Control and Development of Time-based Visual Selection

By

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List of Abbreviations

Attention Deficit Disorder - ADD

Attention Deficit Hyperactivity Disorder - ADHD

Analysis of variance – ANOVA

COntour DEtector theory - CODE

Executive functions – EF

FEB- Full-element baseline

Feature Integration Theory – FIT

HEB –Half-element baseline

Inhibition of Return - IOR

Short-term memory – STM

Preview efficiency – PE

Rapid serial visual presentation - RSVP

Reaction time – RT

SeLective Attention Model - SLAM

Search via Recursive Rejection – SERR

Visual short-term memory - VSTM

Visual working memory – VWM

William’s Syndrome – WS

Working memory - WM

Theory of Visual Attention - TVA

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Declaration

This thesis is submitted to the University of Warwick in support of my application for the degree of Doctor of Philosophy. It has been composed by myself and has not been submitted in any previous application for any degree.

The work presented (including data generated and data analysis) was carried out by the author. The papers and presentations resulting from the work presented in Chapter 2 and 5 were written in collaboration with Derrick G. Watson and Elisabeth Blagrove.

List of publications:

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Abstract

Attention plays an integral role in healthy cognitive functioning, and failures of attention can lead to unfavourable and dangerous consequences. As such, comprehending the nature of attentional mechanisms is of fundamental theoretical and practical importance. One way in which humans can attentionally prioritise new information is through top-down inhibition of old distractors, known as the preview benefit (Watson & Humphreys, 1997). In the preview benefit, time is used to efficiently guide visual selection in space. Given that this ability is based on limited resources, its deployment in everyday life may be hindered by a multitude of factors. This thesis will explore the endogenous and exogenous factors that can facilitate or constrain the preview benefit, and determine its developmental trajectory. Understanding the nature of this mechanism (endogenous and exogenous factors) in adults can elucidate the contexts in which visual selection can efficiently filter old distractors. In turn, a developmental perspective can unravel the hidden aspects of this ability and inform when children are endowed to use temporal information for efficient attentional selection. Chapter 1 introduces the theoretical problems and topics of attentional research in adults and children. Chapter 2 addresses the question of endogenous control of top-down inhibition in time-based visual selection – when can top-down inhibition be controlled by the observer? Chapter 3 examines the exogenous influence of complex stimuli on time-based visual selection. Chapters 4 and 5 focus on the development of time-based visual selection for stationary and moving stimuli, respectively, in children aged 6 to 12 years. These chapters also examine the relative association of the efficiency of the preview benefit with the development of executive functions across different age-groups. Overall, the findings suggest that there exist remarkable endogenous and exogenous constraints in how time guides selection. This may account for why in certain contexts, attentional selection can fail to be efficient. Moreover, time-based visual selection shows striking quantitative and qualitative changes over developmental time, and most importantly, children have a long developmental trajectory in learning to ignore moving items. Unlike children, adults' time-based visual selection is coupled with individual differences in executive functions, highlighting an acquired functional connection. The findings are discussed in terms of their theoretical implications for time-based visual selection, the development of children's attentional control for distractors, and impact routes for educational and clinical practice, and policy makers.

Chapter 1:

An Overview of Attentional Research

Attention is one of the pillars of human cognition. It is the most vital precursor of many cognitive processes, and without it, learning, awareness, memory, and action, would not be possible. Attentional research is therefore at the crux of revealing how the cognitive architecture is sustained at its lower and higher levels, and continually relevant for many applied domains such as mental health, prevention of human error, education, and development of artificial intelligence systems. Inherent to the concept of attention is a limited cognitive apparatus that confines the amount of information that can be extracted from the external world. Thus, there is a very competitive process taking place at early visual stages, which determines the necessity to prioritise and enhance what is relevant for current goals and safety. This is the primary task of *selective attention*. This chapter will describe theoretical models of selective attention, outline the key questions and topics in its areas of investigation, review the basic control mechanisms of selective attention, and provide insights of how these mechanisms develop in childhood. Although early attentional research investigated selection in auditory attention, subsequent research has focused mostly on selection in *visual* attention, thus the effects reviewed here will mostly be specific to the vision modality.

The origins of attentional research are closely tied to the observation of constraints in human information processing. This attentional ‘bottleneck’ was pointed out in Welford’s psychological refractory period (PRP) experiments in the 1950s (see also Craik, 1948; and Telford, 1931, for precursors of this concept). In these experiments, two stimuli were presented with different stimulus onset asynchrony (SOA), and reaction times to the second stimulus were longer if it was temporally close to the onset of the first stimulus (Welford, 1952). Welford argued that this is because processing of the first stimulus needed to be fully completed, before the next could commence. This work was one of the first experimental demonstrations of a largely limited perceptual apparatus. The bottleneck concept, although simple, was vital in emphasising why selection is needed, and in prompting further research over the following decades to determine when and how selection occurs.

When Does Selective Attention Occur? Early vs. Late selection

Some of the first experiments in selective attention were devoted to the question of when selection occurs in information processing, and were inspired by the ‘cocktail party effect’- a phenomenon where one is able to listen to one among numerous surrounding voices. The first influential model of the locus of attentional selection was Broadbent’s (1958) *filter model*, which advocated that selection happens early in information processing. Initial experiments were based on dichotic listening tasks, which consisted of presenting a message binaurally while instructing the participants to attend to only one ear. The results revealed a strong dominance of physical features in determining selection, such as tone or spatial location (Broadbent, 1952a, 1952b). The unattended channel appeared to transmit no information; subjects failed to notice a change in language or reverse speech in the ignored ear (Cherry, 1953). Similar findings of early selection were observed in the visual domain. When briefly (15-500 ms) presented with multiple stimuli, participants could only report the identity of about four items, although being fully aware of seeing a greater number of items (Sperling, 1960). In the partial report condition (Experiment 3), participants had to recall part of the presented display after 50 ms, and the specific subset of stimuli that was required to be recalled was indicated by a tone of high, medium, or low frequency. This experiment showed that in this condition, the capacity of ‘immediate memory’ increased to about 9 items, indicating that more information is accessible at very brief intervals than in comparison to the whole report condition. However, the accuracy of partial reports decreased if the reporting time was extended (Experiment 4), which was not the case with whole reports (Experiment 7). This ‘immediate memory’ was later coined as *iconic memory* (Neisser, 1967), which proved to be too swift to interrogate beyond the time frame of a few hundred milliseconds.

Early selection accounts have been confronted by findings demonstrating that some information from the ignored channel could still break through (e.g., Moray, 1959; Treisman, 1960; Grey & Wedderburn, 1960). In Treisman’s (1960) shadowing task, a passage was presented to an ‘attended’ and ‘ignored’ ear, but in some conditions the narrative was swapped between the ears. Participants followed the words from the unattended channel if the context was consistent with the narrative, and were oblivious that the messages were presented in different channels, showing that both channels were attended. In addition to Broadbent’s model, Treisman (1964) proposed the *attenuated filter* model, suggesting that the early filter attenuates rather than discards information, which is then evaluated by its semantic content and threshold value in order to determine what is subsequently processed.

Such findings also led to the development of *late selection* models, which propose that all is perceived, but selected at the response stage, by cross-referencing the input to representations in long-term memory (Deutsch & Deutsch, 1963; Norman, 1968).

Johnston and Heinz (1978) outlined that the demands of the task were important in determining when selection occurs – the multimode theory of attention. They proposed that attention involves both early and late modes, but that some tasks required early selection (e.g., target differing from non-target words by voice quality – sensory cues) whilst other require late selection (e.g., target differing from non-target by meaning – semantic cues). A divided-attention task served to measure how much capacity was left during the early and late mode tasks. The results showed that late modes consume more resources, evidenced by an increase of reaction times on the secondary task. Late modes are likely to include processing of more non-target information (Experiment 5), thus requiring greater capacity for target selection.

Perceptual processing as a determinant of resource capacity for early or late selection was revisited in the *attentional load theory* (Lavie, 1995). The attentional load theory aims to offer a compromise between early and late accounts (but see Tsal & Benoni, 2010; Benoni & Tsal, 2013; Eltiti, Wallace, & Fox, 2005). According to Lavie (1995), perceptual load determines when selection takes place. If the task at hand is easy, the perceptual apparatus absorbs the maximum information available, allowing for distractors to be processed. This results in selection occurring at the response stage. In a difficult, perceptually demanding task, resources are largely consumed, leaving the distractors unattended and allowing for early selection to occur.

Some formal models of attention also attempt to resolve the early and late selection debate, such as the Theory of Visual Attention (TVA; Bundesen, 1990). The TVA is a unified theory of perception and selection which assumes that if an object is detected in the visual field, it is also selected at the same time. According to the TVA, attention occurs via two simultaneous processes: filtering and categorising. During the first stage, perceptual features (such as shape, colour, or location) of the objects present in the visual field are represented and weighted. The second stage represents selection, in which these features are categorised and encoded in visual short-term memory (VSTM). A common parameter links these two processes and represents the extent to which an object falls within a certain category. These processes occur in a race, where the first object to finish both stages wins the race and is hence the one that is selected.

How is Attention Allocated? Space-Based and Object-Based Attention

Another embroiling debate in attentional research has concerned the question of what is selected – an area in space, or discrete objects? In space-based theories, the ‘attentional spotlight’ illustrates how attention is allocated. Similarly to a beam of light, attention is zoomed in to a particular region in space, and what is illuminated constitutes the content of selection (LaBerge, 1983; Eriksen & Eriksen, 1974; Eriksen & St James, 1986; Treisman & Gelade, 1980). This mental spotlight can vary in size (LaBerge, 1983) and shape – the gradient theory (LaBerge & Brown, 1989. For instance, LaBerge (1983) asked subjects to categorize either 5-letter words or the middle letter of 5-letter words or non-words. A probe task required participants to respond to a number 7 target at one of the possible letter positions, presented either at the onset of processing (Experiment 1) or 500 ms after (Experiment 2). The results indicated that reaction times differed in whether the task required categorizing a word or a letter – slopes were flat for words, and V-shaped for letters. The latter result was because the spotlight was restricted to processing only the middle letter and not the surrounding letters, suggesting that it can be adjusted in size.

Strong support for space-based accounts comes from Posner’s cueing experiments (e.g., Posner, 1980; Posner & Cohen, 1984). In the cueing paradigm, participants are asked to respond to a target stimulus, after being cued peripherally (e.g., a flashing light or square outline) or centrally (e.g., an arrow). These cues can be valid or invalid with regards to the location of the target, and the trials differ in whether they contain a valid or an invalid cue. Valid cues point towards (if the cue is an arrow) or flash at (if the cue is a square outline) the location where the target will be subsequently displayed. Invalid cues point or flash away from the subsequent target location. Typically, a ratio of 80% valid and 20% invalid trials were used in the early studies (Posner, 1980), reinforcing the participant to follow the cues. There are also neutral trials which are not informative of the target location. Comparing these three types of cues shows that valid cues facilitate, while invalid cues hinder the detection of the target, indicating that attention can be drawn to a specific spatial location.

An opposing account is that of object-based attention. Its proponents argue that units of selection are objects, rather than regions in space (Duncan, 1984; Kanwisher & Driver, 1992). One of the exemplars that demonstrates object-based deployment of attention is an adaptation of Posner’s cueing paradigm, in which cues were either placed on the object containing a target, or on an equidistant irrelevant object (Egly, Driver, & Rafal, 1994). Cues were detected more rapidly when falling within the target object than outside of it, indicating an advantage of processing information within the attended object.

There are also formal models that aim to reconcile space-based and object-based attentional accounts. In particular, Logan’s (1996) CODE theory of visual attention (CTVA) provides a computational model that is able to simulate data fitting both accounts. As Logan describes it, CODE is a ‘marriage’ between the Contour Detector (CODE) theory of perceptual grouping by proximity (Compton & Logan, 1993; van Oeffelen & Vos, 1982; 1983) and theory of visual attention (TVA; Bundesen, 1990). Logan (1996) considers that a theory of visual attention must answer five questions: 1) how is space represented? 2) what is an object? 3) what determines the shape of the spotlight? 4) how does selection occur within attention, 5) how does selection occur between objects? CTVA proposes that space can be presented in a bottom-up CODE surface (representing either locations of the items of objects and groups of objects) or top-down (by setting thresholds that result in perceptual groups). The representation created from bottom-up processes are dependent on the proximity of the items in a display. These locations are represented by their distributions, which are summed up by bottom-up processes to create the CODE surface. An object is a perceptual group that is defined by a threshold set by the top-down mechanism. In answering the spotlight question, Logan suggests that it is any region that reaches an above-threshold level either by bottom-up perceptual input or by top-down settings. In order to explain selection within space, Logan incorporates the TVA, suggesting that top-down settings can adjust parameters to bias towards some categories rather than others. Similarly, selection within objects requires top-down language processes. Although the CTVA can simulate a great deal of experimental data such as a variety of visual search experiments, such Eriksen flankers (Eriksen & Eriksen, 1974), illusory conjunctions, etc., its limitations lie in explaining motion, or grouping by similarity, common fate, and other Gestalt principles.

