedly entering the testing area or making excessive noise sometimes occurred. Furthermore, the lack of control over the participant's device setting also posed difficulties. For example, alerts from other programs running in the background could pop-up in front of the search task, occluding the display. As the effects of interest in the present thesis, namely the preview benefit and the loss of the benefit in the preview gap condition, rely on an observers engagement in displays that last less than one second (e.g., 750 msec preview display; 250 msec gap display), minor distractions that occurred as a result of this less controlled online implementation should be considered a limitation here.

Another limitation of the present thesis arises from the complex nature of the data analysis. In chapter 2, the unequal variances in the data are reported (see section 2.1.2). Although several transformations were applied to the data in an effort to rectify this issue, this effort was not successful. For this reason, the data was analysed without any transformation, and this ultimately means that there is a higher chance for Type I (false positive) errors here. One possible option is to apply the bootstrap procedure (Efron & Tibshirani, 1994). The bootstrap procedure involves repeatedly resampling data (with replacement) from the original sample to estimate the distribution of the data. This allows for the estimation of standard error and confidence intervals of a statistic without knowing the shape of the sampling distribution. However, bootstrapping has its limitations does not always produce valid or consistent results (Mooney & Duval, 1993; Young, 1994). Specifically, in cases where the distribution is skewed (like in the present thesis, see section 2.1.2), resampled estimates can become distorted (Mooney & Duval, 1993, p. 54). As such, this procedure was not used here.

Traditionally, visual search data consists of two dependent variables: mean RT and accuracy (Treisman & Gelade, 1980; Wolfe, 2015, 2020). A large body of previous literature, including the fundamental studies that serve as the basis for the research in the present thesis (Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Watson & Humphreys, 1997; Wolfe, 1994), analyse these two variables separately. Accordingly, the data analysis here also uses different ANOVAs for mean RT and accuracy. This presents a limitation in that the relationship between mean RT and accuracy remains unanalysed. A multivariate analysis of variance (MANOVA) that includes both mean RT and accuracy could be used to explore this relationship and simplify the design. Here, although a MANOVA was not used, the efficiency index used in chapters 2 and 3 (see sections 2.1.3 and 3.1.3) serves as a dependent variable that considers this relationship. Furthermore, it is worth noting that, unlike some more difficult experimental tasks, visual search accuracy rates are typically quite high, even in those with attention difficulties (Luo et al., 2021; Mason et al., 2003, 2004; Wang et al., 2016). For example, in the present thesis, the minimum accuracy was above 90% for all studies. As such, accuracy does not necessarily provide much insight into performance compared to mean RT.

5.4.2 Generalisability of Findings

Historically, ADHD has been characterised as a categorical disorder with nonarbitrary boundaries (Sonuga-Barke et al., 2023). Under this characterisation, individuals with ADHD can be clearly distinguished from non-ADHD individuals. This assumption, however, is not supported by the evidence, which instead supports a dimensional disorder, such that diagnosed cases of ADHD represent an extreme expression of a continuous trait present in the general population (Asherson & Trzaskowski, 2015; Hirata et al., 2023; Martin et al., 2014; Sibley et al., 2022; Stergiakouli et al., 2015). As such, the use of clinically diagnosed individuals to comprise ADHD in research may be limited in its generalisability to the disorder as a whole, as the dimensional nature of the disorder is lost. The logical response to this limitation is to attempt to capture this dimensionality by using self-report scales to identify undiagnosed and subthreshold cases to compare against non-cases. However, the poor PPV of these measures means that these groups are likely to fall short in their ability to truly represent the disorder (Harrison & Edwards, 2023; Lovett & Harrison, 2021). This represents a key limitation in ADHD research. Using a sample of individuals who have undergone clinical evaluation and been confirmed to meet the DSM-V requirements for an ADHD diagnosis means they are positively identified. However, it also means that the sample only represents extreme cases, and are most likely to undergo treatment, which has been shown to correct structural differences during and after use (Frodl & Skokauskas, 2012; Fu et al., 2022; Kowalczyk et al., 2019, 2023; Mizuno et al., 2022; Rubia et al., 2014). While using subject self-report scales to identify an ADHD group might circumvent these limitations, there is perhaps an even larger limitation in that, although individuals may have scored high for level of ADHD symptoms on the self-report scales, there is a low chance that the individual truly has the disorder.

Adult ADHD is associated with a number of adverse outcomes that affect the trajectory and quality of life (Gjervan et al., 2012; Groenman et al., 2017; Mannuzza et al., 2008). One adverse outcome that is particularly relevant to the present thesis is the level of educational attainment in adults with ADHD. Indeed, of the adult ADHD population, only a small percentage continues on to higher education. Accordingly, it is important that future research aims to move outside of university-based samples in adult ADHD research.

To summarise, it is essential that ADHD research is comprised of groups that are both confirmed to have a true diagnosis and reflect the dimensionality of the disorder by including participants with varying degrees of ADHD-traits. Furthermore, it is similarly important that adult ADHD research recruits participants from different levels of educational attainment – that is, adults with ADHD who are not involved in higher education. Addressing these issues would significantly increase the generalisability of findings, including the ones presented here. Clearly, the latter of these suggestions is much easier to accomplish than the former. The crux of the issue in the former is the ability to confirm a diagnosis with some objective measure that can be administered as easily as a self-report scale. This problem, as discussed in the next section, could be eventually alleviated through the combined use of simple visual search tasks and neurocomputational modelling.

5.4.3 Future Directions

In the present thesis, it was shown that synaptic strength underlies the overall slower, less accurate performance in children. Furthermore, this mechanism also account for the differences in conjunction search, which are typically attributed to top-down control (see chapter 2). This highlights the importance of considering how differences at the neural level might give rise to large behavioural differences typically attributed to complex psychological concepts like "top-down attention." Future research would certainly benefit from taking these neural interactions into account.

One example of this is considering how differences in the structure and connectivity of the visual hierarchy might contribute to the strength of competitive interactions. The basic architecture of the visual cortex develops within the first postnatal year, and this is reflected in improvements in the ability to detect basic visual features like orientation, colour, and motion (Atkinson & Braddick, 2020; Braddick & Atkinson, 2011; Braddick et al., 1986). Thus, it is likely that sensory competition also follows this early developmental trajectory (Kim & Kastner, 2019). Indeed, recently it has been confirmed that competitive interactions are present in the human visual cortex by 8 years of age (Kim et al., 2021). However, Kim et al. (2021) also found a lesser degree of suppression effects in the children's middle temporal (MT) visual area, which was attributed to the ongoing development of receptive field (RF) architecture in this area, as the RF of area MT of children is smaller than adults (Gomez et al., 2019; Kim et al., 2021). MT is an important area within the dorsal "where" pathway and has been implicated in motion processing (Born & Bradley, 2005). As such, it stands to reason that, if children’s smaller area MT renders them less sensitive to certain visual features like motion, there is less competition, and thus, less of a reason to allocate attentional resources (Lynn & Amso, 2023). Furthermore, the authors noted that surround suppression in areas V1 and V2 was greater for children compared to adults. These variances in children’s strength of suppression ultimately indicate that the process through which sensory competition is resolved in children may, at times, differ from adults, and this may yield differences in behavioural performance (Kim & Kastner, 2019).

The integrity of the visual cortex and its ability to process sensory information is critical to integrity of top-down feedback loops (Gilbert & Li, 2013; Harris & Mrsic-Flogel, 2013; Lamme et al., 1998). As attention, which relies on these feedback loops, further contributes to our perception of the environment around us, issues in the architecture of the visual system could ultimately yield differences in how attention networks develop (Amso & Scerif, 2015; Lynn & Amso, 2023). For example, area MT processes visual motion and is an important site in visual attention due to its reciprocal connections with higher-order regions such as the PFC, FEF and PAC (Born & Bradley, 2005). Motion processing has a long developmental trajectory (Gomez et al., 2019; Wattam-Bell et al., 2010; Zupan et al., 2023), and differences in global motion processing occur in a neurodevelopmental disorders, including autism (Annaz et al., 2010; Silva et al., 2024) and childhood onset schizophrenia (Kéri & Kelemen, 2024). Thus, it has been hypothesized that disorganisation in area MT/the dorsal stream might be a mechanism that substantially contributes to the higher-order difficulties in neurodevelopmental disorders (Braddick et al., 2003). Accordingly, future research should take into consideration the cortical hierarchy as a whole when aiming to understand the functions of attention, how they develop, and how these developmental processes may go wrong in neurodevelopmental disorders.

The present thesis also showed that children with ADHD may present differences in temporal binding (see chapter 3). Simulations using b-sSoTS demonstrated that, at the neural level, reductions in temporal binding for these individuals ultimately led to changes in the way items compete for selection. Again, this provides an example of how seemingly subtle changes in an often-overlooked mechanism can have major effects at the behavioural level. Furthermore, under the preview gap conditions, this reduced temporal binding yields *better* performance compared to those with intact temporal binding. While it might be tempting to associate better performance with increased neural efficiency, computational modelling work provided unique insight into the dynamic activity occurring at the neural level which gave rise to these effects.

Importantly, as the results demonstrate differences in neural competition arising from weakened temporal binding, there is a clearer picture of differences in selective visual attention in ADHD. The concept of attention is often ill-defined in the psychological literature (Anderson, 2011; Hommel et al., 2019; Shomstein et al., 2023) and terminologies often vary from field to field (Narhi-Martinez et al., 2023; Nigg, 2017; Rueda et al., 2023). In the field of ADHD research specifically, studying selective attention has been abandoned far too quickly, perhaps due to confusion over terminology (i.e., selective attention vs. arousal/alertness or executive function; see section 1.2). Furthermore, measures often used in ADHD research to assess selective attention, such as visual cancellation tasks (Ben-Artsy et al., 1996; Jones et al., 2008; Kiliç et al., 2007; Landau et al., 1999), TEA-Ch tasks (Lajoie et al., 2005; Malegiannaki et al., 2019; Manly et al., 2001; Rezazadeh et al., 2011; Salomone et al., 2020) are likely to tap into executive functions like response inhibition, set-shifting/flexibility and maintenance of contextual information (Wilding, 2005). These issues are likely to contribute to the inconsistencies in ADHD research, particularly in the ability to identify selective attention differences. However, this area is rich with potential, and could possibly link lower-level sensory differences in ADHD with higher-level differences in executive function (Amso & Scerif, 2015; Lynn & Amso, 2023).

For example, future work investigating selection in ADHD could take into account the well-documented sensory issues in ADHD (Bijlenga et al., 2017; Cheung & Siu, 2009; Dellapiazza et al., 2021; Panagiotidi et al., 2018). In the visual domain, for example, both children and adults exhibit poorer colour discrimination (Banaschewski et al., 2006; Kim, Al-Haj, et al., 2014; Kim, Chen, et al., 2014; Roessner et al., 2008). While adults with ADHD show difficulties particularly along the blue-yellow axis (Kim, Chen, et al., 2014), children with ADHD have difficulties with colour discrimination both along the blue-yellow axis as well as the red-green axis (Banaschewski et al., 2006; Roessner et al., 2008). Children with ADHD also demonstrate reduced contrast sensitivity (Bartgis et al., 2009; Dönmez et al., 2020; Ulucan Atas et al., 2020), although this has not been reported in adult ADHD. Interestingly, Dönmez et al. (2020) also found that contrast sensitivity improved in children with ADHD when they took methylphenidate, a common psychostimulant pharmaceutical treatment for ADHD. The authors speculated that this improvement may arise from methylphenidate-induced increase of dopaminergic neurotransmission in both central and retinal neurons (Dönmez et al., 2020; Tannock et al., 2006). If this is indeed the case, this would be particularly interesting, as it could implicate ADHD-related dopaminergic dysfunction, which is typically associated with differences in higher-level processes like motivation and/or working memory (Berridge & Arnsten, 2015; Cools & Arnsten, 2022), with lower-level processes of visual perception. Ultimately, whatever the source of these differences in visual function may be, they are important to consider, particularly in their contribution to competitive interactions. After all, neural resources only need to be allocated when there is sufficient competition to resolve (Lynn & Amso, 2023).