To conclude the space-based and object-based debate, in a chapter reviewing visual attention research, Chun and Wolfe (2001) consider that although attention can undoubtedly be attracted to objects, spatial locations are relevant and maintain a valuable role in attentional research.

The Contemporary Position: Attentional Networks

The early vs. late selection and object vs. space-based attention debates were formed around the notion of attention as a uniform concept. A contemporary position is that attention forms a network of different functions (Posner & Dehaene, 1994). A neurophysiological substrate for this model has been found in different brain regions (Petersen & Posner, 2012; Fan, McCandiss, Sonmmer, Raz, & Posner, 2002; Posner & Petersen, 1990). The overall model posits that an attentional network consists of three related, but separable functions: alerting (arousal that prepares a response to a stimulus-driven signal), spatial orienting (overt or covert target selection), and executive attention (top-down guidance towards priority goals). The Attentional Network Task (ANT; Fan et al., 2002) is used to test these three attentional functions in children and adults. In the ANT, the participant’s task is to determine the direction of a centrally presented leftward or rightward arrow by pressing a button indicating their position. This target is flanked by two arrows in either the same direction as the target (congruent condition), in the opposite direction (incongruent condition), or by lines (neutral condition). Typically RTs are fastest in the congruent condition and slowest in the incongruent condition. This task is based on the flanker task by Eriksen and Eriksen (1974), and is used to measure conflict resolution or executive attention. The efficiency of alerting and orienting are measured by taking RTs after presenting four types of cues: no cue, central cue (asterisk), double cue (two asterisks corresponding to the two possible target conditions), and a spatial cue (valid cues at the location of the target) prior to the flanker task. The central cue or warning signal measures alerting, while both alerting and orienting are measured with double and spatial cues. The efficiency measures of the attentional networks were found to have good reliability and are uncorrelated and statistically independent from each other.

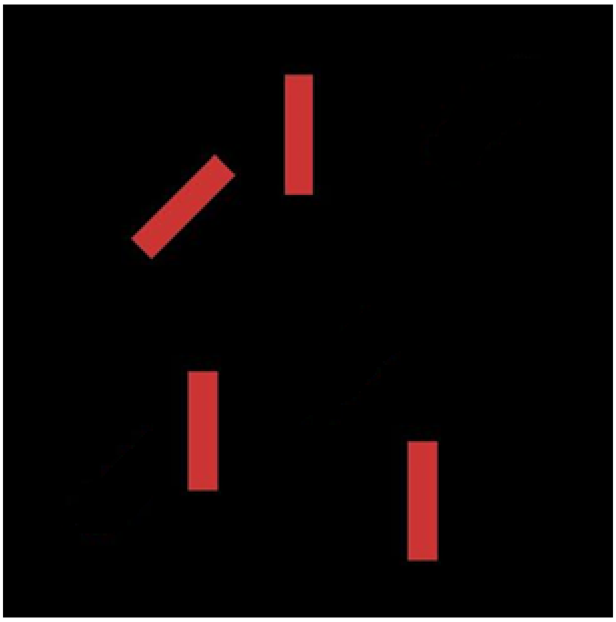
Visual Search: A Tool for Studying Selective Attention

The visual search task is an important tool for understanding selective attention. As the visual world rarely consists of isolated objects, attention often needs to be deployed to one amongst many existing objects. Thus, the visual search paradigm typically consists of presenting one target item among a number of distracting items. By varying the characteristics of the task, one can answer how knowledge, goals, strategies, as well as stimulus properties drive attentional processes, the ease with which attention operates in cluttered environments, and the various mechanisms that work together or independently to achieve this.

Visual search displays used in the lab are typically constructed of artificial stimuli such as letters, geometric shapes, or lines. However, they provide a good estimation of finding a designated object in the real world (Wolfe, 1998; but see Wolfe, Vo, Evans, & Greene, 2011, for a review of how attention is deployed in naturalistic scenes).

Figure 1 shows examples of search displays. Panel A depicts a single feature search display, in which the target is a red tilted line among red vertical distractors. Thus, the target differs from distractors in only one feature (orientation). Panel B depicts a conjunction display, in which the red tilted line is amongst green tilted and red vertical distractors. Here, the target is uniquely defined by a combination of two features. Search in this case takes more time, and grows slower with every added distractor, i.e., increasing display size. Typically, each search display remains visible until the participant makes a response. The response consists of indicating the presence or absence of the designated target by pressing one of two buttons or keys as quickly and accurately as possible. Both reaction times (RTs) and errors are recorded, and RTs are plotted as a function of display size to form search slopes. Figure 2 provides an illustration of search slopes for target-present and target absent single-feature (Panel A) and conjunction searches (Panel B). In single-feature search, RTs are not found to vary as a function of display size, while in conjunction search, RTs increase linearly with the increase in the number of distractors. In single feature search, slopes in target present and target absent trials show little difference, while in conjunction search, slopes for target absent trials are steeper and typically to a 2:1 ratio in comparison to target present slopes (Treisman & Gelade, 1980). In sum, these search functions reveal distinct patterns and variations in search efficiency depending on stimulus attributes and their heterogeneity (e.g., Treisman & Gelade, 1980; Duncan & Humphreys, 1989; Wolfe, 1998). The three theories briefly summarized below have provided accounts of why this might happen.

A) Single-feature search task (Target present)



B) Conjunction search task (Target present)

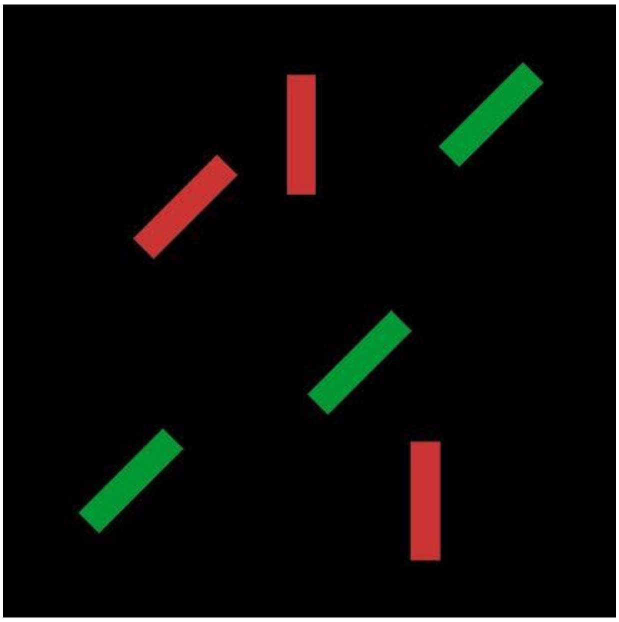
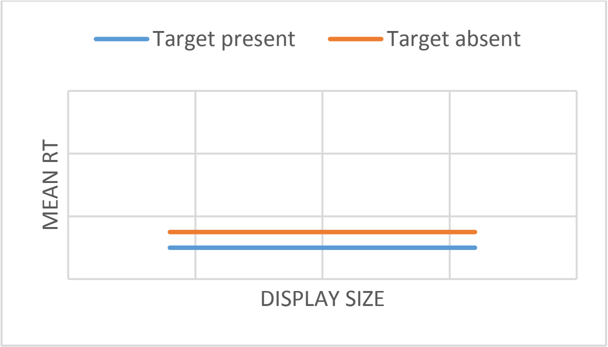


Figure 1. Illustrative examples of target-present single feature (Panel A) and conjunction (Panel B) search displays. The target is defined as a tilted red line.

A)



B)

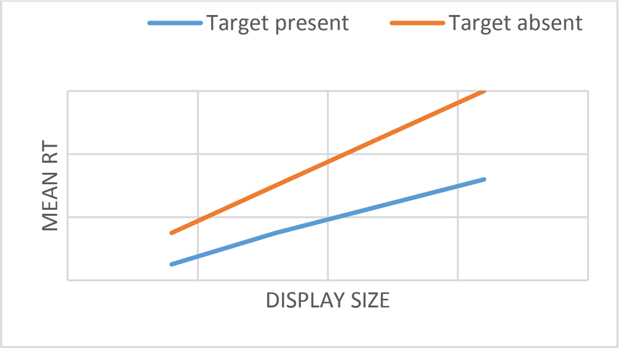


Figure 2. Examples of search slopes as a function of RT and display size for target present and target absent single-feature (Panel A) and conjunction (Panel B) trials, using hypothetical data.

Feature Integration Theory

The first, seminal model of object perception and visual attention, was the Feature Integration Theory (FIT; Treisman, 1988; Treisman & Gelade, 1980; Treisman & Sato, 1990). The initial model, developed by Treisman and Gelade (1980), proposed that sensory features, such as colour, orientation, or shape, are processed preattentively, in parallel, to form ‘maps’ of the feature locations.

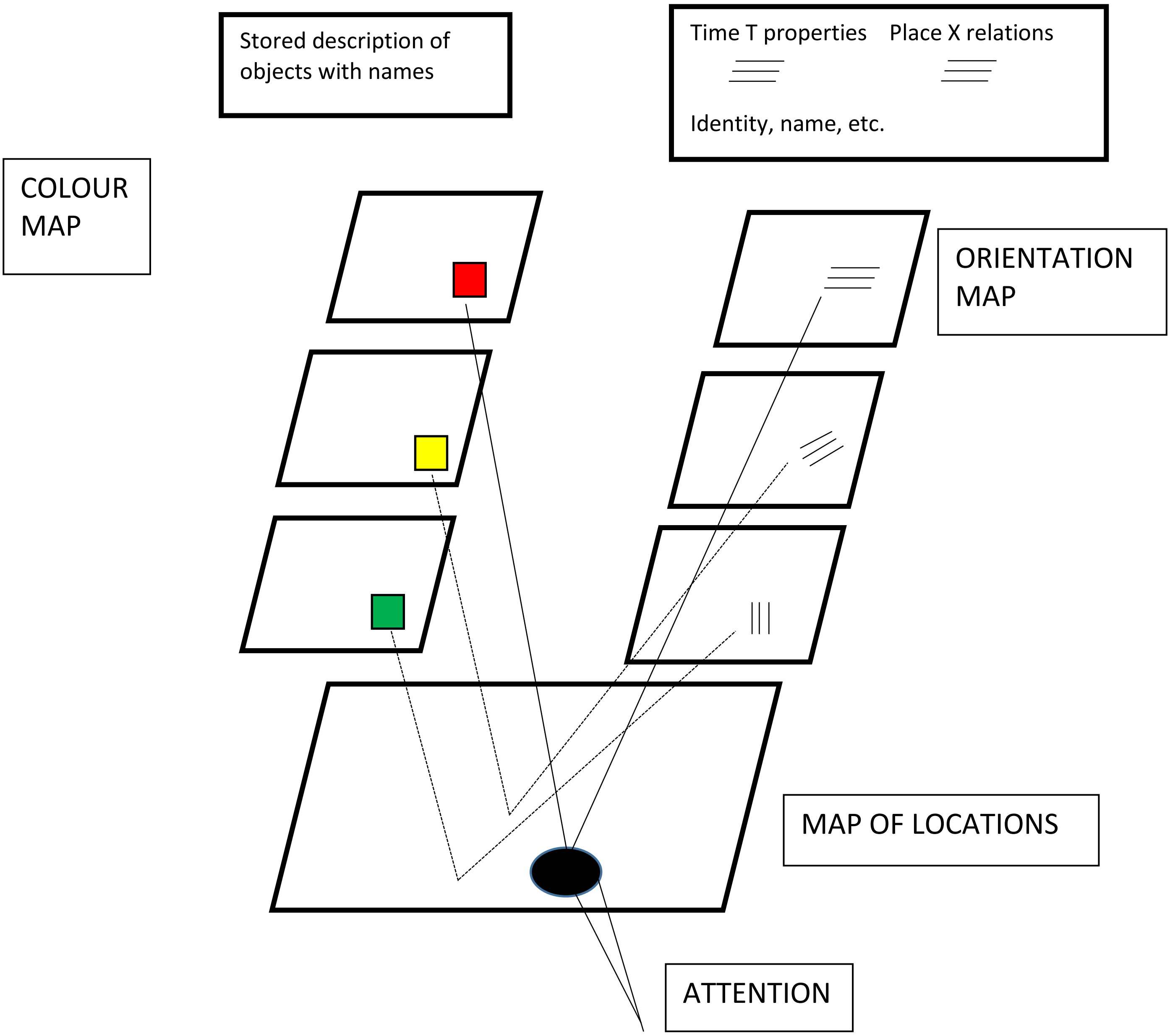


Figure 3. Treisman’s FIT model (from Treisman, 1988)

Conjunctions of features are perceived by using a ‘master map’ that codes feature locations, and attention is needed to glue individual features to form a representation of an object (see Figure 3). Thus, location information is not readily available and is formed in the second stage of the process, once attention is applied to a specific location to bind the features. This renders the FIT a space-based theory of attention. Nevertheless, if only a single feature discerns a target from distractors, no binding is required and the target can be detected at the level of feature maps, i.e., preattentively or in parallel. Since focal attention is not needed, this process is rapid, bottom-up, and does not require resources. Search is efficient, and does not vary as a function of display size. Conversely, if focal attention is needed to bind the features into an object representation, search is slow as it consumes resources, it is top-down, and moves serially from item to item, thus RTs increase linearly with a growing number of distractors. Thus, according to a strict reading of this early model, parallel and serial search are qualitatively different. This also explains the differing search slopes of target present and target absent trials. In single feature search, there is not much difference between target present and target absent trials. In conjunction search, search on target absent trials is about twice as slower than for target present trials. This is because it operates serially, requiring exhaustive inspection of each item before it can be determined that the target is not present. Figure 1a provides an example of a single-feature, preattentive search – the target pops out, resulting in rapid reaction times that do not vary as a function of display size. In contrast, visual search in 1b increases linearly with the number of distracting items, suggesting that search operates ‘serially’ on an item-to-item basis.