5.4.4 Visual Search

Visual search is a popular method in the study of perception and attentional mechanisms in psychology, neuropsychology and neuroscience (Eckstein, 2011; Kristjánsson & Egeth, 2020; Nakayama & Martini, 2011). Despite its popularity and the wealth of knowledge regarding the different attentional mechanisms at work in visual search, it's a sorely underutilized method in ADHD research (Hokken et al., 2023; Mullane & Klein, 2008). Earlier work showed no significant differences between typically developing children and children with ADHD in either single-feature or conjunction search (Hazell et al., 1999), perhaps dissuading researchers from replication. However, an absence of difficulty in these search conditions is far from confirmation of intact selective visual attention. There exists a wide range of relatively simple variations to stimuli – density, contrast, configuration, homogeneity – that can be used to probe subtler, more complex aspects of attention (Nakayama & Martini, 2011; Wolfe, 2020, 2021). Different task conditions have also been thoroughly studied and can be used to examine different attentional mechanisms, such as contingent capture in search with singleton targets and distractors (Folk et al., 1992; Theeuwes et al., 2010; Wolfe, 2021), or the attentional blink using rapid serial visual presentation tasks (Raymond et al., 1992; Yao & Zhou, 2023). The wide range of variations makes it possible to study these mechanisms in a systematic way that's both reliable and easily replicated. When used in this way, visual search has the potential to provide a more thorough picture of what mechanisms are and are not affected in ADHD.

5.4.5 Neurocomputational Models

While behavioural methods like visual search can provide crucial insight into what differences exist between ADHD and non-ADHD individuals, the ultimate aim is to develop a fuller understanding of *how* these differences arise. When measures of performance such as RT and accuracy are analysed, we are faced with a black-box problem. There is a task that needs to be completed (e.g., find the blue letter H) and there is data to characterise the result (e.g., it was found in 500 msec); however, how this problem was solved remains unseen. In order to understand how cognition is achieved, we need to use biologically plausible computational models that are capable of performing the task in question (Ashby & Helie, 2011; Kriegeskorte & Douglas, 2018; Mareschal et al., 2007). When models like b-sSoTS are used, we are able to test theoretical assumptions, analyse their biological plausibility, and generate new hypotheses (Astle et al., 2023; Mavritsaki et al., 2011). Due to this ability to bridge behaviour and biology, neurocomputational modelling will be particularly essential in furthering our understanding of ADHD, as well as other mental disorders, where closing this gap is key (Hauser et al., 2016a; Montague et al., 2012).

Neurocomputational models like b-sSoTS have wide applications due to the ability to change its architecture or synaptic characteristics in order to simulate different types of tasks and/or different populations (e.g., lesion patients, ADHD, Alzheimer's, etc.; Khaleghi et al., 2022; Mavritsaki et al., 2011; Teufel & Fletcher, 2016). Furthermore, these models are capable of simulating different types of neural data, such as BOLD activation in fMRI studies and oscillatory activity and ERPs in EEG studies (De Hollander et al., 2016; Glomb et al., 2022; Glover, 1999). Thus, future research could work toward better understanding of the neural mechanisms in ADHD by altering the synaptic characteristics to simulate proposed differences in dopamine (DA) and norepinephrine (NE) neurotransmission. Indeed, there are very few neurocomputational models of ADHD. This could potentially provide insight into how reduced SNR in ADHD affects selective attention over time (Hauser et al., 2016a).

Using b-sSoTS to simulate neuroimaging data may also yield a greater understanding of the covert neural differences between ADHD and non-ADHD individuals in time-based attention. For example, Mavritsaki et al. (2008, 2010) demonstrated that the model can be used to determine where different mechanisms (e.g., active suppression, target expectancy) occur in the brain by simulating fMRI data. In future work, examining preview and preview gap search with fMRI and simulating this data with the computational model could yield significant insight into not only whether children have reduced activation, but also which function is affected. Additionally, using the computational model to simulate EEG data in preview and preview gap in ADHD may reveal information about the role of certain neurotransmitters. For example, Berggren and Eimer (2018) showed that the P_D component is elicited by preview displays, while the N2pc is elicited by the target item. Comparisons of these ERPs between ADHD and non-ADHD individuals would, again, reveal the presence of neural differences, while computational modelling of any differences might reveal how neurotransmitters contribute to these differences.

5.5 Conclusion

The present thesis used a combination of behavioural and modelling techniques to investigate both age- and ADHD-related differences in selective visual attention. Classic visual search tasks, single-feature, conjunction, preview and preview gap were used to characterise bottom-up and top-down attention across both time and space (Treisman & Gelade, 1980; Watson & Humphreys, 1997). The dynamic contributions of the mechanisms underlying search performance differences were then explored using b-sSoTS, a neurocomputational model that employs biologically plausible activation functions (Mavritsaki et al., 2006; Mavritsaki & Humphreys, 2016). Collectively, the present thesis has provided evidence of how the ability to allocate attention to a particular location in space and moment in time differs in typical development, and how these age-related differences may be compounded by additional difficulties of ADHD. Notably, simulations using the b-sSoTS model revealed age-related differences in speed, accuracy and efficiency in top-down control can be attributed to reduced synaptic strength. Furthermore, it was suggested that ADHD-differences in time-based attention could arise from reduced synaptic strength and weak or absent temporal binding. Ultimately, these results highlight the role of encoding and binding stimuli in the ability to efficiently attend to relevant information and ignore irrelevant information (Gilbert & Li, 2013; Harris & Mrsic-Flogel, 2013; Singer, 2021). Therefore, the present thesis has provided a substantial foundation of knowledge that considers both the behavioural and neural levels of selective attention to account for differences attributable to both typical development and atypical development in ADHD. Here, the use of classic visual search tasks and a neurocomputational model capable of performing these tasks has contributed novel evidence to the literature on development and the literature on ADHD.

Several limitations of the present research must be acknowledged. First, ADHD has been characterised as a categorical disorder with nonarbitrary boundaries (Sonuga-Barke et al., 2023), and this has been recognised in research through the use of groups that comprise of individuals with a clinical diagnosis of ADHD. However, research supports the notion that ADHD is a dimensional disorder with no clear boundary to separate cases from non-cases (Asherson & Trzaskowski, 2015; Hirata et al., 2023; Martin et al., 2014; Sibley et al., 2022; Stergiakouli et al., 2015). Thus, while the use of non-diagnosed individuals who demonstrate high levels of ADHD traits (through self-report measures) here aims to maintain the dimensionality of the disorder, it may also then fail to capture the magnitude of differences in the disorder, which may be more prominent in clinically diagnosed individuals. Furthermore, the use of self-report measures like the ASRS screener are used in clinical diagnosis and initially demonstrated high specificity and sensitivity (Kessler et al., 2007). However, recent research has called this into question with evidence of very low PPV, indicating a high percentage of individuals who score "likely to have ADHD" by these screeners actually do not have the disorder. As such, the use of more valid measures to identify ADHD individuals is needed (Chamberlain et al., 2021; Harrison & Edwards, 2023; Lovett & Harrison, 2021). Finally, while parameter changes highlight the biological plausibility of a hypothesis generated at the behavioural level, this can fall short in its ability to provide a full account of the mechanisms underlying performance differences in varying groups. Future work might uncover more by first implementing changes to the model that reflect age- or ADHD-related differences in the brain and then using this version of the model to perform the visual search task.

Taken together, the ability to connect high-level psychological concepts like selective attention with its low-level physiological neural mechanisms is a promising avenue for research in both typical development and atypical development like ADHD (Hauser et al., 2016a; Kriegeskorte & Douglas, 2018; Lynn & Amso, 2023). Future research should harness the synergistic relationship between behavioural and modelling methods, using alternative search task conditions to identify more prominent ADHD-related differences in attention that remain in adulthood. From a theoretical perspective, by maintaining a foundation in classical psychological theories (e.g., FIT, GSM) and using neurocomputational modelling, the present thesis was able to highlight how more low-level functions involved in encoding and binding of stimuli can contribute to high-level performance differences (Buschman & Kastner, 2015; Harris & Mrsic-Flogel, 2013; Hauser et al., 2016a). At a practical level, the outcomes presented in this thesis revealed how, despite differences in the encoding and binding of stimuli, children with and without ADHD are able to tap into top-down control to overcome these shortcomings, and effectively allocate attention to a particular moment in time (Hokken et al., 2023; Li et al., 2023; Mason et al., 2003, 2004; Ortega et al., 2020; Zupan et al., 2018). The focus on selective attention in the present thesis is indeed reflects the reality that we are exposed to an endless amount of information continuously, and what is attended to (and what is ignored) directs our behaviours and decisions (Peelen & Kastner, 2014; Tsotsos, 1990). Accordingly, the findings of the present thesis and future research could be used to develop a deeper understanding of how attention develops into the fully functional adult state, and how this may go awry in cases of neurodevelopmental disorders.

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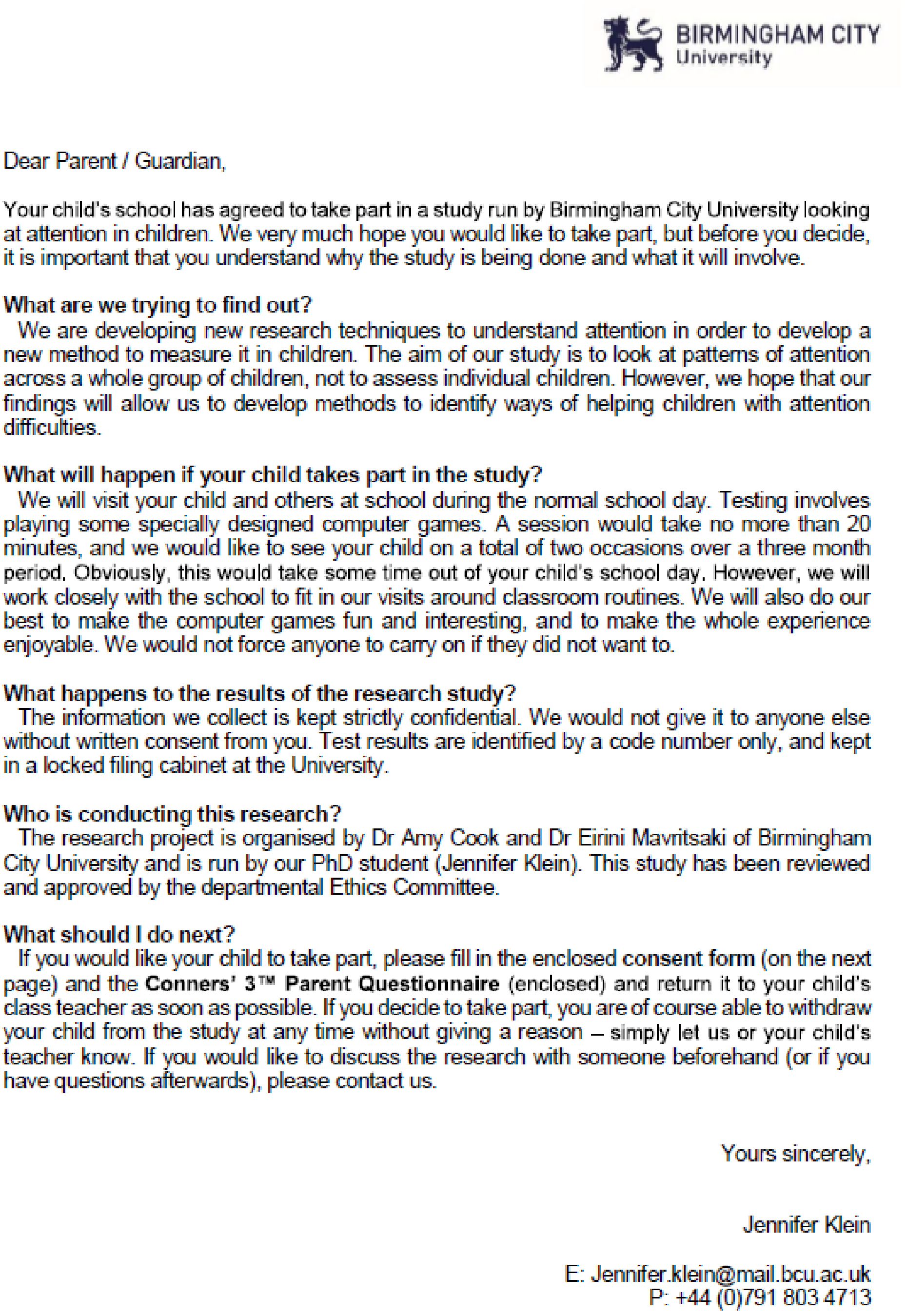
Appendices

Appendix A

Participant Information Sheets

Appendix Figure A.1

Participant Information Sheet for Child ADHD Study



BIRMINGHAM CITY
University

Dear Parent / Guardian,

Your child's school has agreed to take part in a study run by Birmingham City University looking at attention in children. We very much hope you would like to take part, but before you decide, it is important that you understand why the study is being done and what it will involve.

What are we trying to find out?
We are developing new research techniques to understand attention in order to develop a new method to measure it in children. The aim of our study is to look at patterns of attention across a whole group of children, not to assess individual children. However, we hope that our findings will allow us to develop methods to identify ways of helping children with attention difficulties.

What will happen if your child takes part in the study?
We will visit your child and others at school during the normal school day. Testing involves playing some specially designed computer games. A session would take no more than 20 minutes, and we would like to see your child on a total of two occasions over a three month period. Obviously, this would take some time out of your child's school day. However, we will work closely with the school to fit in our visits around classroom routines. We will also do our best to make the computer games fun and interesting, and to make the whole experience enjoyable. We would not force anyone to carry on if they did not want to.

What happens to the results of the research study?
The information we collect is kept strictly confidential. We would not give it to anyone else without written consent from you. Test results are identified by a code number only, and kept in a locked filing cabinet at the University.

Who is conducting this research?
The research project is organised by Dr Amy Cook and Dr Eirini Mavritsaki of Birmingham City University and is run by our PhD student (Jennifer Klein). This study has been reviewed and approved by the departmental Ethics Committee.

What should I do next?
If you would like your child to take part, please fill in the enclosed **consent form** (on the next page) and the **Conners' 3™ Parent Questionnaire** (enclosed) and return it to your child's class teacher as soon as possible. If you decide to take part, you are of course able to withdraw your child from the study at any time without giving a reason – simply let us or your child's teacher know. If you would like to discuss the research with someone beforehand (or if you have questions afterwards), please contact us.

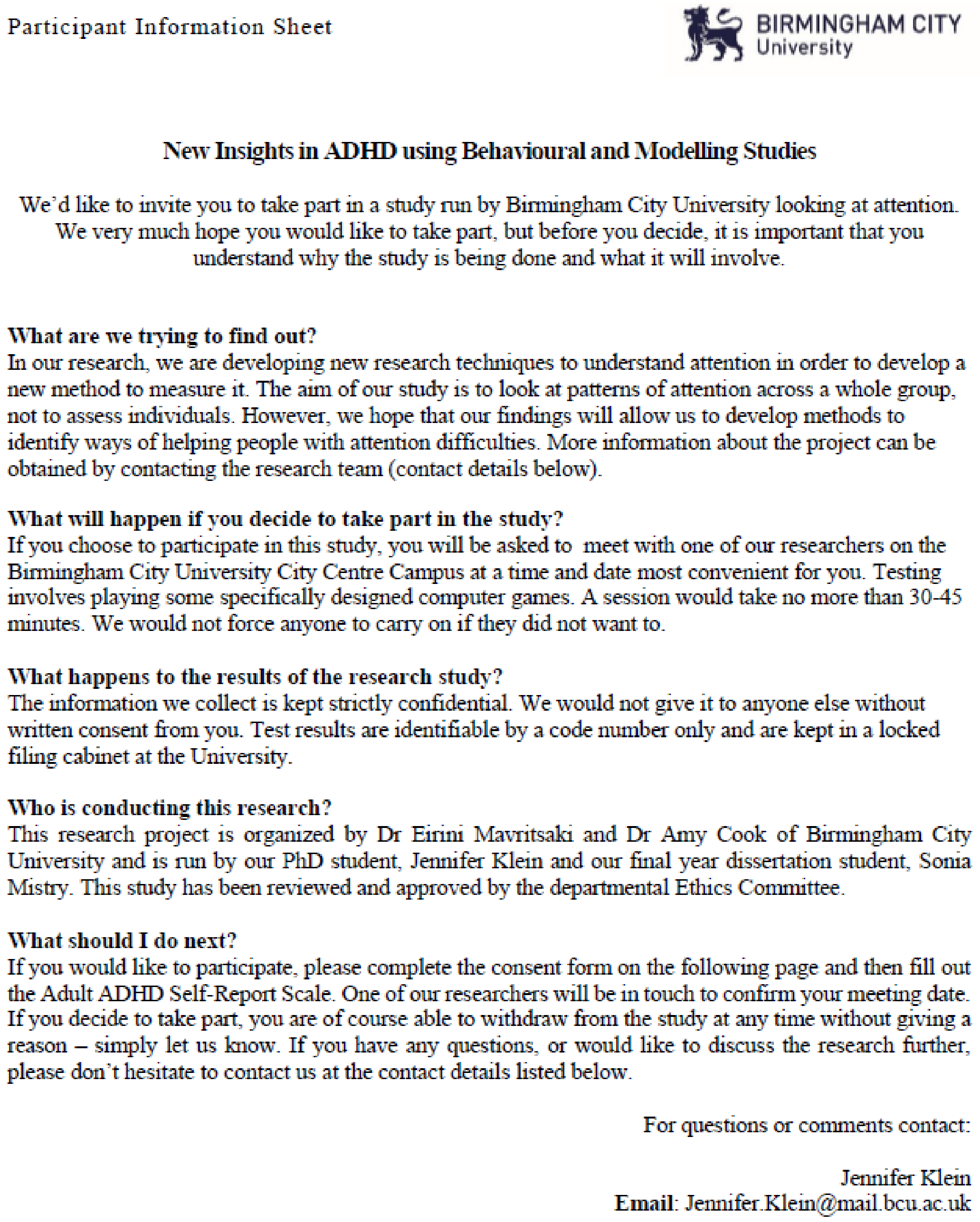
Yours sincerely,

Jennifer Klein

E: Jennifer.klein@mail.bcu.ac.uk
P: +44 (0)791 803 4713

Appendix Figure A.2

Participant Information Sheet for Adult ADHD Study



Participant Information Sheet

BIRMINGHAM CITY
University

New Insights in ADHD using Behavioural and Modelling Studies

We'd like to invite you to take part in a study run by Birmingham City University looking at attention. We very much hope you would like to take part, but before you decide, it is important that you understand why the study is being done and what it will involve.

What are we trying to find out?

In our research, we are developing new research techniques to understand attention in order to develop a new method to measure it. The aim of our study is to look at patterns of attention across a whole group, not to assess individuals. However, we hope that our findings will allow us to develop methods to identify ways of helping people with attention difficulties. More information about the project can be obtained by contacting the research team (contact details below).

What will happen if you decide to take part in the study?

If you choose to participate in this study, you will be asked to meet with one of our researchers on the Birmingham City University City Centre Campus at a time and date most convenient for you. Testing involves playing some specifically designed computer games. A session would take no more than 30-45 minutes. We would not force anyone to carry on if they did not want to.

What happens to the results of the research study?

The information we collect is kept strictly confidential. We would not give it to anyone else without written consent from you. Test results are identifiable by a code number only and are kept in a locked filing cabinet at the University.

Who is conducting this research?

This research project is organized by Dr Eirini Mavritsaki and Dr Amy Cook of Birmingham City University and is run by our PhD student, Jennifer Klein and our final year dissertation student, Sonia Mistry. This study has been reviewed and approved by the departmental Ethics Committee.

What should I do next?

If you would like to participate, please complete the consent form on the following page and then fill out the Adult ADHD Self-Report Scale. One of our researchers will be in touch to confirm your meeting date. If you decide to take part, you are of course able to withdraw from the study at any time without giving a reason – simply let us know. If you have any questions, or would like to discuss the research further, please don't hesitate to contact us at the contact details listed below.

For questions or comments contact:

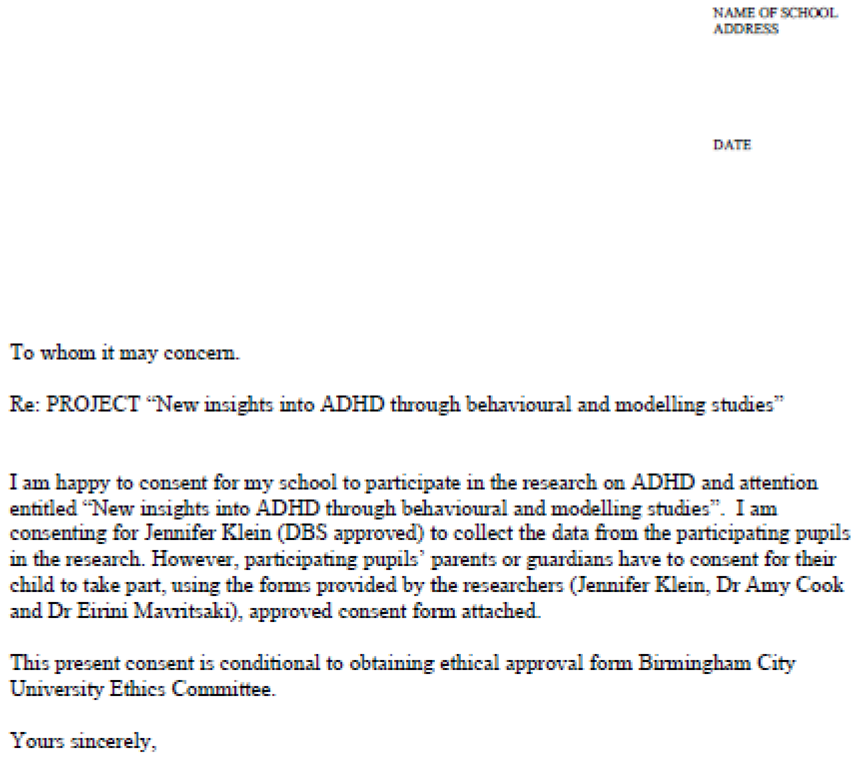
Jennifer Klein
Email: Jennifer.Klein@mail.bcu.ac.uk

Appendix B

Consent Forms

Appendix Figure B.1

Headteacher Consent Form



NAME OF SCHOOL
ADDRESS

DATE

To whom it may concern.