Attentional Engagement Theory

Duncan and Humphreys (1989, 1992) developed an alternative and more general theory that emphasizes the role of similarity between the target and distractors, and distractor heterogeneity in visual search. According to the Attentional Engagement theory, top-down control specifies the target-template, which increases the activation of certain object representations. Thus, the greater the similarity of the target template with the distractors, the more difficult it is for selection to control input into visual short term memory (VSTM). Similarly, grouping effects of similar distractors can ease their suppression, as activation loss in one distractor leads to activation loss in the remainder. As such, this theory presumes no qualitative difference between features and conjunction search, allowing for a continuous range of search slopes, and challenges the postulates of serial-parallel processing in the FIT.

Guided Search

Wolfe's Guided Search model (Wolfe, 1994) is rooted in the FIT, but proposes a continual, rather than dichotic division of parallel and serial processes. Search performance is described on the basis of its *efficiency* measured as a function of RTs and set size. Certain stimulus attributes (e.g., orientation, size, colour) are coded preattentively into feature maps and are used to guide search more or less efficiently towards the target and away from distractors. Top-down processes activate the relevance of certain features, and the activation peaks guide search to the likeliest locations to contain the target (see Figure 4).

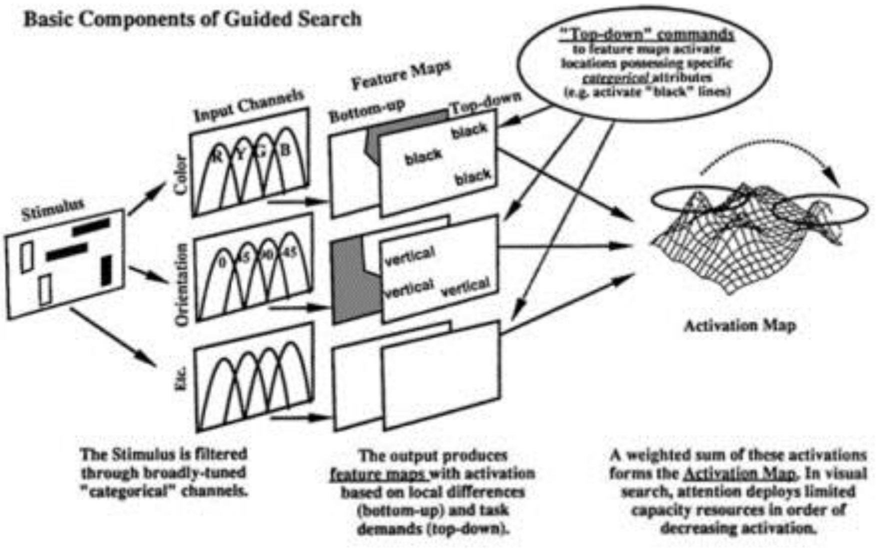


Figure 4. Wolfe's Guided Search 2.0 model (from Wolfe, 1989)

Some attributes guide attention better than others, e.g., colour, orientation, motion, and size (Wolfe & Horowitz, 2004). Therefore, some conjunction searches can be very efficient (0-10 ms/item) – such as an X target amongst Os, whilst others result in slow, inefficient (< 20 ms/item) search times, such as search for an S target among Ƨ distractors (Wolfe, 1998). The fact that some single feature searches can be inefficient while some conjunction searches can be inefficient, demonstrates that the serial/parallel categories do not hold. Similarly, when there is more information provided such as in the case of triple conjunctions, search becomes more efficient than in the case of two conjunctions (Wolfe, Cave, & Franzel, 1989), – which is consistent with Guided search but not with FIT. Search for triple conjunctions (e.g., colour × size × form) is very efficient, almost parallel and does not depend on display size (Quinlan & Humphreys, 1987; Wolfe et al., 1989). To test the efficiency of search in a triple conjunction task, Wolfe et al. (1989) compared four conditions: two triple conjunction tasks in which the target differed in one dimension from the distractors, one triple conjunction tasks in which the target differed in two dimensions from the distractors, and a simple conjunction task. The results showed that search for triple conjunctions differing in two dimensions produced efficient, 4-5 ms/item search slopes, whereas the triple conjunction task in which the target differed in two dimensions and the simple conjunction task had less efficient, 7-10 ms/item search slopes and did not differ statistically from each other. According to the FIT, all triple conjunctions should produce inefficient search because more features need to be bound together, thus requiring the commitment of substantial resources. The results were in line with the Guided search model, which predicts that three features are more efficient in guiding search than two features, as the distractors differ from the target in two dimensions and provide more information for evaluation at the preattentive level.

Other Theories

It is worth mentioning that there are other approaches to understanding visual search, such as connectionist or formal mathematical models. Connectionist models are composed of networks of nodes that are mutually connected with excitatory or inhibitory connections – mimicking neural networks of the brain. These models are able to ‘learn’ which output to produce based on certain inputs, by adjusting the strength of their connections. Examples of connectionist models of visual search are SeLective Attention Model (SLAM; Phaf, van der Heijden, & Hudson, 1990) and SERR (Search via Recursive Rejection; Humphreys & Müller, 1993). Formal mathematical models aim to provide a mathematical solution which best describes or simulates the empirical data. Some well-known examples of formal models of attention are Bundesen’s Theory of Visual Attention (TVA; 1990) and Logan’s COntour DEtector theory (CODE; Logan, 1996).

Attentional Control: Top-Down vs. Bottom-Up

Posner (1980) proposed that attention can be deployed in two ways: endogenously (arising from the observer’s goals, knowledge, and expectations), and exogenously (automatically driven by the stimulus properties). This terminology can also be translated into top-down, and bottom-up attention (Yantis, 1998). From the visual search models described above, it is evident that all predict a role for both top-down and bottom-up factors when deploying attention.

The biased competition theory (Desimone & Duncan, 1995) is a neural theory of visual attention that describes attention as a highly competitive process in which bottom-up and top-down processes actively determine what is finally selected. Thus, this theory advocates that attention is an emergent property of the competition influenced by these processes, rather than a spotlight that scans the visual field.

According to the biased competition theory, a representation of a single object will be at the expense of another due to a limited processing capacity. For instance, single-cell physiology studies examined neural responses to a single visual stimulus in comparison to two stimuli presented simultaneously in the receptive field. Typically, responses of the two stimuli are smaller than the sum of the responses by individual stimuli, but are rather a weighted average of the individual responses (e.g., Snowden, Treue, Erickson & Andersen, 1991; Rolls & Tovee, 1995). To resolve this competition and filter out irrelevant items, bottom-up and top-down mechanisms act to enhance stimulus representations according to their properties and/or their relevance to the task.

Bottom-up signals bias competition by separating figures from their background or by perceptual grouping principles. Desimone and Duncan (1995) suggest that in addition to bias occurring in the spatial domain, it also occurs at the temporal domain. They consider stimulus novelty to be another important bottom-up factor. Evidence from animal subjects showed that novel stimuli and stimuli that have not been recently seen will produce stronger neural signals and gain greater competitive advantage in the visual cortex (e.g., Li et al., 1993). Similar results have been obtained in human ERP and imaging studies (Begleiter, Porjesz, & Wang, 1993; Squire et al., 1992).

Top-down signals bias competition by introducing signals from the fronto-parietal cortex to the visual cortex that match the internal representation to the object. This can be done by enhancing the location or the feature of the item.

An example for top-down signals enhancing locations comes from Moran and Desimone’s (1985) study with monkeys. When performing a discrimination task, the target location was indicated to the monkey by cues at the start of a trial. When a cue is provided, the neuronal response was determined primarily by the target, indicating little suppressive response from the non-target stimulus.

Desimone and Duncan (1995) point out that selection based on features takes place when the location of the object is not known in advance, and uses memory to hold the template of the sought-after object. Chelazzi, Miller, Duncan and Desimone (1993) presented monkeys with a ‘good’ cue that elicited a strong neural response or a ‘bad’ cue that elicited a poor neural response. After a delay, both cues were presented simultaneously at an extra-foveal location, and the animal had to saccade to the target stimulus that matched the cue. When the target was the poor stimulus, the response to the good distractor stimulus was suppressed and this response was recorded at about 100 ms before the onset of the saccade. This activation indicated a top-down bias.

In the following section, some basic mechanisms of bottom-up and top-down attentional control will be described. The overview of these mechanisms will not be exhaustive, but will provide a framework that is pertinent for the subsequent chapters in this thesis. Importantly, both types of control will include examples of mechanisms that provide *excitation* for target features or locations, as well as *inhibition* of distractors.

Bottom-up Mechanisms

Bottom-up mechanisms can automatically and rapidly draw attention. Below, some relevant bottom-up attentional mechanisms will be briefly outlined: capture by abrupt luminance changes, singleton capture, and inhibition of return (IOR).

Attentional capture by abrupt visual onsets. Yantis and Jonides (1984) developed a paradigm which showed that targets that are defined by sudden luminance changes capture attention. In Experiment 1, premasks in the shape of a figure 8 were presented for 1000 ms, after which there was a gradual offset of the irrelevant segments to form letters. At the end of this offset, an item (target or distractor) abruptly appeared at a previously unoccupied location. Thus, the target could appear either by either abrupt onset or gradual camouflage removal. The display size consisted of either two or four items. The results showed that targets that abruptly occurred at a previously blank location produced parallel search slopes indicating that attention was automatically attracted to the new location. In comparison, RTs for targets that occurred through gradual camouflage removal from a placeholder, varied as a function of display size. Further experiments ruled out that this was due to perceptual factors, or whether the irrelevant segments were removed gradually or abruptly. The automatic capture by abrupt onsets was due to the appearance of a new object, rather than luminance increments (Yantis & Hillstrom, 1994), which could not be easily ignored even when subjects were instructed to do so (Remington, Johnston, & Yantis, 1992). However, the capacity of abrupt onset capture is limited to four novel items (Yantis & Johnson, 1990; Yantis & Jones, 1991).

Attentional capture by perceptually salient singletons. It is not only luminance onsets that are capable of drawing attention automatically – a perceptually salient singleton also attracts attention as a target, as well as a distractor, and it was proposed that top-down control cannot attenuate this (Theeuwes, 1991, 1992, 1994). Similar results were discovered earlier by Pashler (1988), who demonstrated that when searching for a target defined by orientation, an irrelevant colour singleton will slow response times. There is, however, evidence that top-down control can override attentional capture in certain contexts (Bacon & Egeth, 1994; Folk & Anderson, 2010; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994), and this will be discussed in the subsequent section overviewing top-down mechanisms.

Inhibition of return (IOR). Inhibition of return (IOR) is a phenomenon where attention is first automatically drawn to a location of a peripheral cue (light flash) for 100-300 ms, and subsequently withdrawn from the same location, so that target detection is impaired if its onset occurs 300 ms after the cue (Posner & Cohen, 1984). This inhibitory aftereffect is only found with peripheral, exogenous cues, and not with endogenous, central cues. Rafal, Calabresi, Brennan, and Scioloto, (1989) suggested that if a signal in the visual periphery leads to oculomotor priming that results in IOR, then it must be possible to generate IOR when preparing an eye movement even when it is subsequently cancelled (Experiment 4). They introduced three conditions: an eyes-fixed condition, saccade execution condition, and a saccade- preparation condition. On saccade preparation trials, participants were cued on some trials to cancel the preparation. The results indicated that IOR was found with endogenous cues in all conditions apart from the eyes-fixed condition. Based on these results, Rafal et al. (1989) argued that IOR is not a result of sensory processes as hypothesized by Posner and Cohen (1984), but is a mechanism of attention. These results suggested that oculomotor programming has an integral role in IOR. However, recent findings by Chica, Klein, Rafal, and Hopfinger (2010) failed to replicate the findings of Rafal et al. (1989) across five experiments, and concluded that endogenous saccade preparation does not generate IOR.