Re: PROJECT "New insights into ADHD through behavioural and modelling studies"

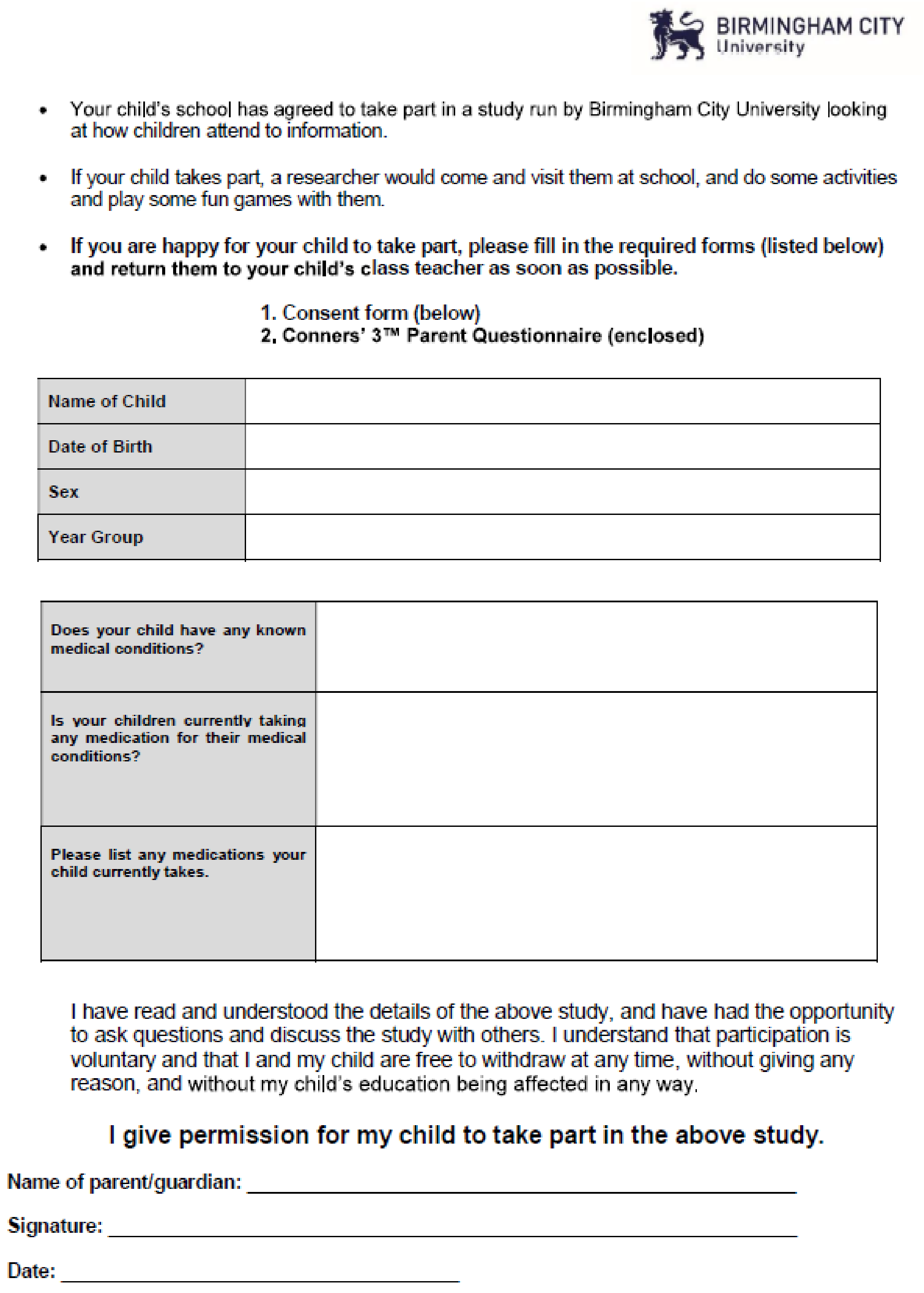
I am happy to consent for my school to participate in the research on ADHD and attention entitled "New insights into ADHD through behavioural and modelling studies". I am consenting for Jennifer Klein (DBS approved) to collect the data from the participating pupils in the research. However, participating pupils' parents or guardians have to consent for their child to take part, using the forms provided by the researchers (Jennifer Klein, Dr Amy Cook and Dr Eirini Mavritsaki), approved consent form attached.

This present consent is conditional to obtaining ethical approval form Birmingham City University Ethics Committee.

Yours sincerely,

Appendix Figure B.2

Parent/Guardian Consent Form



BIRMINGHAM CITY
University

- Your child's school has agreed to take part in a study run by Birmingham City University looking at how children attend to information.
- If your child takes part, a researcher would come and visit them at school, and do some activities and play some fun games with them.
- **If you are happy for your child to take part, please fill in the required forms (listed below) and return them to your child's class teacher as soon as possible.**

1. Consent form (below)
2. **Conners' 3™ Parent Questionnaire (enclosed)**

Name of Child	
Date of Birth	
Sex	
Year Group	

Does your child have any known medical conditions?	
Is your children currently taking any medication for their medical conditions?	
Please list any medications your child currently takes.	

I have read and understood the details of the above study, and have had the opportunity to ask questions and discuss the study with others. I understand that participation is voluntary and that I and my child are free to withdraw at any time, without giving any reason, and without my child's education being affected in any way.

I give permission for my child to take part in the above study.

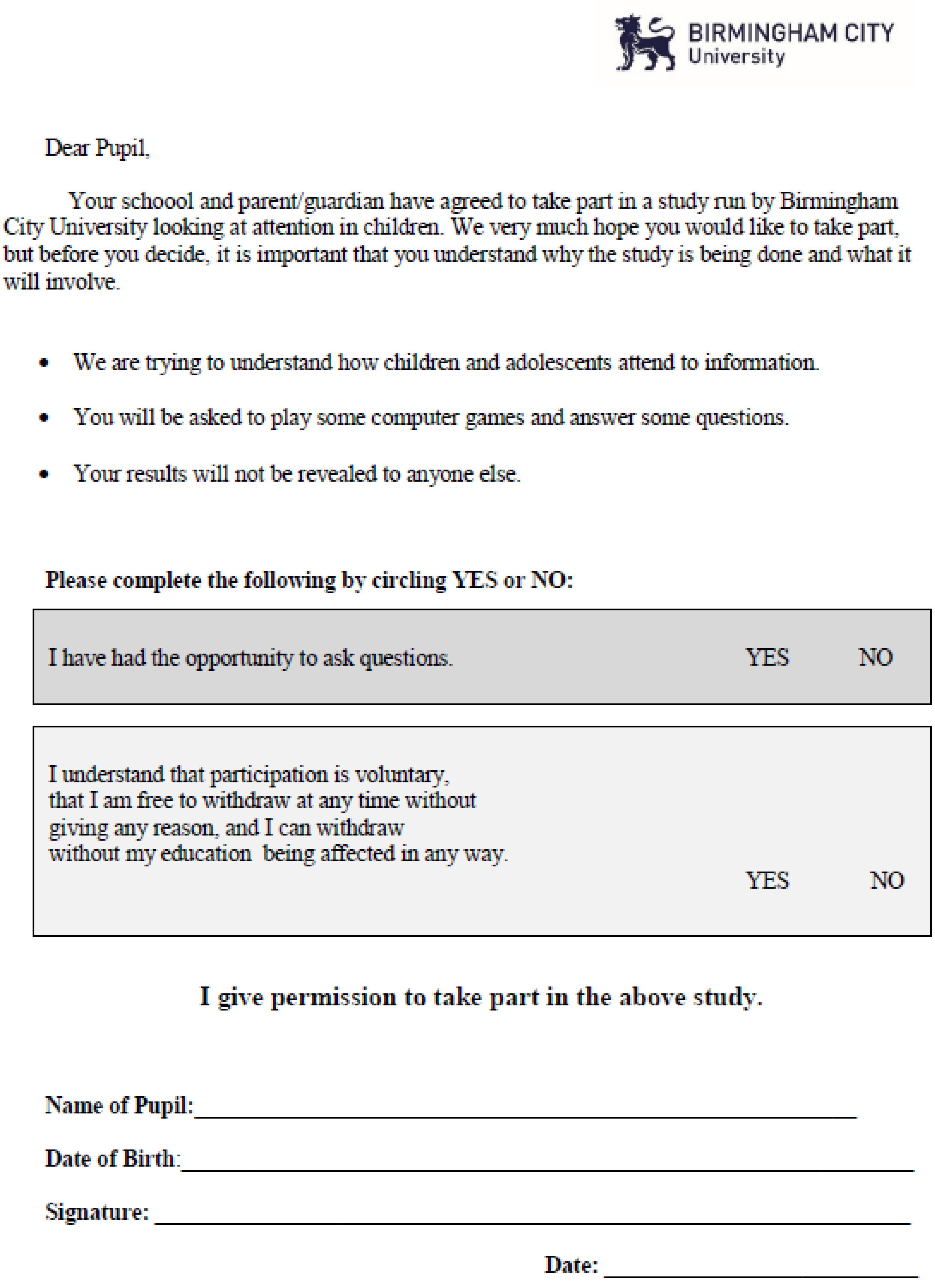
Name of parent/guardian: ____

Signature: ____

Date: ______________________________

Appendix Figure B.3

Child Consent Form



BIRMINGHAM CITY
University

Dear Pupil,

Your schoool and parent/guardian have agreed to take part in a study run by Birmingham City University looking at attention in children. We very much hope you would like to take part, but before you decide, it is important that you understand why the study is being done and what it will involve.

- We are trying to understand how children and adolescents attend to information.
- You will be asked to play some computer games and answer some questions.
- Your results will not be revealed to anyone else.

Please complete the following by circling YES or NO:

I have had the opportunity to ask questions.	YES	NO
I understand that participation is voluntary, that I am free to withdraw at any time without giving any reason, and I can withdraw without my education being affected in any way.	YES	NO

I give permission to take part in the above study.

Name of Pupil:____

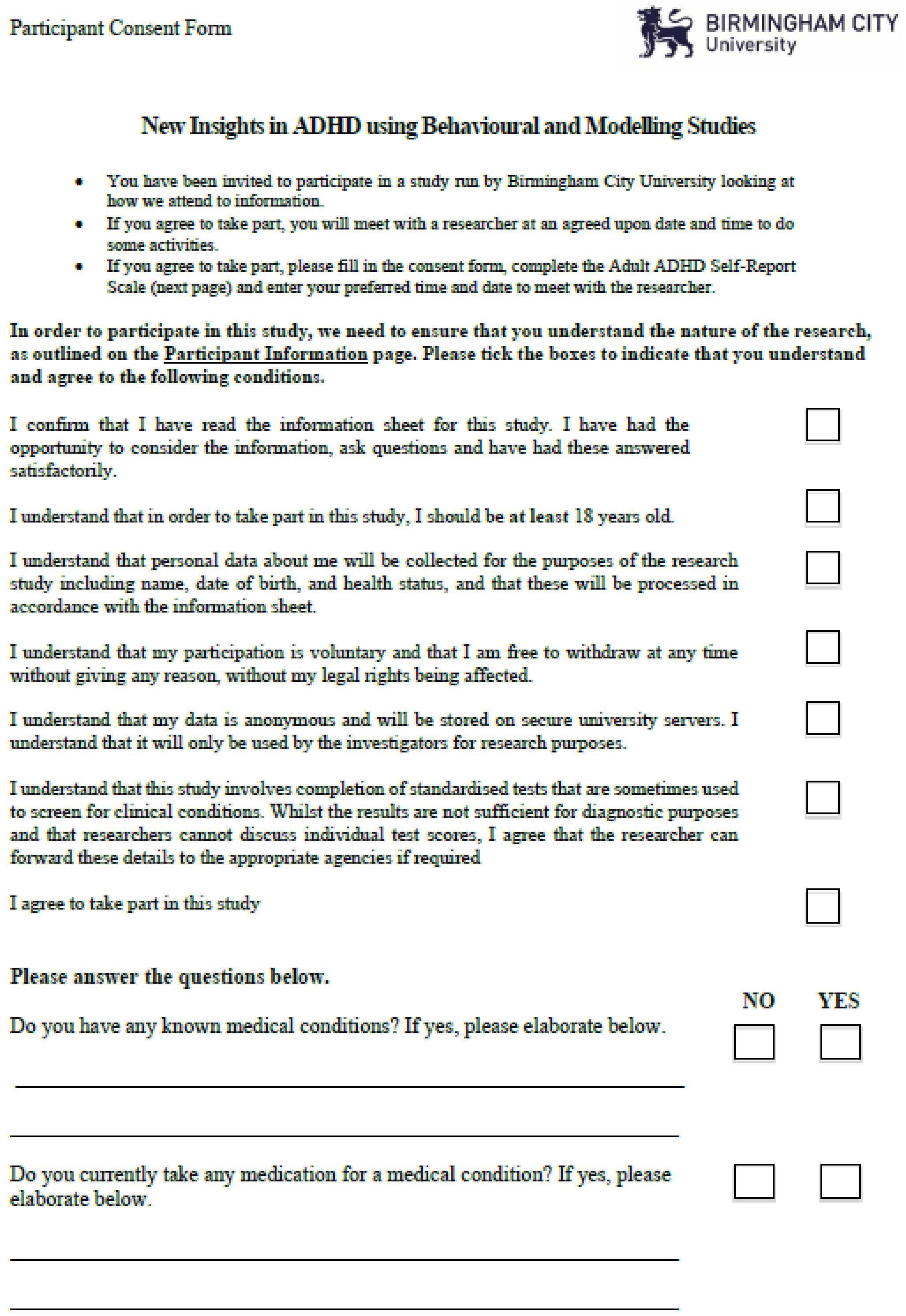
Date of Birth:____

Signature: ____

Date: ____________________

Appendix Figure B.4

Adult Consent Form



Participant Consent Form

BIRMINGHAM CITY
University

New Insights in ADHD using Behavioural and Modelling Studies

- You have been invited to participate in a study run by Birmingham City University looking at how we attend to information.
- If you agree to take part, you will meet with a researcher at an agreed upon date and time to do some activities.
- If you agree to take part, please fill in the consent form, complete the Adult ADHD Self-Report Scale (next page) and enter your preferred time and date to meet with the researcher.

In order to participate in this study, we need to ensure that you understand the nature of the research, as outlined on the Participant Information page. Please tick the boxes to indicate that you understand and agree to the following conditions.

I confirm that I have read the information sheet for this study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

I understand that in order to take part in this study, I should be at least 18 years old. ☐

I understand that personal data about me will be collected for the purposes of the research study including name, date of birth, and health status, and that these will be processed in accordance with the information sheet. ☐

I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my legal rights being affected. ☐

I understand that my data is anonymous and will be stored on secure university servers. I understand that it will only be used by the investigators for research purposes. ☐

I understand that this study involves completion of standardised tests that are sometimes used to screen for clinical conditions. Whilst the results are not sufficient for diagnostic purposes and that researchers cannot discuss individual test scores, I agree that the researcher can forward these details to the appropriate agencies if required ☐

I agree to take part in this study ☐

Please answer the questions below.

	NO	YES
Do you have any known medical conditions? If yes, please elaborate below.	☐	☐
Do you currently take any medication for a medical condition? If yes, please elaborate below.	☐	☐

Appendix C

Certificate of Completion

Certificate of Completion

THIS CERTIFICATE IS AWARDED TO

Thanks for completing the search game and for helping Birmingham City University better understand how attention works!!

DATE

Appendix D

Ethical Approval Letters

Appendix Figure D.1

Ethical Approval Reference Number: Klein /3199 /R(A) /2019 /Mar /BLSS FAEC

BIRMINGHAM CITY
University

Faculty of Business, Law & Social Sciences Research Office
Curzon Building, 4 Cardigan Street
Birmingham
B4 7BD

BLSSethics@bcu.ac.uk;

19/Mar/2019

Miss Jennifer Klein

jennifer.klein@mail.bcu.ac.uk

Dear Jennifer ,

Re: Klein /3199 /R(A) /2019 /Mar /BLSS FAEC - New insights into ADHD through behavioural and modelling studies

Thank you for your application and documentation regarding the above activity. I am pleased to take Chair's Action and approve this activity.

Provided that you are granted Permission of Access by relevant parties (meeting requirements as laid out by them), you may begin your activity.

I can also confirm that any person participating in the project is covered under the University's insurance arrangements.

Please note that ethics approval only covers your activity as it has been detailed in your ethics application. If you wish to make any changes to the activity, then you must submit an Amendment application for approval of the proposed changes.

Examples of changes include (but are not limited to) adding a new study site, a new method of participant recruitment, adding a new method of data collection and/or change of Project Lead.

Please also note that the Business, Law and Social Sciences Faculty Academic Ethics Committee should be notified of any serious adverse effects arising as a result of this activity.

If for any reason the Committee feels that the activity is no longer ethically sound, it reserves the right to withdraw its approval. In the unlikely event of issues arising which would lead to this, you will be consulted.

Keep a copy of this letter along with the corresponding application for your records as evidence of approval.

If you have any queries, please contact BLSSethics@bcu.ac.uk;

I wish you every success with your activity.

Yours Sincerely,

Dr Eugene Nulman

On behalf of the Business, Law and Social Sciences Faculty Academic Ethics Committee

Appendix E

Debrief Sheet

New Insights in ADHD using Behavioural and Modelling Methods

Debriefing Form

Thank you for participating in this study. Please read all of the following information.

The purpose of this study is to look at patterns of attention across a whole group of individuals in order to develop methods to identify ways of helping people with attention difficulties.

Please remember that your individual responses will remain anonymous, and that the data will be examined on a grouped basis only. Any personal data that has been collected for the purposes of the research study including name, date of birth, and health status, will be processed separate from your questionnaires and experimental task responses. These results are only identifiable by a code number only and are securely stored on the university's servers.

If you have any questions, comments or feedback about this study, please contact the Principal Investigator for this study, Jennifer Klein, via email at mailto:Jennifer.Klein@mail.bcu.ac.uk. If you should have any concerns that the Principal Investigator is unable to address, you may also contact the Business, Law, and Social Sciences Faculty Academic Ethics for Birmingham City University at BLSSethics@bcu.ac.uk.

Furthermore, if you would wish to raise a concern or make a complaint about the research or conduct that occurred at any point throughout this study, please contact BLSSethics@bcu.ac.uk.

Your participation and cooperation is greatly appreciated.

Appendix F

2.1 Supplementary Tables

Appendix Table F.1

Statistics for Omnibus ANOVAs Comparing Children and Adults

Effect	Mean RT			Accuracy			Efficiency		
	F	*p*	η^2	*F*	*p*	η^2	*F*	*p*	η^2
Group (G)	155.46	< .001	.54	29.69	< .001	.18	161.00	< .001	.54
Condition (C)	188.65	< .001	.58	0.02	.998	.00	166.75	< .001	.55
Display (D)	536.30	< .001	.80	0.95	.389	.01	489.78	< .001	.78
G x C	25.67	< .001	.16	0.29	.836	.00	25.29	< .001	.16
G x D	21.02	< .001	.14	.39	.748	.00	25.45	< .001	.16
C x D	69.87	< .001	.34	2.62	.016	.02	57.26	< .001	.30
G x C x D	3.74	.001	.03	0.97	.447	.01	3.90	.002	.03

Note. Children and adults were compared on the three behavioural measures shown above using a 2 (group) x 4 (condition) x 3 (display size) mixed ANOVA. Group (children x adults) was a between-subjects factor. Condition (single-feature x conjunction x preview x preview gap) and display size (2 x 4 x 8 for single-feature ; 4 x 8 x 16 for conjunction, preview and preview gap) were within-subject factors.

Appendix Table F.2

Statistics for the Follow Up ANOVAs Comparing Children and Adults on Mean RTs

Effect	SF vs. CJ		CJ vs. PV		SF vs. PV		CJ vs. PVG		SF vs. PVG		PV vs. PVG	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Group (G)	156.31	< .001	146.16	< .001	129.93	< .001	162.94	< .001	150.17	< .001	132.1	< .001
Condition (C)	517.29	< .001	236.46	< .001	49.87	< .001	67.04	< .001	183.62	< .001	63.2	< .001
Display (D)	447.73	< .001	392.87	< .001	227.57	< .001	464.87	< .001	381.34	< .001	320.52	< .001
G x C	71.69	< .001	32.3	< .001	7.13	0.008	10.98	0.001	22.87	< .001	6.79	0.01
G x D	21.26	< .001	18.95	< .001	9.77	< .001	17.57	< .001	11.16	< .001	10.12	< .001
C x D	164.85	< .001	74.36	< .001	19.2	< .001	18.67	< .001	96.31	< .001	28.05	< .001
G x C x D	8.88	< .001	4.14	0.02	1.26	0.29	4.02	0.02	1.8	0.17	0.86	0.42

Note. SF = single-feature; CJ = conjunction; PV = preview; PVG = preview gap.

Appendix Table F.3

Statistics for the Follow Up ANOVAs Comparing Children and Adults on Efficiencies

Effect	SF vs. CJ		CJ vs. PV		SF vs. PV		CJ vs. PVG		SF vs. PVG		PV vs. PVG	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Group (G)	159.34	< .001	160.89	< .001	133.91	< .001	166.01	< .001	143.23	< .001	138.98	< .001
Condition (C)	459.24	< .001	223.80	< .001	49.75	< .001	54.77	< .001	149.05	< .001	54.71	< .001
Display (D)	371.66	< .001	330.46	< .001	6.93	.009	403.77	< .001	318.86	< .001	316.36	< .001
G x C	70.40	< .001	35.69	< .001	179.93	< .001	10.38	.002	19.93	< .001	7.04	.009
G x D	21.77	< .001	18.06	< .001	8.72	< .001	21.68	< .001	16.31	< .001	14.60	< .001
C x D	119.58	< .001	69.92	< .001	10.55	< .001	10.74	< .001	83.11	< .001	30.93	< .001
G x C x D	7.27	< .001	5.13	.007	0.44	.643	2.36	.096	4.02	.019	2.63	.074

Note. SF = single-feature; CJ = conjunction; PV = preview; PVG = preview gap.

Appendix G

Leaky Integrate-and-Fire Neuron Equations

This section is dedicated to providing additional details about the spiking neurons used in the b-sSoTS model, which are referred to as leaky integrate-and-fire (LIF) neurons (Tuckwell, 1998). As mentioned in section 2.2.2, when the LIF neuron's sub-threshold membrane potential reaches a threshold, it “fires” (i.e., becomes active). After firing, this membrane potential is then reset to a fixed value. The sub-threshold membrane potential of the neuron is shown in (3). The synaptic currents used are described by the following equations.

The AMPA recurrent currents $I_{\mathrm{AMPA,rec}}$:

$$I_{\mathrm{AMPA,rec}}(t) = g_{\mathrm{AMPA,rec}}(V(t) - V_{\mathrm{E}}) \sum_{j=1}^{N_{\mathrm{E}}} w_i s_j^{\mathrm{AMPA,rec}}(t) \tag{5}$$

where V_{E} is the excitatory reversal potential, w_j are the synaptic weights, $g_{\mathrm{AMPA,rec}}$ is the synaptic conductance and $s_j^{\mathrm{AMPA,rec}}$ is the receptor’s fraction of open channels.

The voltage of the *NMDA* recurrent currents $I_{\mathrm{NMDA,rec}}$ is dependent on the extra-cellular magnesium $[\mathrm{Mg}^{2+}]$ concentration (Jahr & Stevens, 1990):

$$I_{\mathrm{NMDA,rec}}(t) = \frac{g_{\mathrm{NMDA}}(V(t) - V_{\mathrm{E}})}{1 + [\mathrm{Mg}^{2+}]\exp(-0.062V(t)/3.57} \sum_{j=1}^{N_{\mathrm{E}}} w_i s_j^{\mathrm{NMDA}}(t) \tag{6}$$

where $[\mathrm{Mg}^{2+}]$ is the concentration of magnesium, g_{NMDA} is the synaptic conductance and s_j^{NMDA} is the receptor’s fraction of open channels.

The voltage of inhibitory GABA currents I_{GABA}:

$$I_{\mathrm{GABA}} = g_{\mathrm{GABA}}(V(t) - V_I)\sum_{j=1}^{N_{\mathrm{I}}} s_j^{\mathrm{GABA}}(t) \tag{7}$$

where g_{GABA} is the synaptic conductance and s_j^{GABA} is the receptor's fraction of open channels.

Connections with external neurons follow *AMPA*-like dynamics and the voltage $I_{\mathrm{AMPA,ext}}$ follows the equation:

$$I_{\mathrm{AMPA,ext}}(t) = g_{\mathrm{AMPA,ext}}(V(t) - V_{\mathrm{E}})\sum_{j=1}^{N_{\mathrm{E}}} w_i s_j^{\mathrm{AMPA,ext}}(t) \tag{8}$$

where $g_{\mathrm{AMPA,ext}}$ is the synaptic conductance and $s_{j=1}^{\mathrm{AMPA,ext}}$ is the receptor's fraction of open channels. The parameters for Equations (5) - (8) are provided in Table 2.5.