A study by Maylor and Hockey (1985) was informative regarding some of the basic IOR's characteristics. Namely, they found that IOR lasts for about a second, that it is coded in the environment rather than in the retina, and that it decreases with the distance from the cued location. Furthermore, IOR was found to play a role in visual search (Klein, 1988). Klein (1988) used a probe-dot procedure following a presentation of a parallel or serial search display. He found that detection was longer at previously occupied locations in serial, but not parallel search (see also Müller & von Mühlenen, 2000; Takeda & Yagi, 2000, for findings showing that IOR occurs in search tasks only if the stimuli remain visible after the inhibitory tagging). The finding that IOR is observed in serial search only, confirmed Posner and Cohen's (1984) prediction that IOR prevents attention from returning to a previously inspected location. In addition, Klein (1988) proposed an extension of IOR's functional role: a facilitator of foraging behaviour.

Although stemming from space-based cueing paradigms, IOR can also be object-based. Tipper, Driver, and Weaver (1991) showed that when a cued square moved in an array of other rotating squares, response to probes was found to be slower on the cued square rather than on the uncued square despite the change of location. Jordan and Tipper (1999) further demonstrated that IOR can spread from cued to uncued locations within an object (Jordan & Tipper, 1999).

Top-Down Mechanisms

Top-down or endogenous mechanisms are those under volitional control, such as interpreting a central cue to orient attention towards the target (e.g., Posner, 1980). In this section, some examples of how top-down, goal-oriented and strategic behaviour is applied to enhance target selection will be described. As we will see, top-down control can be used to override automatic capture (e.g., Bacon & Egeth, 1994; Folk et al., 1992), as well as to reduce interference from irrelevant distractors, such as negative priming (Tipper, 1985), and visual marking (Watson & Humphreys, 1997).

Overcoming automatic capture via top-down control. A number of findings suggest an interactive and moderating role of top-down control on the contents of attentional capture. One example is Bacon and Egeth's (1994) study, in which they demonstrated that if participants adopt a search strategy for a singleton, it will result in the singleton capturing attention. In contrast, if a feature-based strategy is recruited, a target containing a unique shape or colour will lead to attentional capture (but see Theeuwes, 2004). If no specific search strategy is adopted, participants show a preference for the singleton search strategy. Leber and Egeth (2006) extended this finding by showing that training in either one of these strategies can also influence what is detected. Taken together, these findings suggested that automatic capture is not completely bottom-based, as was initially proposed. A further demonstration of the influence of top-down control over bottom-up processes comes from research on contingent involuntary attentional orienting (Folk & Anderson, 2010; Folk et al., 1992; Folk et al., 1994). In the first study of contingent involuntary attentional orienting, Folk et al. (1992) showed that whether peripheral cues attracted attention depended on how the target was defined; if defined differently than the cue (e.g., abrupt onset vs. colour discontinuity), than the invalid cue did not produce search costs. Attentional capture was therefore ‘tuned’ by internal top-down settings.

Negative priming. Negative priming is a paradigm that can be used to study inhibitory effects for distractors. In this paradigm, suppression occurs when subjects respond to a target that was held as a distractor on a preceding trial (Tipper, 1985). Negative priming can occur with mutual priming of pictures and words, indicating its formation at higher semantic and representational levels, and as such being of a top-down origin (Tipper & Driver, 1988). The distractor inhibition model has been the first and most dominant account of negative priming, proposing that it is an effect of residual inhibition in selective attention (Tipper, 1985). However, further evidence showed that negative priming can occur over extended periods of time (DeSchepper & Treisman, 1996; Grison, Tipper, & Hewitt, 2005), suggesting that memory retrieval might be implicated in the effect as well. This generated support for models that include a role for memory retrieval, ranging from those that propose an exclusive role for episodic memory retrieval (Neill, Valdes, Terry, Gorfein, 1992; Mayr & Buchner, 2007), as well as those that hypothesize the role of both attention and memory retrieval, such as the Houghton-Tipper model (Houghton & Tipper, 1994), or temporal discrimination between the prime and the probe (Milliken, Joordens, Merikle, Seiffert, 1998). In addition, there is also the featural mismatching model which suggests that negative priming does not occur as a result of distractor inhibition, but is caused by a mismatch of symbol identities and their subsequent locations (Park & Kanwisher, 1994). In an extensive overview of each of the possible accounts of negative priming, Tipper (2001) reasons that although memory retrieval may be involved in negative priming, there is no unambiguous evidence that would discount the role of attentional inhibition. Rather, the effect is likely to be constructed by both encoding and retrieval stages (Tipper, 2001).

Time-based visual selection. The use of inhibition in attention as a means of filtering distractors is elegantly evidenced in time-based visual selection (Watson & Humphreys, 1997). Time-based selection is studied via the *preview search* task (Watson & Humphreys, 1997). In this task, distractors in visual search are separated in time, with one set of distractors (e.g., green Hs) previewed before another set of distractors (e.g., blue As) containing the target (e.g., a blue letter H). As the target is only ever present in the second set of items, the first set of items is always irrelevant (see Figure 5 for an example of a preview search trial).

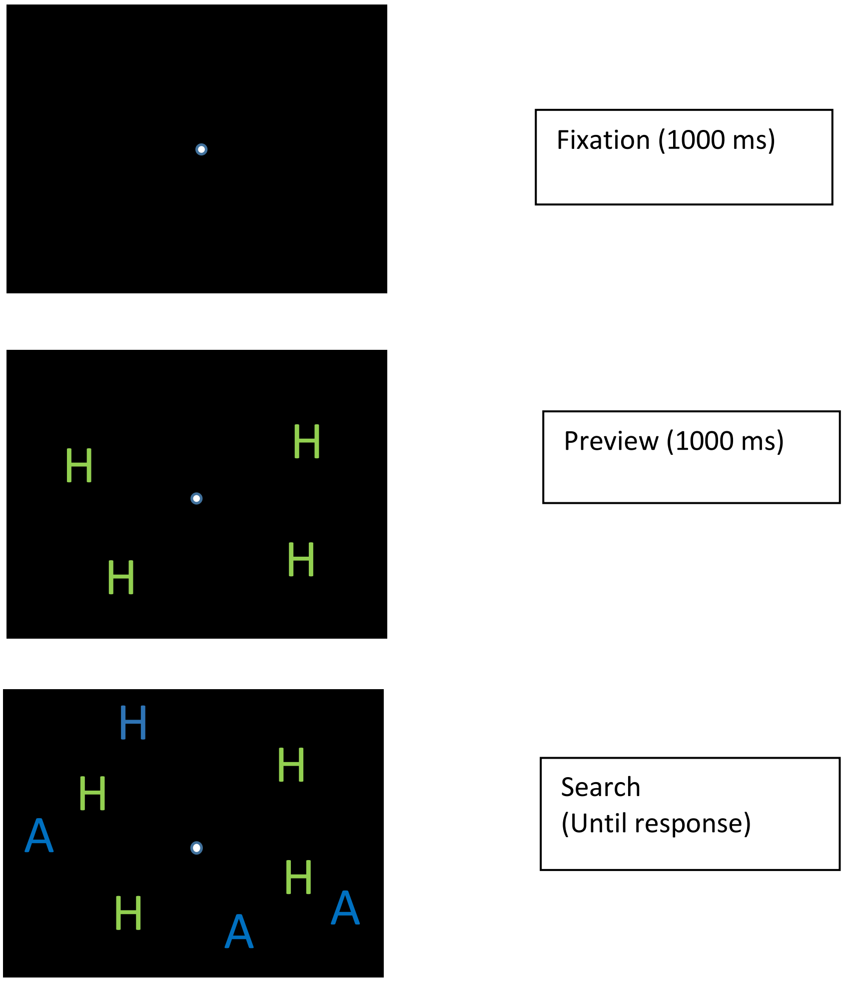


Figure 5. An example of a preview search trial

Search efficiency in *preview search* is often compared to a *full-element baseline (*FEB) task in which all the display items are presented simultaneously. Search in the preview task is typically found to be more efficient, indicating a preview benefit. Moreover, preview search is often equally efficient as a *half-element baseline (*HEB), which consists of the second set of items in the preview condition. If the preview and HEB do not differ in efficiency, this indicates that only the second set of items had been searched. Watson and Humphreys (1997) have proposed that the preview benefit is driven by a mechanism they called *visual marking*, which operates on the basis of top-down inhibition. The role of visual marking as a novel mechanism has been tested by ruling out existing inhibitory and other accounts, such as inhibition of return, negative priming, change blindness, inattentional blindness, and those based on attentional blink phenomena (Watson and Humphreys, 1997; Watson, Humphreys, & Olivers 2003). These arguments will be outlined briefly below.

Visual marking vs. IOR. As described earlier, IOR is a passive mechanism that prevents attention and eye movements from visiting an exogenously cued location after approximately 300 ms (Klein, 1988; Posner & Cohen, 1980). Old items in preview search are presented for 1000 ms, which coincides with the time frame allowing for IOR to occur. To test the IOR account, Watson and Humphreys (1997) conducted an experiment (Experiment 6) where old items were initially displayed for 750 ms, then disappeared for 250 ms, after which they reappeared together with the second set of items. If IOR was the mechanism behind preview benefit, prioritization of new items should occur, as the offset of items in IOR does not impair it (Terry, Valdes, & Neill, 1994; Tipper, Weaver, & Houghton, 1994; but see Müller & von Mühlenen, 2000; Takeda & Yagi, 2000). Instead, the preview benefit was abolished, which Watson and Humphreys (1997) considered as discounting for the involvement of IOR. Olivers, Humphreys, Heinke, and Cooper (2002) additionally tested the IOR account by conducting a double search task, where preview items had to be searched for a target, after which the second set of items was presented. Recall that IOR is found to be more effective in serial than in parallel search (Klein, 1998; Müller & von Mühlenen, 2000), thus searching the first set of items should be sufficient to produce a stronger preview benefit in a double search task. Instead, a double search task reduced the preview benefit, ruling out the IOR account.

Visual marking vs. negative priming. Negative priming is another possibility that could account for the preview benefit and the preview benefit might be driven by inhibition of feature-maps (cf. Treisman, 1988). To test this possibility, Watson and Humphreys (1997) manipulated the number of distractors (green H's) in the old and the new items (Experiment 7) in stationary displays (i.e., there were no moving items). There was always an equal number of green H's, but they were unequally distributed between the old and new items (1, 4, or 7 items in the old and 7, 4, 1 in the new, and vice versa). If negative priming was responsible for the preview benefit, we should expect the items in the preview display to act as a prime, and all subsequently presented distractors to be inhibited on the basis of sharing identity with the prime, resulting in an equally efficient preview benefit regardless of the number of the green Hs in the second set of items. Similarly, if it was a result of inhibition of feature maps, it should also spread onto the newly arriving green Hs. Instead, the preview search became less efficient with more distractors, indicating that neither negative priming nor feature-map inhibition could account for the preview benefit. More recent work has however, shown that feature based inhibition can play a role for inhibiting stationary stimuli in some situations. Specifically, the colour-carryover paradigm has provided some results suggesting that residual colour-based inhibition can carry-over to the new items (Braithwaite, Humphreys, & Hodsoll, 2003, 2004).

Visual marking vs. change blindness. Change blindness is a phenomenon where a substantial change in a visual scene is not noticed by the observer. Typically, change blindness is investigated with the flicker paradigm, in which an initial and modified image alternate with a blank screen presented in between them, until the subjects report a change in the second image (Rensink, O’Regan, & Clark, 1997). Although most changes are reported, it takes a long time to detect them, even when they are substantial. This suggests that motion signals that usually accompany change are crucial in drawing attention to the changed location or object. If these location specific motion signals do not accompany the change due to the flicker in the change blindness paradigm, it takes a longer time for attention to be drawn to the critical location, resulting in change blindness (Simons & Rensink, 2005). Watson et al. (2003) suggested that the template representation of old items by the visual marking mechanisms may be similar to that of the nexus. A nexus is a single structure where visual information about an object is collected. It is connected to lower-level visual structures which pool specific information about the object, such as shape and colour and encode perceptual changes (Rensink, 2000). However, the difference between change blindness and time-based visual selection is that selection in the preview benefit is biased away from old items, whereas in change blindness, old information needs to be re-inspected to detect the relevant change. Another critical point can be added to Watson et al.’s (2003) argument: in preview search, selection of new items is enhanced, contrary to change blindness where detection of the novel item is slowed down. Therefore, these two phenomena act in an opposite manner.

Visual marking vs. inattentional blindness. An unexpected stimulus can fail to be noticed if observers are fully engaged in another attentional task – inattentional blindness (Rock, Linnett, Grant, & Mack, 1992). Watson et al. (2003) note that there might be similarities between visual marking and inattentional blindness. Nevertheless, I suggest that there still are large distinctions between inattentional blindness and visual marking. First, similar to change blindness, the stimulus that fails to be detected in inattentional blindness is new, rather than old, while in visual marking new items gain priority. Second, inattentional blindness assumes failure to process the unexpected stimulation, while in preview search, old items are actively processed in order to be rejected. This is indicated by findings where any substantial change to the old items, such as shape or meaning (e.g., Watson & Humphreys, 1997, 2002; Osugi, Kumada, & Kawahara, 2009), cause an elimination of the preview benefit. In addition, introducing longer time to encode the old items enables or improves the preview benefit (Watson & Humphreys, 1997, 1998; Braithwaite, Hulleman, Watson, & Humphreys, 2006). This suggests that inattentional blindness does not underlie the preview benefit.