Finally, there is an additional current here that aims to simulate a frequency adaptation mechanism. The spike frequency adaptation mechanism employed here used I based on [Ca^{2+}]-activated $[\mathrm{K}^{+}]$ hyperpolarising current I_{AHP}. This is according to the assumption that this is the primary current that produces this mechanism during the first 300 ms of adaptation (Madison & Nicoll, 1984). The I_{AHP} can be described by the equation:

$$I_{\mathrm{AHP}}(t) = -g_{\mathrm{AHP}}[\mathrm{Ca}^{2+}](V(t) - V_K) \tag{9}$$

where V_K is the reversal potential of the K^{+} and g_{AHP} is the synaptic conductance. Every time an action potential is generated, there is an influx of a small amount of $[\mathrm{Ca}^{2+}]\alpha$, so that the intra-cellular level of $[\mathrm{Ca}^{2+}]$ increases, which then leads to further increment in the I_{AHP}. The $[\mathrm{Ca}^{2+}]$ between spikes can be described by the following equations:

$$\frac{\mathrm{d}[\mathrm{Ca}^{2+}]}{\mathrm{d}t} = \frac{[\mathrm{Ca}^{2+}]}{\tau_{\mathrm{Ca}}} \tag{10}$$

If $V(t) = V_{\mathrm{thr}}$, then $[\mathrm{Ca}^{2+}]$ = $[\mathrm{Ca}^{2+}] + a$ and $V = V_{\mathrm{reset}}$.

Where, α is the $[\mathrm{Ca}^{2+}]$ influx and τ_{Ca} is the leaky integrator's decay constant. $[\mathrm{Ca}^{2+}]$ concentration is initially set to 0 and the values for the rest of the parameters given here are detailed in Table 2.5.

The fraction of open channels are given by the following equations:

$$\frac{\mathrm{d}s_j^{\mathrm{AMPA,rec}}(t)}{\mathrm{d}t} = \frac{s_j^{\mathrm{AMPA,rec}}(t)}{\tau_{\mathrm{AMPA}}} + \sum_k \delta(t - t_j^k) \tag{11}$$

where $\tau_{\mathrm{AMPA}}$is the decay time constant.

$$\frac{\mathrm{d}s_j^{\mathrm{NMDA}}(t)}{\mathrm{d}t} = \frac{s_j^{\mathrm{NMDA}}(t)}{\tau_{\mathrm{NMDA,decay}}} + a x_j(t)(1 - s_j^{\mathrm{NMDA}}(t)) \tag{12}$$

$$\frac{\mathrm{d}x_j(t)}{\mathrm{d}t} = \frac{x_j(t)}{\tau_{\mathrm{NMDA,rise}}} + \sum_k \delta(t - t_j^k) \tag{13}$$

where $\tau_{\mathrm{NMDA,decay}}$ is the decay time constant and $\tau_{\mathrm{NMDA,rise}}$ is the rise time constant.

$$\frac{\mathrm{d}s_j^{\mathrm{GABA}}(t)}{\mathrm{d}t} = \frac{s_j^{\mathrm{GABA}}(t)}{\tau_{\mathrm{GABA}}} + \sum_k \delta(t - t_j^k) \tag{14}$$

where τ_{GABA} is the decay time constant.

$$\frac{\mathrm{d}s_j^{\mathrm{AMPA,ext}}(t)}{\mathrm{d}t} = \frac{s_j^{\mathrm{AMPA,ext}}(t)}{\tau_{\mathrm{AMPA}}} + \sum_k \delta(t - t_j^k) \tag{15}$$

The values for $\tau_{\mathrm{NMDA,rise}}$, $\tau_{\mathrm{NMDA,decay}}$, τ_{AMPA} (Hestrin et al., 1990; Spruston et al., 1995) and τ_{GABA} (Salin & Prince, 1996; Xiang et al., 1998) are given in Table 2.5. The rise time constants for AMPA and GABA are absent due to the fact that they are extremely small. Furthermore, it is considered that the spikes emitted from the pre-synaptic neuron j at time t_j^k are of the form of $\delta - \mathrm{peaks}$ $\left(\delta(t)\right)$.

Appendix H

Mean Field Approximation

This section describes the mean field approximation (used by Mavritsaki et al., 2006) to identify the parameters of the b-sSoTS model. This particular approximation was derived by Brunel and Wang (2001) and Deco and Rolls (2005) and is derived from the spiking neuron approach (see Brunel & Wang, 2001; Deco & Rolls, 2005). The use of this formulation assumes the network of integrate-and-fire neurons is in a stationary state.

The potential of a neuron in the mean field is given by the equation:

$$\tau_x \frac{\mathrm{d}V(t)}{\mathrm{d}t} == V(t) + \mu_x + \sigma_x \sqrt{\tau_x}\eta(t) \tag{16}$$

where μ_x is the mean value of the membrane potential in the absence of spiking and fluctuations, σ_x is the magnitude of fluctuations, η is Gaussian process with time constant τ_{AMPA}, $V(x)$ is the membrane potential, x is the population of neurons and τ_x is the membrane time constant. μ_x and σ_x^2 are given by the equations below:

$$\mu_x = \frac{(T_{\mathrm{ext}}v_{\mathrm{ext}} + T_{\mathrm{AMPA}}n_x + \rho_1 N_x)V_{\mathrm{E}} + \rho_2 N_x \langle V \rangle + T_{\mathrm{I}} w_{I,x} v_{\mathrm{I}} V_{\mathrm{I}} + V_L + \frac{g_{\mathrm{AHP}}[\mathrm{Ca}^{2+}]_x V_K}{g_m}}{S_x} \tag{17}$$

$$\sigma_x^2 = \frac{\left(g_{\mathrm{AMPA,ext}}^2 v_{\mathrm{ext}} + g_{\mathrm{AMPA,rec}}^2 v_x\right)(\langle V \rangle - V_{\mathrm{E}})^2 \tau_{\mathrm{AMPA}}^2 \tau_x}{g_m^2 \tau_m^2} \tag{18}$$

where $w_{I,x}$ are the weights from the neurons in the inhibitory pools (I = 1, . . ., 3) to the pool neurons in the pool x, v_{I} is the average spiking rate of the inhibitory pool I, $[\mathrm{Ca}^{2+}]_x$ is the population average cytoplasmic $[\mathrm{Ca}^{2+}]$ concentration, $\tau_m = \frac{C_m}{g_m}$ with different values depending on which pool is considered (excitatory or inhibitory), and v_{ext} is the external spiking rate as a summation of the spontaneous activity v_{sp}, external stimuli $\lambda_{\text{in}}$and top-down attention λ_{att} with v_{ext} = $v_{\text{sp}} + \lambda_{\text{in}} + \lambda_{\text{att}}$. The rest of the quantities are given by the equations below:

$$S_x = 1 + \ T_{\text{ext}} v_{\text{ext}} + \ T_{\text{AMPA}} n_x + (\rho_1 + \rho_2) N_x + \ T_{\text{I}} w_{I,x} v_{\text{I}} + \frac{g_{\text{AHP}} [\text{Ca}^{2+}]_x}{g_{\text{m}}} \tag{19}$$

$$\tau_x = \frac{C_m}{g_m S_x} \tag{20}$$

$$n_x = \sum_{j=1}^{n} f_j w_{j,x} v_j \tag{21}$$

where p is the number of excitatory pools, f_x is the fraction of neurons in the x excitatory pool and $w_{j,x}$ is the wright from pool j to pool x.

$$N_x = \sum_{j=1}^{p} f_j w_{j,x} \psi(v_j) \tag{22}$$

$$\psi(v) = \frac{v\tau_{\text{NMDA}}}{1 + v\tau_{\text{NMDA}}} \left(1 + \frac{1}{1 + v\tau_{\text{NMDA}}} \sum_{n=1}^{\infty} \frac{\left(-a\tau_{\text{NMDA,rise}}\right)^n T_n(v)}{(n+1)!} \right) \tag{23}$$

$$T_n(v) = \sum_{k=0}^{n} -1^k \binom{n}{k} \frac{\tau_{\text{NMDA,rise}} (1 + v\tau_{\text{NMDA}})}{\tau_{\text{NMDA,rise}} \, (1 + v\tau_{\text{NMDA}}) + k\tau_{\text{NMDA,decay}}} \tag{24}$$

$$\tau_{\text{NMDA}} = a\tau_{\text{NMDA,rise}} \tau_{\text{NMDA,decay}} \tag{25}$$

$$T_{\text{ext}} = \frac{g_{\text{AMPA,ext}} C_{\text{ext}} \tau_{\text{AMPA}}}{g_m} \tag{26}$$

$$T_{\text{AMPA}} = \frac{g_{\text{AMPA,rec}} N_{\text{E}} \tau_{\text{AMPA}}}{g_m} \tag{27}$$

$$\rho_1 = \frac{g_{\mathrm{NMDA}} N_{\mathrm{E}}}{g_m J} \tag{28}$$

$$\rho_2 = \beta \frac{g_{\mathrm{NMDA}} N_{\mathrm{E}} (< V > - V_{\mathrm{E}})(J - 1)}{g_m J^2} \tag{29}$$

where β = 0.062

$$J = 1 + \gamma \exp\,(-\beta \langle V \rangle) \tag{30}$$

where γ = $[\mathrm{Mg}^{2+}]$/3.5 and $\langle V_x \rangle$ has a value between -55mV and -50mV.

$$T_{\mathrm{I}} = \frac{g_{\mathrm{GABA}} N_{\mathrm{I}} \tau_{\mathrm{GABA}}}{g_m} \tag{31}$$

$$\langle V_x \rangle = \mu_x - (V_{\mathrm{thr}} - V_{\mathrm{reset}}) v_x \tau_x \tag{32}$$

The equations presented below are solved numerically in parallel.

$$\tau_x \frac{\mathrm{d}v_x}{\mathrm{d}t} = -v_x + \phi(\mu_x, \sigma_x) \tag{33}$$

$$\tau_{\mathrm{Ca}} \frac{\mathrm{d}[\mathrm{Ca}^{2+}]_x}{\mathrm{d}t} = -[\mathrm{Ca}^{2+}]_x + \alpha \tau_{\mathrm{Ca}} v_x \tag{34}$$

where $v_x = \phi(\mu_x, \sigma_x)$ is the spiking rate of a pool as a function of the above equations and

$$\phi(\mu_x, \sigma_x) = (\tau_{\mathrm{rp}} + \tau_x \int_{\beta(\mu_x, \sigma_x)}^{\alpha(\mu_x, \sigma_x)} \mathrm{d}u \sqrt{\pi} \exp(u^2)\, [1 + \mathrm{erf(u)}]^{-1} \tag{35}$$

$$\alpha(\mu_x, \sigma_x) = \frac{(V_{\mathrm{thr}} - \mu_x)}{\sigma_x} \left(1 + 0.5 \frac{\tau_{\mathrm{AMPA}}}{\tau_x}\right) + 1 \cdot 03 \sqrt{\frac{\tau_{\mathrm{AMPA}}}{\tau_x}} - 0.5 \frac{\tau_{\mathrm{AMPA}}}{\tau_x} \tag{36}$$

$$\beta(\mu_x, \sigma_x) = \frac{(V_{\mathrm{reset}} - \mu_x)}{\sigma_x} \tag{37}$$

where erf is the error function and τ_{rp} is the refractory period. The parameter values are shown in Table 2.5.