Visual marking vs. the attentional blink. In the attentional blink paradigm (Raymond, Shapiro, & Arnell, 1992; Shapiro, Raymond, & Arnell, 1997), stimuli are presented in a rapid serial visual presentation (RSVP) of letters or numbers, at a rate of 6 to 20 items/second. Raymond et al. (1992) asked participants to identify a target (e.g., a white letter) among black distractor letters in the RSVP stream, after which they had to identify a second target (e.g., Letter X) occurring within the stream. The second target could occur from 100 to 800 ms after the first target. Detection of the second target was impaired for up to 400-500 ms after detecting the first target – the attentional blink.

There are several accounts that may explain the attentional blink phenomenon. I will outline the three most prominent theories of the attentional blink: the filter-based account (Raymond et al., 1992), the interference account (Shapiro, Raymond, & Arnell, 1994), and the two-stage processing account (Chun & Potter, 1995). Similarly to the debate of early or late selection in theories of attention, these accounts propose, respectively, that the attentional blink is a result of early, late, or a compromise between early and late processes.

The filter-based account suggests that the attentional blink is a result of a limited capacity attentional mechanism resolving perceptual confusion between the two targets (Raymond et al., 1992). The first target is detected preattentively based on its perceptual features after which identification processes in VSTM are initiated. If the second target is presented before the identification process of the first target is completed, its perceptual features are processed and compete for identification in VSTM. This lasts for approximately 300 ms until the correct colour is matched to the correct identity. Raymond et al (1992) suggest that a greater similarity between the two targets will result in greater uncertainty (Duncan & Humphreys, 1989). This uncertainty initiates temporary suppressive processes to eliminate the confusion, creating the attentional blink. Therefore, Raymond et al. (1992) propose that the extent of suppression should depend on the temporal interval between the targets, as well as on the extent of similarity between the targets, and target 2 and distractors.

Follow-up experiments suggested that the interference account may provide a better fit to the attentional blink effect than the inhibition account (Shapiro et al., 1994). They found that the attentional blink occurs in an all-or-none fashion even when the targets are very dissimilar, suggesting that the attentional blink is not a function of perceptual similarity between the targets. However, when there was no ‘object’ during the interval, the attentional blink did not occur. Instead, the attentional blink was highly dependent on the first item presented after the target, as well as on the number of distractors in the series. Shapiro et al. (1994) suggested that the cause of the attentional blink is due to retrieval difficulties due to the competition of target and non-target items in VSTM. This account is thus a late account of the attentional blink in comparison to Raymond et al.’s (1992) early account.

In the Two-Stage Processing Theory, Chun & Potter (1995) proposed that processing items in a RSVP requires two stages. The first stage involves rapidly detecting the targets based on their perceptual features. If there is an item being presented before target 1 in the first stage has been consolidated, this creates a bottleneck. This bottleneck delays the onset of the second stage which involves late capacity-limited conscious retention of the target. Thus, for the recognition of target 2 in the second stage, the first stage must be completed.

A computational model that has been developed around the two-stage processing theory is Bowman and Wyble’s (2007) ST^2 (Simultaneous-Type-Serial-Token) model. This connectionist model uses the types-tokens account (Kanwisher, 1987; Mozer, 1989) to describe how items are encoded in VSTM. Types are all perceptual properties of the item, while tokens are the episodic properties (such as identity and temporal order of the stimuli) that are associated to the item on a particular occasion. Thus, types and tokens become associated when an item is encoded into VSTM. In the first stage of the ST^2 model, target features are input in the lowers layers of the model. In the second stage, an item is ‘tokenized’, by being encoded by connecting its type to a working memory token. At end of this stage, the target can be identified by the ST^2 model. Only one token can be active at a time, thus a serialisation of encoding is achieved by inhibiting other tokens. Finally, temporal attention occurs by a *blaster* that spreads excitation to nodes in the later layers of stage one, activating the targets for the tokenization process. Once the tokenization is initiated, the excitation from the blaster is suppressed until the target is encoded. This suppression prevents the second target from firing the blaster until tokenisation of the first target is completed. Watson et al. (2003) consider that the attentional blink falls in the same time-window that is required for old items to be encoded and consolidated (400- 500 ms; Watson & Humphreys, 1997). The filter and bottleneck accounts of the attentional blink can be related to the preview benefit. Similarly to the filter theory, if the second set of items in preview search is presented before the first set has been processed, these items compete for attention and result in no preview benefit (Watson & Humphreys, 1997). The effects would differ in comparison to the attentional blink in that such a mechanism would create the attentional blink, while it would abolish the preview effect.

Of most interest is the mechanism of Bowman and Wyble's (1997) ST^2 model. This account could transfer to explaining the preview benefit such that the first set of items, upon being perceptually identified as a type may be tokenized (with temporal occurrence being coded as episodic information) and then suppressed so that the second set of items could gain priority. An issue with this model in explaining the preview benefit may be that the capacity of the preview benefit is about 30 or more old items (Theeuwes, Kramer, & Atchley, 1998), which by far exceeds the number of items that can be encoded in VSTM (Cowan, 2001; Luck & Vogel, 1997) as a token. An account that discusses the role of visual working memory (VWM) in the preview benefit (Al-Aidroos, Emrich, Ferber, & Pratt, 2012) will be discussed in the following subsection.

Watson et al. (2003) consider visual marking to involve an extra process in comparison to the attentional blink, that enables prioritization of novel items that goes beyond the resources required to encode the old items, but enables their filtering from future search lasting at least 3s (Braithwaite, Humphreys, Hulleman, & Watson, 2007).

Accounts of the preview benefit. Three main mechanisms have been suggested to account for how new stimuli come to be prioritised in preview search. First, luminance transients produced by the novel items might capture attention automatically (e.g., Donk, 2005, 2006; Donk & Theeuwes, 2001, 2003; Donk & Verburg, 2004). Second, the second set of items might be prioritised because attention can be allocated to a temporally segregated signal for the two sets of stimuli (e.g., Jiang, Chun, & Marks, 2002a). Third, old items might be actively inhibited, which would reduce their competition for attention when new items arrive; a process that Watson and Humphreys (1997) called *Visual Marking*. It is currently held that all three accounts contribute to maintaining a preview benefit. An inhibitory account has the greatest flexibility to account for the findings, but bottom-up factors can also abolish the benefit, as initially suggested by Watson and Humphreys (1997). These accounts are not mutually exclusive, and current research suggests that all play a role in generating a preview benefit to some degree depending on the particular search conditions (e.g., Olivers, Humphreys, Braithwaite, 2006; Donk, 2006).

Automatic capture by abrupt onsets. A bottom-up account of the preview benefit was suggested by Donk and Theeuwes (2001), in which abrupt luminance increments associated with the arrival of new items automatically draw attention. In their study, Donk and Theeuwes manipulated the luminance change generated by the onsets of the old and new items, and found that a preview benefit was contingent on the new items being accompanied with an abrupt luminance onset. Based on this result, Donk and Theeuwes (2001) concluded that the preview benefit is a result of automatic prioritization of new elements by luminance onset capture (e.g., Yantis & Johnson, 1990; Yantis & Jones, 1991; Yantis & Jonides, 1984, 1990). Donk and Theeuwes (2003) extended this position, by showing that new items are prioritised even when the target was presented amongst the old elements by equiluminantly changing colour, suggesting that there is no top-down modulation (see also Pratt, Theeuwes, & Donk, 2007).

However, many findings contradict the onset account as a full explanation of the preview benefit. For instance, in the case of Donk and Theeuwes' (2003) results, Watson and Humphreys (2002) previously showed that equiluminant colour changes do not disrupt inhibition, but shape changes do (Watson & Humphreys, 2002), explaining why the equiluminant colour change did not impact the preview benefit. Furthermore, it has been found that the preview benefit can also be obtained with stimuli isoluminant with their background, if more time is provided for the previewed items to be perceived and encoded (Braithwaite et al., 2006). Moreover, past representations of the old items influence the ability to find new items (Kunar, Humphreys, & Smith, 2003a; Hodsoll & Humphreys, 2005). Probe-dots are difficult to find at old item locations compared with new item or neutral, no-item locations, indicating an inhibitory component (Watson & Humphreys, 2000; Osugi et al., 2009; but see also Agter & Donk, 2005). The preview benefit shows evidence of a semantic and representational level, as it is preserved when old items change from Japanese symbols to images with the same meaning, but not if the meaning also changes (Osugi, Kumada, & Kawahara, 2010). There is also evidence for colour-based inhibition carrying over from old to new items (i.e., Braithwaite et al., 2003, 2004), which is especially observed with moving stimuli as predicted by the inhibitory account (Andrews, Watson, Humphreys, & Braithwaite, 2011). Additionally, Watson and Humphreys (1998) have found that a preview benefit is obtained with moving stimuli, providing there is a colour difference between the old and the new items. According to the onset account, a preview benefit should not be possible with moving displays because changes in luminance do not capture attention, unless they separate a single perceptual element from its perceptual group (Hillstrom & Yantis, 1994). Finally, the onset account has a capacity limit of 4 new items (Yantis & Johnson, 1990), while the preview benefit is observed with up to 15 new items if a single target has to be responded to (Theeuwes et al., 1998) and 6-7 new items when all items require responding to (Watson & Kunar, 2012).

Temporal asynchrony. The temporal asynchrony account (Jiang et al., 2002a) proposes that the preview benefit is a result of attention being deployed to items based on their temporal onset. Jiang et al. (2002a) found that if the old items changed in shape or luminance when the new items were added, the preview benefit was abolished (Experiment 1). However, if changes to old items were made before the new items were added, the preview benefit was preserved (Experiment 3). This showed that changes are grouped into one or two temporal events. Moreover, old items can also be prioritised and new deprioritised if the old items are relevant and if they are separated into two groups (Experiment 4). Thus, Jiang et al. (2002a) concluded that temporal asynchrony was a crucial factor in maintaining the preview benefit. However, even if temporal asynchrony is necessary for the preview benefit, this account does not describe the mechanism which segregates the two groups. For instance, the actions of mechanisms such as onset capture or visual marking might be what actually produces the ability to separate two sets of items on the basis of their temporal asynchrony. In addition, Watson and Humphreys (1997) have shown the preview benefit follows a time-course and requires approximately 500 ms for the old items to be consolidated. This means that a mere temporal asynchrony at short durations is not sufficient for the preview benefit to occur. Theoretically, the temporal asynchrony account can rather be incorporated as a necessary factor for the operating of other mechanisms rather than being a stand-alone account of the preview benefit.

Visual marking. Watson and Humphreys (1997) suggested that new items in preview search are prioritised by filtering out old distractors from future search by top-down inhibition – *visual marking*. Thus, time-based visual selection demonstrates behaviour mediated by the current goal state (see Figure 6).

At a broad level, the meaning of the term ‘inhibition’ is used to describe any substance, process, or mechanism that decreases a certain activity, whether at a chemical, biological, or behavioural level. A definition of inhibition in cognition is proposed by Nigg (2000):

> “it can refer to suppressing a stimulus that pulls for a competing response so as to carry out a primary response, to suppressing distractors that might slow the primary response, or to suppressing internal stimuli that may interfere with the current operations of working memory.”
>
> (Nigg, 2000, p. 222)

In the context of visual marking, inhibition refers to supressing the locations and /or features of old stimuli to prevent them from competing for selection in visual search. Watson and Humphreys (1997) distinguish inhibition in visual marking from stimulus-driven attentional priority for new objects, IOR, negative priming and feature map inhibition. Inhibition in visual marking is resource-limited - a central load task in which participants read aloud the numbers displayed at the center at the time when the old items were displayed abolishes the effect (Experiment 8). This disruption showed that attentional resources were required to prioritise the new items. Watson and Humphreys (1997) proposed that the presentation of old items resulted in the observer developing an inhibitory goal state consisting of a template for the locations of the distractors. This template is coded within a master-map of locations or within a single-feature map. If any subsequent activity (such as rapid luminance or feature changes, movement, etc.) occurred at a corresponding location, this would feed back to the inhibitory template and reset it at that location.

Further evidence of inhibition in visual marking requiring a top-down component comes from Humphreys, Watson, and Jolicoeur’s(2002) study, where they found that disruption occurred with not only a visual, but also with an auditory secondary task if presented at the start of the preview period before the old items are consolidated. A secondary visual task presented during the preview period disrupts the preview benefit, which is not the case with a secondary auditory task. This suggests that there is a maintenance component of the preview benefit that relies on visual resources.

Another example that shows that the preview benefit requires attentional resources uses the attentional blink paradigm (Raymond et al., 1992). Olivers and Humphreys (2002) demonstrated that t the preview was abolished when the old items are presented during the attentional blink (i.e., 500 ms after processing a previous target), in which attentional processing is compromised (Raymond et al., 1992).