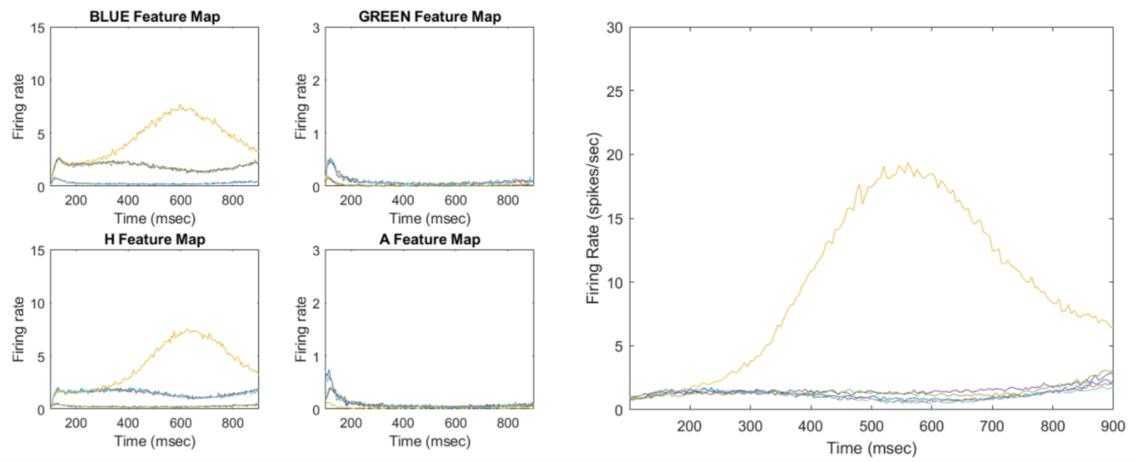
Appendix I

2.2 Supplementary Figures

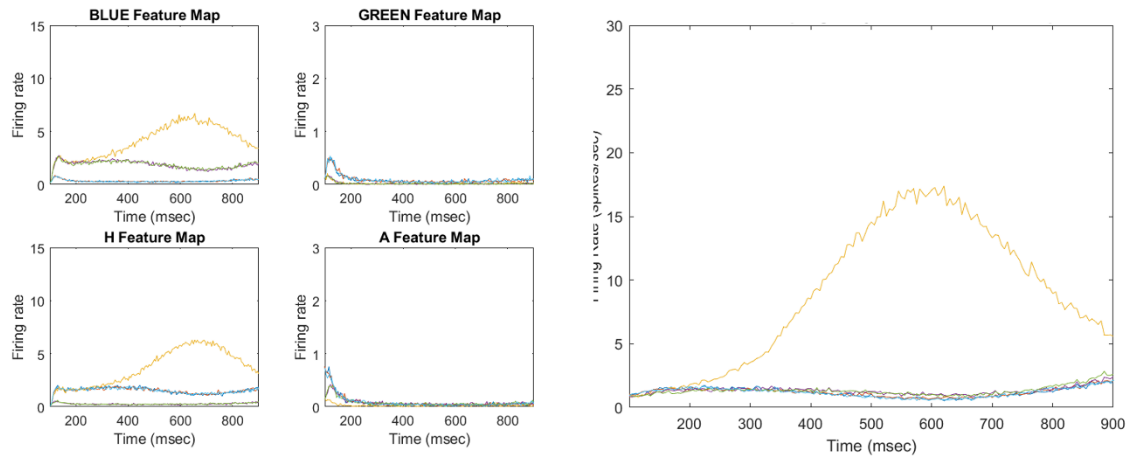
Appendix Figure I.1

Activation of Feature and Location Maps for Conjunction Search for Simulated Adults and Children

Simulated Adults



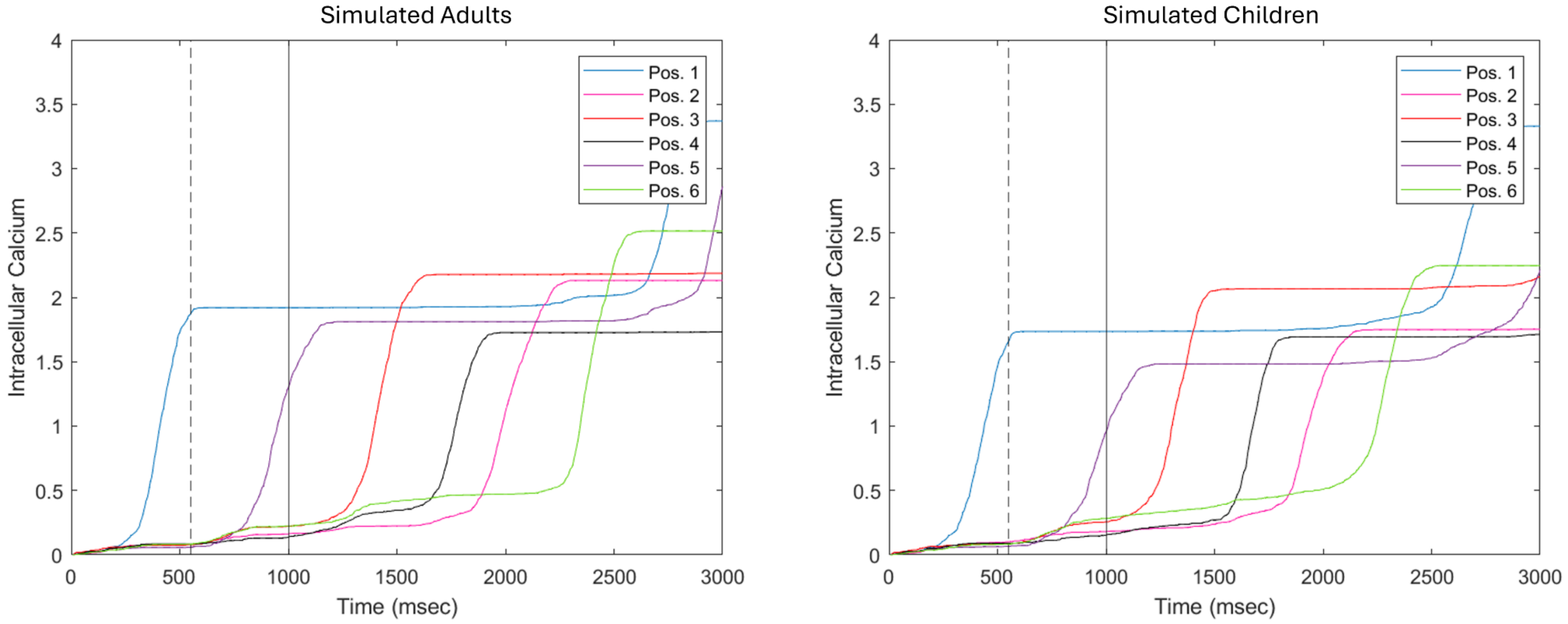
Simulated Children



Note. Each graph depicts the average rate of firing for each of the six pools in each of the four feature maps (smaller graphs on the left) and in the location map (larger graph on the right). While the five distractor pools all have similar firing rates, the target pool (the yellow line) can be clearly distinguished. For simulated children, the reduction in the w_+ weight means it takes the target more time to gain power and win the competition.

Appendix Figure I.2

Intracellular Calcium Levels in the Preview Gap Condition for Simulated Adults and Children



Note. When a neuron has a higher rate of firing, it also has a higher concentration of intracellular Ca^{2+}, and thus the time course of frequency adaptation is faster (Mavritsaki et al., 2011). In the simulated adults, the concentration of Ca^{2+} for all items is slightly higher than that of simulated children. This occurs because the reduced w_+ values reduces overall firing rates for all items, which in turn affects how much Ca^{2+} enters the cell, and thus the time course of frequency adaptation. Despite this, the change in Ca^{2+} concentration when w_+ was reduced only minimally affected the time course of visual marking for simulated children.

Appendix J

Conners 3 ADHD Index Form

Instructions: Here are some things that parents might say about their children. Please tell us about your child and what he/she has been like in the past month. Read each item carefully, then mark how well it describes your child by circling only one answer for each item. For items you find difficult to answer, please give your best guess.

Each item was rated on a scale ranging from 1 (Not true at all) to 3 (Very much true)

Not true at all	Just a little true	Pretty much true	Very much true
(Never, Seldom)	(Occasionally)	(Often, Quite a bit)	(Very often, Very frequently)
0	**1**	**2**	**3**

1. Fidgeting.
2. Does not seem to listen to what is being said to him/her.
3. Doesn’t pay attention to details; makes careless mistakes.
4. Inattentive, easily distracted.
5. Has trouble organising tasks or activities.
6. Gives up easily on difficult tasks.
7. Fidgets or squirms in seat.
8. Restless or overactive.
9. Is easily distracted by sights or sounds.
10. Interrupts others (for example, butts into conversations and games).

Appendix K

Calculation of WISC-IV Short Form Deviation Quotients

In the present thesis, a short form of the WISC-IV was used to measure intelligence in children with low and high levels of ADHD traits. In line with previous research (Mason et al., 2003), this short form included four of the fifteen subtests of the WISC-IV, including Block Design, Vocabulary, Similarities, and Picture Completion. First, for each participant, standardised scores were calculated each of these subtests, then these scores were used to calculate an estimate of IQ, referred to as a deviation quotient (DQ). The method used here for calculating DQs was first put forth by Sattler (1982) and was updated for the WISC-IV. Sattler's (1982) equation for calculating short-form DQs considers: (1) the total number of standardised-score points obtained on all the subtests of the short form (i.e., the composite score); (2) the number of subtests in the short form; and (3) the intercorrelations between the subtests. This equation is shown in (38.

$$\text{Deviation Quotient} = \left(\frac{15}{S_c}\right)(X_c - M_C) + 100 \tag{38}$$

where S_c = $S_s\sqrt{n + 2\sum r_{jk}}$, which is the standard deviation of the composite score; X_C is the composite score; $M_c$is the normative mean, which is equal to 10*n*; S_s is the subtest standard deviation, which is equal to 3; *n* is the number of component subtests, and $\sum r_{jk}$ is the correlations between component subtests. A more direct version of the DQ formula is shown in (39.

$$\text{Deviation Quotient} = (\text{composite score } \times\, a) + b \tag{39}$$

where $a = 15/S_c$ and $b = 100 - n(150)/S_c$.

Using this DQ equation then, the first step in obtaining a participant's DQ was to sum the standardised scores of the four subtests to obtain the individual's composite score. Next, the intercorrelations between the subtests must be summed to obtain $\sum r_{jk}$. The intercorrelations between subtests for the WISC-IV are shown below in Appendix Table K.1 for 7- to 12-years old.

Appendix Table K.1

Intercorrelations of the WISC-IV Subtests for Ages 7 to 12

Subtest	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12
BD x VC	0.41	0.46	0.55	0.52	0.50	0.55
BD x SI	0.49	0.50	0.48	0.50	0.53	0.53
BD x PCm	0.43	0.57	0.64	0.52	0.57	0.55
VC x SI	0.73	0.77	0.81	0.77	0.73	0.74
VC x PCm	0.43	0.51	0.62	0.54	0.55	0.53
SI x PCm	0.37	0.45	0.58	0.49	0.53	0.51

Note. WISC-IV = Wechsler's Intelligence Scale for Children, 4th Edition; BD = Block Design; VC = Vocabulary; SI= Similarities; PCm = Picture Completion. From *Wechler Intelligence Scale for Children (WISC-IV) Administration and Scoring Manual*, by D. Wechsler, 2003, Appendix A, Tables A..2-A.7. Copyright 2003 by Pearson.

Accordingly, the $\sum r_{jk}$ values were 2.86, 3.26, 3.68, 3,34, 3.41 and 3.41 for age 7, 8, 9, 10, 11 and 12, respectively. After obtaining the $\sum r_{jk}$ values, the appropriate a and b values can be found (see Appendix Table K.2). Finally, these constants are inserted, along with the composite score, into Equation (39 to compute the DQ.

Appendix Table K.2

Constants for Deviation Quotient Formula

Sum of subtest intercorrelations	a	b
3.95 – 4.85	1.4	44
3.21 – 3.94	1.5	40
2.60 – 2.90	1.6	36
2.09 – 2.59	1.7	32
1.66 – 2.08	1.8	28
1.29 – 1.65	1.9	24
0.98 – 1.28	1.0	20

Note. From *Assessment of Children, Revised and Updated Third Edition* by J.M. Sattler, 1992, p. 850.

Copyright 1992 by Jerome M. Sattler Publisher, Inc.

Appendix L

3.1 Supplementary Tables

Appendix Table L.1

Interpretation Guidelines for the Conners 3AI T-scores

T-score	Interpretation
70+	**Very Elevated Score** (Many more similar responses to youth with ADHD than are typical for this age/gender)
60 - 69	**Elevated Score** (More similar responses to youth with ADHD than are typical for this age/gender)
40 - 59	**Average Score** (Average levels of similar responses to youth with ADHD for this age/gender)
< 40	**Low Score** (Fewer similar responses to youth with ADHD than are typical for this age/gender)

Note. From *Conners 3rd Edition*, by C.K. Conners, 2008, p. 82. Copyright 2008 by Multi-Health Systems, Inc.