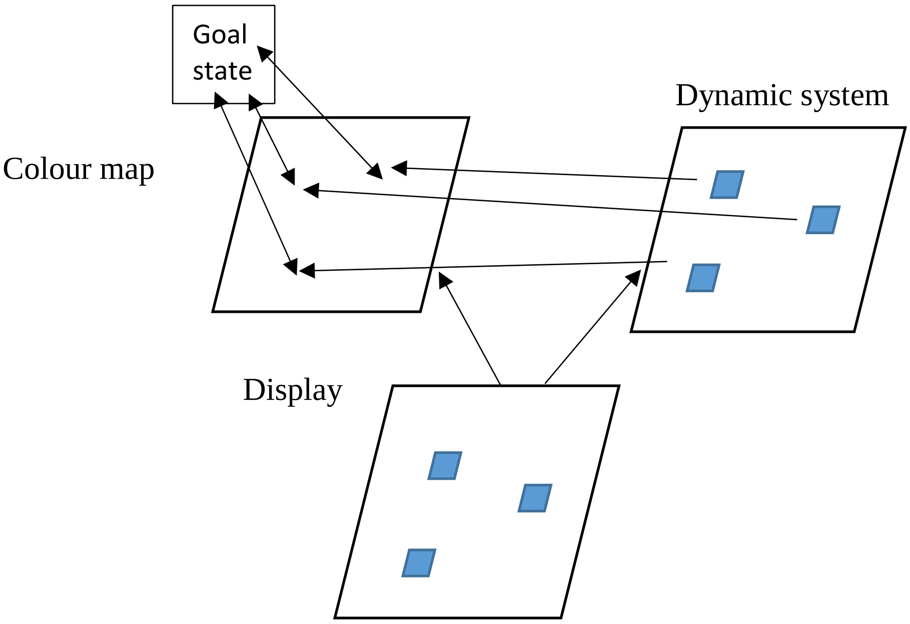


Figure 6. Top-down inhibition is mediated by the goal state (Watson & Humphreys, 1997)

Watson and Humphreys (1997) originally suggested that inhibition of old items is location-based, and not feature-based. Much evidence for location-based inhibition comes from probe-dot experiments (Watson & Humphreys, 2000; Osugi et al., 2009). For instance, Watson and Humphreys (2000) presented a probe dot at the locations of the old or new items in the minority of trials, whereas in the majority participants had to detect a standard target. Participants were less accurate in detecting probes presented on old item locations than on new item locations, demonstrating location-based inhibition. Interestingly, when probe dots were to be detected on all trials, participants withheld inhibition of old items, clearly showing goal-oriented behaviour (see also Olivers, Humphreys, Heinke, & Cooper, 2002, for further examples of strategic behaviour in preview search).

Although initially the feature-based account of the preview benefit was discarded (Watson & Humphreys, 1997), evidence for feature-based inhibition was obtained from visual marking with moving stimuli (Watson & Humphreys, 1998). Watson and Humphreys (1998) performed the same feature-map inhibition test on preview search with moving stimuli as with stationary stimuli (Watson & Humphreys, 1998), which was described in the earlier section comparing visual marking to negative priming. In this case, they found no evidence of systematic change in RT performance when up to 4 novel distractors that shared the features with the old items were added (suggesting that they had been inhibited at the feature level). However, Experiment 4 showed if a larger number of new items sharing the same feature with old items were added, the efficiency of search was reduced - especially when there was a small number of old distractors. This is because a large change in the feature map would reset inhibition. Olivers, Watson, and Humphreys' (1999) study confirmed this by showing that there was no preview benefit if there was no colour difference between the old and new items (see also Kunar, Humphreys, Smith, 2003b). However, Watson (2001) showed that a colour difference is not needed if the motion is rotational (i.e., items rotate around their center).

Thus, Experiments 4 and 5 showed that the mechanism for marking moving items relied on inhibition applied at the level of whole-feature-maps. It was later discovered that some feature-based inhibition seemed to play a role with stationary stimuli as well, since selection of new items was less efficient if they shared features with the old (the colour-carryover paradigm; Braithwaite et al., 2003; 2004). A useful way to determine the contribution of feature and location-based inhibition in preview search would be through using formal models such as the TVA (Bundesen, 1990). In the TVA, perceptual properties of objects such as locations and features are assigned with differential coefficient weights in the first stage of the model.

Assigning negative parameters to these locations and features of old items in the first stage of the model might simulate preview search patterns. Such a simulation could reveal the individual contributions of feature and location-based inhibition and provide further evidence for the visual marking account. Importantly, inhibition in visual marking is highly adaptive. Behaviourally-relevant changes, such as shape changes of old items remove inhibition, whereas less-relevant changes, such as colour or luminance do not (Watson & Humphreys, 1997, 2002). An adaptive and high-level component is also clearly demonstrated by Osugi et al. (2010), who showed that the preview benefit is preserved if old items changed shape from a symbol (Japanese character representing a butterfly) to an image retaining the same meaning (butterfly).

Visual working memory (VWM). A very recent study has also suggested a role of visual working memory (VWM) in the preview benefit at small display sizes (Al-Aidroos et al., 2012). In Experiments 1 and 2, Al-Aidroos et al. (2012) showed that preview inhibition is more effective when the number of old items falls below the capacity of VWM of about 4 objects (Cowan, 2001; Luck & Vogel, 1997), and that the effectiveness of preview search at small display sizes is correlated with individual differences in spatial-based visual working memory, but not colour-based working memory (Experiment 4). Al-Aidroos et al. (2012) note that the study was not designed compare VWM to other possible mechanisms of the preview benefit, but to test whether VWM can fit within the existing mechanisms, to ‘support’ the preview benefit at small display sizes. Thus, it seems that further research is needed to confirm unambiguously whether VWM is sufficient for a preview benefit to occur at small display sizes in absence of other mechanisms, such as top-down inhibition.

Nevertheless, this study suggested that preview benefit can be mediated by different mechanisms at small and large display sizes.

The current position. It is likely that all of the above-described mechanisms contribute to forming the preview effect (Olivers, Humphreys, & Watson, 2006). Similarly to the principles of the biased competition theory (Desimone & Duncan, 1995), the above described accounts of the preview benefit assume competition between old and new stimuli, and consider that both top-down and bottom-up mechanisms may resolve this competition between old and new stimuli. Although the biased competition theory considers old information to lose activation in a bottom-up manner, the above evidence suggests that in the preview benefit this loss of activation needs to be topped by an extra biasing mechanism that would enhance activation to the novel stimuli. For instance, at the physiological level ERP data suggest that the preview benefit (with a 1000 ms interval between old and new stimuli) is accompanied by a negative N1 /N2 waveform 250-750 ms after the occurrence of the old stimuli (Jacobsen, Humphreys, Schroger, & Roeber, 2002), suggesting the presence of top-down activation.

Although the biased competition theory discusses top-down and bottom-up mechanisms separately, it considers that these mechanisms are likely to interact in everyday life. Future research needs to resolve precisely how and when these interactions occur (Beck & Kastner, 2009). The preview benefit can be disrupted by bottom-up factors such as rapid luminance changes (Watson & Humphreys, 1997). However, the exact contribution of bottom-up and top-down mechanisms in producing the preview benefit remains a question for further research (Watson, Humphreys, & Olivers, 2003).

Development of Attention

The above section provided a brief history of attentional research, outlining its evolution from simple bottleneck concepts to complex attentional networks. In addition, the above section described the major theories of visual attention, and showed the key mechanisms that construct human attention. However, all of these findings are based on results obtained with adult participants. As such, this research is informative of only a part of the human life-span, and the same principles might not apply to attention at different points in life. Further insights into attentional mechanisms in adulthood can come from studying the development of attention from birth to adolescence. This is because attentional development can dissociate many hidden processes involved in a way that other research techniques cannot, due to varying maturational rates of the mechanisms involved (Astle & Scerif, 2009). Astle and Scerif (2009) suggest that for this reason, tracking the development of attention can be used as a technique to inform adult cognitive neuroscience. Furthermore, besides understanding attention at different developmental milestones from a theoretical and scientific perspective, studying the development of attentional processes in childhood has the potential for applied impact in the areas of education, child psychopathology, and various safety policies.

Crucially, the complex attentional system that adults are equipped with is not readily available at birth. Instead, multidimensional attentional processes are implemented over time, at varying rates and levels before the attentional end-state of an adult is reached. In the developmental attention literature (e.g., Rueda et al., 2004; Colombo, 2001; Amso & Scerif, 2015) it is often proposed that the attentional networks model, which includes alerting, orienting, and executive components (Posner & Petersen, 1991), is a useful framework to study attentional development.

This model is useful for studying attentional development because of the different components having varying cognitive demands, allowing them to be tracked over developmental time.

Babies are equipped with exogenous, bottom-up attentional mechanisms. For instance, the alerting component has rudimentary foundations in new-born babies (Amso & Johnson, 2006). The first exogenous mechanisms, both activational and inhibitory (IOR), reach functionality between 3 and 6 months of age (Butcher, Kalverboer, & Geuze, 2000; Hood, 1993; Johnson, Posner, & Rothbart, 1991; Johnson & Tucker, 1996; Colombo, 2001). It is only at approximately 5 years of age that children begin to orient attention endogenously, based on central cues (Jakobsen, Frick, & Simpson, 2013), after which alerting and orienting show stability beyond 6 years of age (Rueda et al., 2004; but see Schul, Townsend, & Stiles, 2003, for results showing improvements in attentional orienting over the school years), while executive attention development shows continual development up until early adolescence (e.g., Davidson, Amso, Anderson, Diamond, 2006; Crone, 2009).

Selective attention studied via the visual search task also shows substantial developmental change. Search rates for conjunction targets are slower in childhood, while parallel search slopes are similar to adults', albeit having a higher RT intercept (Donnelly et al., 2007; Trick & Enns, 1998; Hommel, Li, & Li, 2004; Ruskin & Kaye, 1990; Thompson & Massaro, 1989; Taylor, Chevalier, Lobaugh, 2003). For instance, Donnelly et al. (2007) investigated top-down and bottom-up development of visual search processes in children aged 6-7, 9-10, and young adults. They compared search performance for a known target in a conjunction condition, to search performance for a singleton target. Targets could differ from distractors in colour, size, or orientation. The results showed that search slopes decreased with age in the conjunction condition, with slopes of 102 ms/item, 37 ms/item, and 30 ms/item for target-present trials for 6-7-year-olds, 9-10-year-olds, and young adults, respectively. Age-related differences were also observed with singleton targets, where younger children were inclined to search for colours before orientation or size. Follow-up experiments showed that this result was not due to the effect of packing density on discriminating colour, orientation, or size (Experiment 2) nor was it due to children's ability to discriminate colour from orientation (Experiment 3). This led the authors to the conclusion that top-down capacity increases with age, and that it is also possible that top-down inhibition used to guide search, is reduced in children. Furthermore, Donnelly et al. (2007) argued that conjunction search was less efficient in children due to a reduced VSTM or due to a difficulty in guiding search to potential target features. The results also suggested that children cannot monitor over multiple dimension maps as easily as adults, and instead focus on a single feature. In addition, they showed that there may be a development of bottom-up factors as well, where sensitivity to colour differences is greater than for other types of features.

Similar to Donnelly et al. (2007), Trick and Enns (1998) have previously suggested that improvements in search rate for conjunction targets is due to the development of the top-down system. Moreover, top-down processes that enable children to shift attention voluntarily, become more efficient at around 8 years of age (Ristic & Kingstone, 2009). Primary developmental challenges are linked to overcoming distractibility and interference (Hommel et al., 2004; Pasto & Burack, 1997), which have a later onset than engaging and moving attention (Michael, Lété, & Ducrot, 2013). Indeed, some theories propose that strengthening of inhibitory performance drives cognitive development (e.g., Dempster, 1992; Bjorklund &

Harnishfeger, 1990). According to these theories, developmental change does not occur due to an increasing resource capacity, but that interference by irrelevant information reduces due to the strengthening inhibitory mechanism. This enables greater storage space, sharper focus, and execution of multiple executive processes (Harnishfeger & Bjorklund, 1993).

That said, further research is needed to determine whether and when in development children are able to use inhibitory mechanisms to filter distractors. As previously discussed, much research has indirectly inferred the deficiency of selective attention in childhood to be due to an insufficiently developed top-down inhibitory mechanism, but has not directly tested this account. This is particularly relevant as children who have attentional deficit hyperactivity disorder (ADHD) might be susceptible to impaired inhibitory control (Schachar, Mota, Logan, Tannock, & Klim, 2000). Brodeur and Pond (2001) suggest that in order to examine the nature of selective attention in children diagnosed with ADHD, it is vital to understand how attention develops in typically developing children. Time-based visual selection (Watson & Humphreys, 1997) incorporates many under-researched aspects of developmental attention: the ability to use time of appearance to select goal-relevant information and the trajectory of developing top-down inhibitory processes in attention. Uniquely, the use of inhibition here is embedded in a selective attentional process, as opposed to executive function inhibition tasks (e.g., Antisaccade task, Go/no-go task, Stop-signal task, Stroop task) that show executive inhibition (Miyake et al., 2000) but not a direct application to another cognitive process. Thus, the preview paradigm can directly show how inhibition improves selective attention. Moreover, research into the development of attention has mostly focused on the development of space-based attention, but has not considered the development of time-based attention. The development of the ability to use time to guide attention in space is just as important to investigate, since time frames many of the activities and events that occur in the real world. The developing ability to use time-based visual selection will be one of the main components of this thesis, and will be examined in Chapters 3 and 4.

Overview of the Thesis

The overarching goal of this thesis is to understand the control and development of time-based attentional prioritization of goal-relevant information. What are the endogenous and exogenous factors that enhance or constrain our ability to efficiently select information in time, and when in development can we begin to use this ability? Questions of how observers modulate their attention, what are the limits when ignoring distractors, and how equipped are children with these sophisticated processes, are not well-understood from the perspective of cognitive science and developmental psychology.

The purpose of Chapter 1 has been to provide a brief overview of the origins and progression of the most important attentional research over the past decades, as well as some insights into findings of the development of children's attention. More detailed descriptions of further research in this area will be addressed in the introductory sections of the following chapters. Chapter 2 will be devoted to the question of how observers control top-down inhibition to ignore distractors. Since inhibition in time-based visual selection is claimed to be wilful, effortful, and under intentional control of the observer (Watson & Humphreys, 1997, 2000), this chapter will experimentally explore the precise meaning of these properties. How strategic is top-down inhibition as a means of ignoring distractors? Broadly, this chapter will engage with the ancient philosophical questions of the nature of human agency, consciousness, and free will, but concretely applied to attention. In a series of experiments, Chapter 2 will show when higher-level attentional mechanisms are consciously experienced and available to observer to freely modulate in different contexts.

While Chapter 2 focuses on endogenous, subject-driven abilities and limitations in ignoring old distractors, Chapter 3 will investigate how external, stimulus properties may influence top-down inhibition. Given that in the real-world we seldom experience simplistic stimuli used in lab-based experiments, the principles derived from these experiments may not always be applicable to everyday cognitive operations. Chapter 3 focuses on the question of how efficient is top-down attentional inhibition when the distractors consist of complex stimuli that require perceptual grouping (a multi-element object perceived as a single unit). This question is important, because it addresses how environmental factors may alter the efficiency of attentional selection, and underscores capacity limitations of the human attentional system. The overall theme of this chapter falls under the intersection of perception and attention, and investigates the interplay of these two cognitive processes.

Chapters 4 and 5 will offer a dynamic view of how the ability to select new information and ignore old distractors emerges in human development. The developmental approach used in these chapters is pertinent in two ways. First, developmental trajectories of cognitive functions can be used as a methodology to unravel different components of the cognitive system that appear unitary in adulthood, due to their different maturational rates (Astle & Scerif, 2009). Second, it will reveal when in development can children use endogenous attentional control to ignore old distractors. Top-down attentional control leads to better cognitive processing and more efficient learning, rendering it a topic of critical interest for developmental psychology. Chapter 4 will explore the developmental trajectory of time-based selection with stationary stimuli in children aged from 6 to 12 years. It will establish whether children can use temporal information to enhance attentional processing of stationary stimuli, whether this ability differs across age groups, and whether it aligns with the broader cognitive development of executive functions and working memory. The uniqueness of this study will be its clear delineation of the mechanisms that enable efficient time-based attentional processing in development, as opposed to providing a descriptive overview of task performance in different age groups. Chapter 5 will investigate the development of time-based visual selection with moving stimuli. The rationale for investigating the development of this ability with moving items, is that two separate inhibitory systems are likely to underpin filtering of stationary and of motion stimuli - location-based (Watson & Humphreys, 1997) and feature-based inhibition (Watson & Humphreys, 1998), respectively. Furthermore, a past study that examined the effects of ageing on time-based visual selection, found that visual marking of moving stimuli declines in older adults (Watson & Maylor, 2002). Thus, it is plausible that these two systems have asynchronous developmental patterns. Finally, the deployment of attention to motion in childhood has been an understudied topic in cognitive development, despite its apparent relevance for many everyday activities and developmental psychopathology. Chapter 5 will also address whether the development of time-based visual selection of moving stimuli ties in with executive function (EF) and short-term memory (STM) development.

Finally, Chapter 6 will outline the converging evidence and research conclusions from this thesis. Furthermore, it will discuss the relevance of these results for psychological science, and propose the impact and practical implications of the discovered findings.

Chapter 2

Inhibition in Time-based Visual Selection: Strategic or by Default?

Synopsis

The Visual Marking mechanism (Watson & Humphreys, 1997) allows new objects to be prioritised by applying top-down inhibition to a set of previewed distractors, increasing the efficiency of future visual search. However, if this inhibition results in little or no search facilitation, do people continue to apply it or do they strategically withhold it? This chapter consists of six experiments in which it was examined how participants control this inhibitory mechanism. Experiments 1 to 3 showed that in difficult search contexts, participants did not modulate the extent to which they applied inhibition based on the proportion of trials in which inhibition would have been useful. This was the case, even when explicitly cued before each trial as to the utility of applying inhibition (Experiment 4). In contrast, when search was conducted in predominantly easy search contexts, there was some evidence that inhibition was applied strategically (Experiments 5 and 6); however, the extent of this control was relatively modest. The findings are discussed in terms of the mechanisms of top-down attentional control and implications for failures of attention in real world contexts.

Introduction

Humans possess numerous top-down attentional mechanisms that provide a volitional ability to select among competing items. As such, attention can to some extent be directed freely, without being controlled exclusively by the changing nature of our surroundings. This top-down attentional system serves an active role in guiding our behaviour in goal-relevant ways. It is often claimed that top-down control allows processing to be strategically applied in effortful tasks. For example, strategic, volitional behaviour has been previously observed in visual search tasks that investigate the deployment of selective attention (Smilek, Enns, Eastwood, & Merikle, 2006; Bacon & Egeth, 1994). In the current chapter, I examine whether and to what extent people exercise strategic control over a top-down inhibitory mechanism in selective attention.

Strategic Attentional Control

Previous work has shown that asking participants to adopt particular cognitive strategies can influence general visual search efficiency. Illustrating this, Smilek et al. (2006) found that instructing participants to search *actively* or to remain in a *passive* state (i.e., waiting for a target to become visible), influenced search efficiency depending on whether the task was easy or difficult. Passive search instructions led to more efficient search when the task was difficult, most likely because participants relied more on fast automatic processes than on slower executive control processes. Similarly, Bacon and Egeth (1994) have shown that participants can adopt a singleton search mode, in which any featurally unique target (e.g., a unique shape or colour), captures attention. Alternatively, they can adopt a feature-based mode, in which only targets possessing a particular feature (e.g., a specific shape), capture attention (but see Theeuwes, 2004).

Importantly, the type of search mode or strategy that participants adopt can be manipulated by the contextual factors of the task. For example, if the target is always the unique item in a display, then a singleton mode is likely to be adopted, while if the target is not reliably defined by being the only singleton in the display, then a feature-based mode will be used (Bacon & Egeth, 1994; see also Folk & Anderson, 2010; Folk et al., 1992; Folk et al., 1994, Horstmann & Becker, 2008, for related work on contingent involuntary attentional orienting). In contingent involuntary attentional orienting, Folk et al. (1992) asked participants to either identify a colour target or an abrupt onset target. The target could be placed in one of four boxes displayed on the screen. Before the target was presented, one of the boxes was precued. There were four precue conditions: invalid (inaccurately indicating the location of the target), valid (accurately indicating the location of the target), central (not informative of the target location) and no-cue. Experiment 1 used abrupt onset-cues and Experiment 2 used colour cues. The comparison between invalid cues and neutral cues were used as an index of automatic shifts of attention. The results indicated that invalid cues slowed down target detection only when they were compatible with target properties, but not when they differed from the target features. This indicated that top-down setting were crucial in specifying when automatic processes will occur.

In terms of time-based selection, some previous studies have indicated that the inhibition of old items might also be strategic and intentional. For example, in Watson and Humphreys’ (2000) work, participants performed a preview search task on the majority (76%) of trials within a single block. On the remaining 24% of trials, a tone indicated that participants should look for a small probe dot which was presented at either the location of an old or a new item, rather than completing the search task. In this situation, successful probe dot detection was much poorer for old-location probes than for new-location probes (see also Osugi et al., 2009). In contrast, when participants were instructed to detect a probe dot on *every* trial, performance did not depend on the location of the probe dot. This indicates that the inhibition of the old items had been withheld (Watson & Humphreys, 2000). This finding provides some support to the notion that inhibition might only be applied when there is an advantage for people to do so, and that it is flexibly controlled depending on observer instructions (Watson & Humphreys, 1997, 2000). However, it is not known whether observers will spontaneously choose to adopt the process of ignoring old items, and what factors affect their strategy to do so.

Previous work has also argued that intentionally ignoring old stimuli is an effortful process, requiring both visual and attentional resources (e.g., Watson & Humphreys, 1997; Humphreys et al., 2002; Olivers & Humphreys, 2002). Given the resource limited nature of visual processing, one might expect that a cognitively consuming process would not be implemented in situations in which it is of little use. Furthermore, if this inhibitory process is susceptible to strategic control, we could consider whether it is modulated in an all-or-none fashion, or continuously. For example, if there is little benefit from applying inhibition to increase task performance, participants might choose to abandon the use of inhibition altogether, or they might apply inhibition selectively on certain trials based on the perceived value it brings.

Another possibility is that participants follow a default state of always ignoring the old items, in order to enhance the selection of new stimuli (which could arguably be an overriding ‘objective’ for the visual system). For example, ‘knowing’ that the target is not present in the current set of (previewed) items might trigger participants to apply inhibitory processes by default. Thus, observers might invest resources in inhibiting old items in all time-based selection situations, irrespective of whether it helps them or not, or potentially impairs task performance overall.

Overview of the Experiments

Six experiments examined spontaneously-generated strategic inhibition in preview search. In Experiments 1-4, the general approach was to present observers with two different time-based search conditions. In one condition, inhibiting the old items was beneficial for task performance on the majority of trials, and so would produce an overall improvement in target search and task efficiency. In another condition, on the majority of trials, the old items changed in ways which would disrupt any inhibition that might have been applied to them. As a result, old items would compete strongly for attention with the new items. In this situation, applying inhibition to the old items would provide an advantage on only a minority of trials. Thus, in the first four experiments, it was tested whether disruption of inhibition would encourage participants to modify their attentional strategy (from applying to not applying inhibition), by predicting that inhibition would be of no use through a repeated number of trials, and reconfiguring their cognitive set to withhold inhibition. In Experiments 5 and 6, a highly salient target was presented on the majority of the trials, making the search sufficiently easy for the target to be detected without having to ignore the old items. This tested whether inhibition is more likely to be strategically modulated when on the majority of occasions search can be performed without the need to suppress previously presented items, and can be performed using an alternative and more efficient strategy.

Experiment 1: Disrupting Location-Based Inhibition

The aim of Experiment 1 was to establish whether disruptions of location-based inhibition would encourage strategic behaviour. There were two main trial types, standard preview and jump. On a *standard preview* trial, one set of distractors (the preview items) was added to the display, followed 1 second later by a second set. The target was only ever present in the second set (as in Watson & Humphreys, 1997). On a *jump* trial, the first set of items ‘jumped’ (i.e., moved abruptly to new locations) when the second set of stimuli was added to the display. Based on previous work, such a jump should disrupt any inhibition applied to the old items (Watson & Humphreys, 1997, but see also Kunar, Humphreys, Smith, & Hulleman, 2003). These two types of trials were presented in differing ratios in two separate blocks of trials. In the *standard preview* block, the majority of trials were standard preview trials and the minority were jump trials. In the *jump* block, this was reversed.

If participants apply inhibition to the old items strategically, they should be more likely to apply it in the *standard preview block,* and less likely to apply it in the *jump* block. This would result in efficient search for standard preview trials in the *standard preview* block (where it would be advantageous overall to apply inhibition) and less efficient search for standard preview trials in the *jump* block (where applying inhibition would only be useful on a relatively small number of trials). However, if 1) inhibition in preview search is not applied strategically, or 2) disruptions in location-based inhibition are not sufficient to drive a change in inhibitory strategy, or 3) changing old item locations is not sufficient to disrupt the inhibition of old items (cf. Kunar et al., 2003), then there should be no difference in performance in the standard preview trials across the two blocks. Note that in this design, there is no requirement for the typical FEB and HEB conditions to be included. This is because the most important comparison is between search performance in the standard preview trials across the two main conditions (i.e., performance on standard preview trials in the Standard Preview block vs. performance on standard preview trials in the Jump block).

Method

Participants. Participants were 12 undergraduates (all female) from the University of Warwick, who received course credit for participating. Their ages ranged from 18-44 (*M* = 21.3, *SD* = 7.34 years). Participants reported normal or corrected to normal visual acuity in this and all remaining experiments.