Appendix Table L.2

Interpretation Guidelines for the Conners 3AI Probability Scores

Probability (%)	Interpretation
> 80	**Very high**; responses are very similar to those for youth with ADHD; a classification of ADHD is very likely.
61 – 79	**High**; responses are similar to those for youth with ADHD; a classification of ADHD is likely.
51 – 60	**Borderline**; responses are slightly more similar to youth with ADHD than to the general population.
50	**Equal Probability**; this score is equally likely to occur for youth from the general population and youth with a diagnosis of ADHD.
40 – 49	**Borderline**; responses are slightly more similar to youth with ADHD than to the general population.
20 – 39	**Low**; responses are similar to those for the general population; a classification of ADHD is unlikely.
< 20	**Very Low**; responses are very similar to those for the general population; a classification of ADHD is highly unlikely.

Note. From *Conners 3rd Edition*, by C.K. Conners, 2008, p. 77. Copyright 2008 by Multi-Health Systems, Inc.

Appendix Table L.3

Statistics for Omnibus ANOVAs Comparing Low and High Conners 3AI Groups

Effect	Mean RT			Accuracy			Efficiency		
	F	*p*	η^2	*F*	*p*	η^2	*F*	*p*	η^2
Group (G)	3.30	.074	.05	0.23	0.643	.00	3.25	.077	.05
Condition (C)	85.96	< .001	.59	0.05	.986	.00	75.13	< .001	.56
Display (D)	205.64	< .001	.78	0.69	.503	.01	189.55	< .001	.76
G x C	1.09	.353	.02	0.50	.684	.01	0.77	.515	.01
G x D	1.26	.289	.021	0.10	.901	.00	1.16	.318	.02
C x D	25.32	< .001	.30	1.61	.143	.03	20.70	< .001	.26
G x C x D	1.13	.347	.02	0.52	.793	.01	0.86	.523	.01

Note. Low and high Conners 3AI were compared on the three behavioural measures shown above using a 2 (group) x 4 (condition) x 3 (display size) mixed ANOVA. Group (low Conners 3AI x high Conners 3AI) was a between-subjects factor. Condition (single-feature x conjunction x preview x preview gap) and display size (2 x 4 x 8 for single-feature ; 4 x 8 x 16 for conjunction, preview and preview gap) were within-subject factors.

Appendix Table L.4

Statistics for the Follow Up ANOVAs Comparing Low and High Conners 3AI Groups on Mean RTs

Effect	SF vs. CJ		CJ vs. PV		SF vs. PV		CJ vs. PVG		SF vs. PVG		PV vs. PVG	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Condition (C)	250.76	< .001	103.90	< .001	23.04	< .001	31.86	< .001	79.63	< .001	28.05	< .001
Display (D)	184.90	< .001	151.25	< .001	86.54	< .001	172.34	< .001	134.09	< .001	114.35	< .001
C x D	62.51	< .001	28.17	< .001	6.86	.002	10.99	< .001	30.32	< .001	6.93	001

Note. SF = single-feature; CJ = conjunction; PV = preview; PVG = preview gap.

Appendix Table L.5

Statistics for the Follow Up ANOVAs Comparing Low and High Conners 3AI Groups on Efficiencies

Effect	SF vs. CJ		CJ vs. PV		SF vs. PV		CJ vs. PVG		SF vs. PVG		PV vs. PVG	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Condition (C)	217.85	< .001	101.85	< .001	21.92	< .001	26.33	< .001	62.84	< .001	23.51	< .001
Display (D)	150.54	< .001	122.85	< .001	66.80	< .001	149.91	< .001	117.61	< .001	118.40	< .001
C x D	41.88	< .001	26.89	< .001	3.33	.039	5.25	.007	28.53	< .001	10.38	< .001

Note. SF = single-feature; CJ = conjunction; PV = preview; PVG = preview gap.

Appendix M

Adult Self-Report Scale-V1.1 (ASRS.-V.1.1) Screener

Instructions: Check the box that best describes how you have felt and conducted yourself over the past 6 months.

Each item was rated on a scale ranging from 0 (Never) to 4 (Very Often)

Never	Rarely	Sometimes	Often	Very Often
0	**1**	**2**	**3**	**4**

1. How often do you have trouble wrapping up the final details of a project, once the challenging parts have been done?
2. How often do you have difficulty getting things in order when you have to do a task that requires organization?
3. How often do you have problems remembering appointments or obligations?
4. When you have a task that requires a lot of thought, how often do you avoid or delay getting started?
5. How often do you fidget or squirm with your hands or feet when you have to sit down for a long time?
6. How often do you feel overly active and compelled to do things, like you were driven by a motor?

Appendix N

4.1 Supplementary Tables

Appendix Table N.1

Statistics for Omnibus ANOVAs Comparing Low, Borderline and High ASRS Groups

Effect	Mean RTs			Accuracy		
	F	*p*	η^2	*F*	*p*	η^2
Group (G)	1.49	.231	.04	0.80	.455	.02
Condition (C)	136.68	< .001	.65	0.36	.785	.01
Display (D)	433.39	< .001	.86	0.43	.650	.01
G x C	0.85	.533	.02	1.52	.174	.04
G x D	1.41	.233	.04	0.53	0.713	.01
C x D	69.75	< .001	.49	2.18	.044	.03
G x C x D	1.37	.179	.04	2.22	.010	.06

Note. Low, borderline and high ASRS groups were compared on the three behavioural measures shown above using a 3 (group) x 4 (condition) x 3 (display size) mixed ANOVA. Group (low ASRS x borderline ASRS x high ASRS) was a between-subjects factor. Condition (single-feature x conjunction x preview x preview gap) and display size (2 x 4 x 8 for single-feature ; 4 x 8 x 16 for conjunction, preview and preview gap) were within-subject factors.

Appendix Table N.2

Statistics for the Follow Up ANOVAs Examining Mean RTs

Effect	SF vs. CJ		CJ vs. PV		SF vs. PV		CJ vs. PVG		SF vs. PVG		PV vs. PVG	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Condition (C)	343.34	< .001	202.08	< .001	34.22	< .001	43.79	< .001	154.00	< .001	41.86	< .001
Display (D)	307.23	< .001	346.56	< .001	228.39	< .001	398.79	< .001	355.39	< .001	291.76	< .001
C x D	139.86	< .001	61.77	< .001	28.83	< .001	6.79	.002	109.22	< .001	68.19	< .001

Note. SF = single-feature; CJ = conjunction; PV = preview; PVG = preview gap.

Appendix Table N.3

Statistics for the Follow Up ANOVAs for Comparing the Conditions in the Low, Borderline and High ASRS Groups for Accuracy

Comparison/Effect		Low ASRS			Borderline ASRS			High ASRS		
		F	*p*	η^2	*F*	*p*	η^2	*F*	*p*	η^2
SF vs. CJ	C	0.85	.369	.05	0.27	.608	.01	1.12	.299	.04
	D	2.00	.150	.10	0.72	.492	.02	4.77	.013	.16
	C x D	2.82	.073	.14	2.03	.141	.07	0.62	.542	.02
CJ vs. PV	C	0.27	.610	.02	4.27	.048	.13	0.89	.355	.03
	D	0.23	.800	.01	0.26	.776	.01	1.60	.212	.06
	C x D	6.67	.003	.27	1.41	.252	.05	3.04	.056	.11
SF vs. PV	C	0.02	.895	.00	7.07	.013	.20	3.11	.090	.11
	D	1.07	.355	.06	2.16	.124	.07	0.58	.565	.02
	C x D	2.62	.087	.13	0.07	.935	.00	1.82	.172	.07
CJ vs. PVG	C	0.06	.810	.00	0.31	.583	.01	0.23	.635	.01
	D	3.06	.059	.15	0.06	.946	.00	0.19	.831	.01
	C x D	1.92	.162	.10	1.24	.297	.04	8.21	.001	.24
SF vs. PVG	C	0.29	.600	.02	0.78	.386	.03	0.36	.554	.01
	D	1.71	.195	.09	1.14	.328	.04	0.11	.896	.00
	C x D	0.09	.912	.01	0.79	.460	.03	3.59	.035	.12
PV vs. PVG	C	0.18	.680	.01	1.07	.309	.04	1.67	.207	.06
	D	1.05	.360	.06	0.84	.438	.03	2.07	.136	.07
	C x D	2.09	.139	.10	0.22	.807	.01	0.92	.406	.03

Note. ASRS = ADHD Self-Report Scale; C = condition; D = display; SF = single-feature; CJ = conjunction; PV = preview; PVG = preview gap..

Appendix O

Barratt Impulsiveness Scale-Brief (BIS-B)

Instructions: People differ in the ways they act and think in different situations. This is a test to measure some of the ways in which you act and think. Read each statement and put an X on the appropriate circle on the right side of this page. Do not spend too much time on any statement. Answer quickly and honestly.

Each item was rated on a scale ranging from 1 (Rarely/Never) to 4 (Almost Always/Always)

Rarely/Never	Occasionally	Often	Almost Always/Always
0	**1**	**2**	**4**

1. I plan tasks carefully.
2. I do things without thinking.
3. I don’t “pay attention.”
4. I am self-controlled.
5. I concentrate easily.
6. I am a careful thinker.
7. I say things without thinking.
8. I act on the spur of the moment.

Appendix P

4.2 Supplementary Tables

Appendix Table P.1

Statistics for Omnibus ANOVAs Comparing Low ASRS, Borderline ASRS, High ASRS, and High ASRS + BIS-B Groups

Effect	Mean RTs			Accuracy		
	F	*p*	η^2	*F*	*p*	η^2
Group (G)	2.31	.081	.07	0.63	.596	.02
Condition (C)	133.68	< .001	.60	8.48	< .001	.09
Display (D)	509.93	< .001	.85	10.72	< .001	.11
G x C	2.47	.010	.08	1.13	.340	.04
G x D	2.22	.043	.07	1.65	.135	.05
C x D	59.07	< .001	.40	2.66	.015	.03
G x C x D	1.33	.163	.04	0.79	.107	.03

Note. Low ASRS, borderline ASRS, high ASRS and high ASRS + BIS-B groups were compared on the three behavioural measures shown above using a 4 (group) x 4 (condition) x 3 (display size) mixed ANOVA. Group (low ASRS x borderline ASRS x high ASRS x high ASRS + BIS-B) was a between-subjects factor. Condition (single-feature x conjunction x preview x preview gap) and display size (2 x 4 x 8 for single-feature ; 4 x 8 x 16 for conjunction, preview and preview gap) were within-subject factors.

Appendix Table P.2

Statistics for the Follow Up ANOVAs Comparing Low ASRS, Borderline ASRS and High ASRS and High ASRS + BIS-B Groups on Mean RTs

Effect	SF vs. CJ		CJ vs. PV		SF vs. PV		CJ vs. PVG		SF vs. PVG		PV vs. PVG	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Group (G)	1.97	.124	3.25	.026[a]	1.90	.136	2.51	.064	1.13	.340	2.48	.066
Condition (C)	307.65	< .001	211.10	< .001	88.15	< .001	72.73	< .001	86.81	< .001	3.19	.077
Display (D)	400.79	< .001	390.68	< .001	309.22	< .001	431.38	< .001	358.08	< .001	335.14	< .001
G x C	4.19	.008[1]	0.70	0.56	3.62	.016[3]	2.58	.059	0.85	.47	1.96	.125
G x D	1.733	.116	2.51	.024[2]	1.54	.168	1.88	.086	1.13	.346	2.30	.037[4]
C x D	133.85	< .001	38.95	< .001	49.82	< .001	17.79	< .001	98.34	< .001	10.96	< .001
G x C x D	1.51	.178	0.90	.50	2.29	.037[a]	1.31	.257	1.65	.135	0.58	.743

Note. SF = single-feature; CJ = conjunction; PV = preview; PVG = preview gap. [1] Higher mean RTs in the high ADHD + impulsive group compared to the low ADHD group in the conjunction condition (*p* = .037). [2] Higher mean RTs in the high ADHD + impulsive group compared to the low ADHD group at display size 8 (*p* = .046) and display size 16 (*p* = .014). [3] Higher mean RTs in the high ADHD + impulsive group compared to the low ADHD group in the preview condition (*p* = .022).[4] Higher mean RTs in the high ADHD + impulsive group compared to the low ADHD group at display size 8 (*p* = .022).[a] No significant differences seen in the main omnibus ANOVA indicates false positive.