Stimuli and apparatus. A Samsung 550P5c-S03 laptop was used to present the displays and record the participants’ responses. Stimuli were displayed on the 15-inch laptop monitor, at the panel’s native resolution of 1366 × 768 pixels and 60 Hz update rate. Displays were generated and responses recorded by a custom written computer program. The target was a light blue [RGB values = 68, 164, 176; CIExy = .234, .225; lum = 34 cd/m^2] square and distractor stimuli were light blue circles and pink [RGB values = 211, 103, 126; CIExy = .333, 236; lum = 30 cd/m^2] squares, presented against the black monitor background. The sides of the squares measured 8 mm and the circles had a diameter of 10 mm. There was an equal number of blue and pink items present in each search display, with the target taking the place of one of the blue distractors. Search displays were generated by placing items at random into the cells of an invisible, centrally-placed 6 × 6 grid, with the constraint that there was an equal number of each type of distractor on the left and right side of the display. Grid spacing was 110 pixels (28 mm) center-to-center and stimulus locations were further jittered by +/- 20 pixels (5 mm) in the x- and y-axes, in order to reduce stimulus regularity. The number of items in the final search display in all conditions (the display size) was 4, 8, or 12. The target item was constrained to fall into the two most leftward or rightward columns (columns 1, 2, 5, or 6). This ensured that the target was always unambiguously to the left or right of display center. Responses were recorded via an 8-button gamepad interface device, connected via a USB interface.

Design and procedure. There were two types of trials, *standard preview* and *jump*. A trial in the *standard preview* condition consisted of a blank screen (500 ms), followed by a central white [RGB = 180,180,180] fixation dot (2 mm × 2 mm), and then 2, 4, or 6 pink squares. After a further 1000 ms, 1, 3, or 5 blue circles, respectively, were added to the display along with the blue square target, to form a final display size of 4, 8, or 12 items. Search displays remained visible until participants responded, which started the next trial. Participants indicated the location of the target by pressing the left-shoulder button of the game pad, if the target was on the left side of the display, or the right-shoulder button if it was on the right side of the display. A trial in the *jump* condition was similar, except that the set of previewed items ‘jumped’ to new locations when the second set of stimuli (which contained the target) was added (see Figure 7). Participants were not explicitly informed that the stimuli would jump, nor of the 80:20 split in the block, in order to encourage spontaneous and ecologically valid behaviour.

Importantly, a preview item could not jump to a location previously occupied by a different preview item. In addition, the items in the second set of stimuli could not be placed in the location of a previously-occupied preview item. This ensured that any residual location-based inhibition across displays could not impact on search efficiency.

The two types of trials were combined in different proportions to form two types of search blocks. In the *standard preview* block, 80% (144 trials) of trials were standard preview trials and 20% (36 trials) were jump preview trials. In the *jump* block, 80% (144 trials) of trials were jump preview trials and 20% (36 trials) were standard preview trials. Each block contained 180 search trials, with each combination of target location and display size represented equally. In addition to the search trials, each block also contained 18 (10%) *catch* trials, in which no target was present. On catch trials, participants responded by pressing a third button on the gamepad. These target-absent catch trials prevented participants from being able to respond by searching only half of the display (e.g., concluding that the target is on the right, if it is not found on the left; see e.g., Al-Aidroos et al., 2012; Blagrove & Watson, 2010, for previous uses of this method). Trial order was individually randomized for each block, and block order was counterbalanced across participants. Participants completed an 18 trial practice block before each of the full blocks of trials. Within each block, there was a break after 60 trials. The break was self-paced by the participant, and lasted until the participant pressed any key on the keyboard.

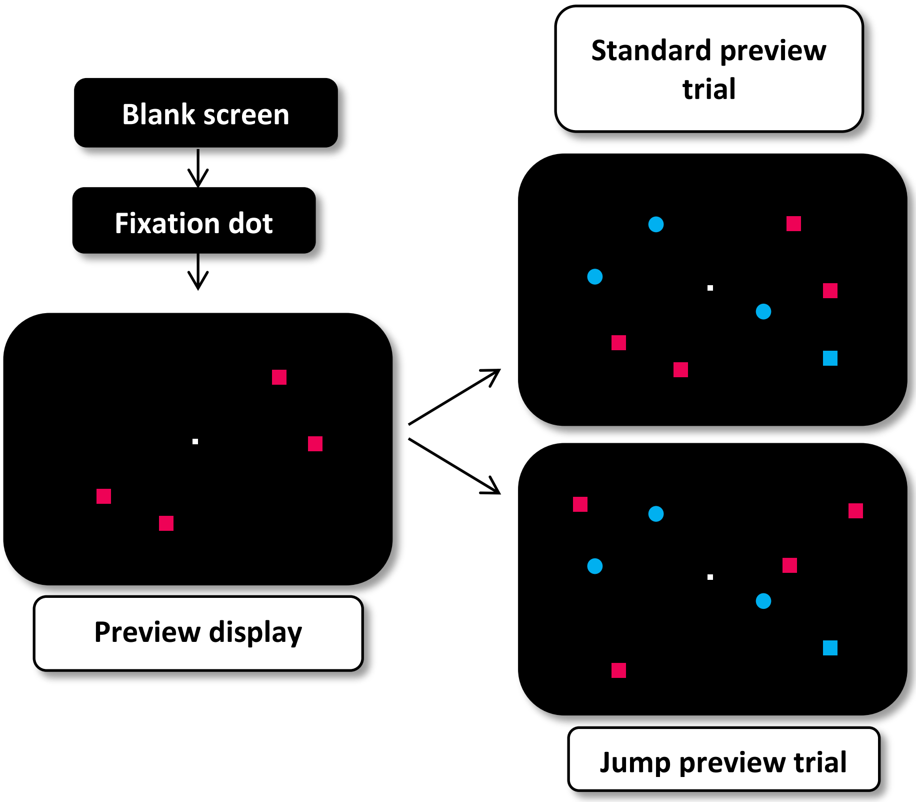


Figure 7. Example trial sequence from Experiment 1. The task was to indicate the location (left/right of center) of the blue square which appeared amongst the second set of items. On a standard preview trial, the new items were added to the preview items. On a jump trial, the old items jumped to new locations when the new items were added. The mostly standard block consisted of 80% standard preview trials and 20% jump trials. This ratio was reversed for the 80% jump block.

Results

Reaction times. Trials with RTs less than 200 ms or greater than 10,000 ms were removed as outliers (0.86% of the data). RTs below 200 ms would have been too fast to represent an actual response time and are likely to have originated from something other than the participant’s response to the target (e.g., holding the response button for too long). Longer reaction times were not trimmed up to 10 000 ms due to there being no rationale to assume that these values did not reflect an actual reaction time. According to Ratcliff (1993), using cutoffs generally results in greater power when analyzing reaction times in comparison to using medians, both with and without outliers. In addition, median RTs cannot be used when comparing unequal numbers of trials in experimental conditions due an overestimation bias (Miller, 1988). The above rationale for using RT means instead of medians and the RT cut-off thresholds was applied to all the remaining experiments in Chapter 2. Overall mean correct RTs are shown in Figure 8 and search slope statistics in Table 1. Mean correct RTs were analyzed using a 2 (Block type: 80% Jump or 80% Standard Preview) × 2 (Trial Type: Jump or Standard Preview) × 3 (Display size) repeated measures ANOVA. There was no main effect of block, $F < 1$, $\eta_p^2 < 0.1$, but there were significant main effects of trial type $F(1,11) = 13.07$, MSE = 13588.25, $p < .005$,$\eta_p^2 = .54$ and display size $F(2,22) = 49.18$, MSE = 4431.19, $p < .001$, $\eta_p^2 = .82$. RTs were longer for jump trials, and increased as the display size increased. There was a significant Trial Type × Display Size interaction $F(2,22) = 18.97$, MSE = 3539.66, $p < .001$, $\eta_p^2 < 0.1$. Jump trials were more influenced by display size than standard preview trials. Neither the Block × Trial Type nor the Block × Display Size interactions reached significance, both *Fs* < 1, $\eta_p^2 < 0.1$. The three-way Block × Trial Type × Display Size interaction was also non-significant $F(2,22) = 1.07$, MSE = 8873.43, $p = .36$, $\eta_p^2 = .09$. These analyses suggest that the strength or likelihood of applying inhibition to the old items did not depend on the proportion of jump versus standard preview trials within a single block. However, as further confirmation of this, conducted two planned were comparisons comparing the jump trials from each type of block and the standard preview trials from each type of block separately.

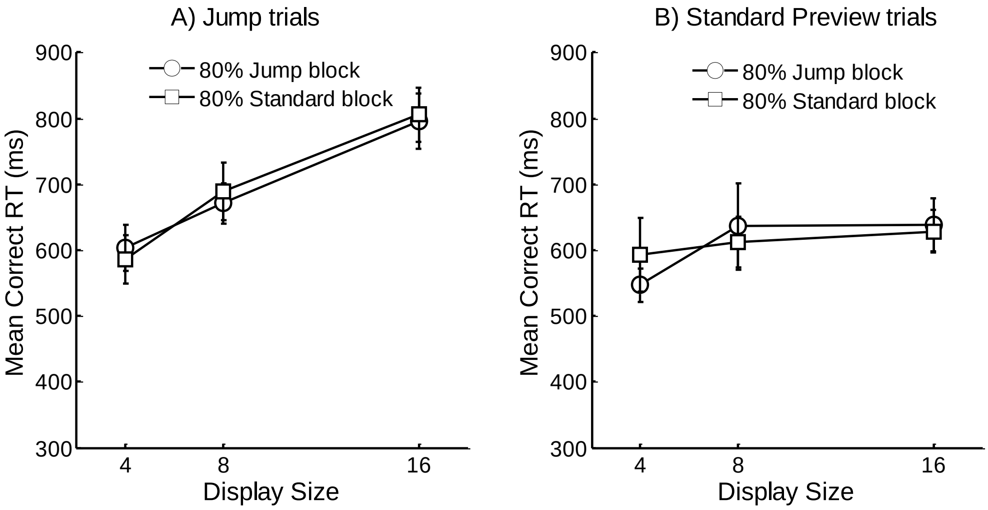


Figure 8. Mean correct RTs for jump trials (Panel A) and standard preview trials (Panel B) as a function of block and display size for Experiment 1. Error bars represent standard errors and function in an arelational role (Rouder & Morey, 2005). If inhibition was being applied strategically, we would expect more efficient search for standard preview trials in the 80% standard preview block than in the 80% jump block.

Table 1. *Search slope statistics for Experiment 1.*

	80% Jump Block		80% Standard Preview Block	
	Jump Trials	Standard Trials	Jump Trials	Standard Trials
Slope (ms/item)	23.99	11.40	27.48	4.49
Intercept	498.38	515.78	473.74	575.14
R^2	0.97	0.77	0.99	0.99

Jump trials only: A 2 (Block: 80% Jump or 80% Standard Preview) × 3 (Display size) repeated-measures ANOVA showed that RTs increased with display size, $F(2,22) = 104.57$, MSE = 2456.55, $p < .001$, $\eta_p^2 = .91$. There was a numerical trend for the search slope of the 80% Jump block to be shallower than the 80%

Standard Preview block, however, neither the main effect of block nor the Block × Display Size interaction reached significance, both *F*s < 1, η_p^2s< 0.1.

Standard preview trials only*:* RTs increased with display size, *F*(2,22) = 5.11, MSE = 5514.31, $p < .05$, $\eta_p^2 = .32$. There was also a numerical trend for search in the 80% Standard block to be more efficient than in the 80% Jump block. Nevertheless, neither the main effect of block nor the Block × Display Size interaction approached significance, both *F*s < 1, η_p^2s< 0.1.

Errors. Mean percentage errors were low overall (1.46%) and are shown in Table 2.

Table 2. *Mean percentage error rates for Experiment 1.*

	Display size		
	4	8	16
80% Jump Block			
Jump trials	1.22	0.87	3.29
Standard trials	1.39	2.78	1.39
80% Standard Block			
Jump trials	1.39	1.39	2.08
Standard trials	1.39	1.22	1.04

Errors were analyzed using a 2 (Block: 80% Jump or 80% Standard Preview) × 2 (Trial type: Jump or Standard Preview) × 3 (Display size) repeated measures ANOVA. The main effects of block, trial type, and display size were not significant, nor were the Block × Trial Type, Block × Display Size interactions, all *F*s < 1, η_p^2s < 0.1. The Trial Type × Display Size interaction was also not significant *F*(2,22) = 1.48, MSE = 17.09, $p = .12$, $\eta_p^2 = .12$, nor the three-way Block × Trial Type × Display Size interaction, $F < 1$, $\eta_p^2 < 0.1$. The overall error rate on catch trials was 3.70%, which confirms that participants were searching over the whole display. Due to the small number of trials, catch trial errors were not analyzed further.

Discussion

The first consideration, given that the typical HEB and FEB conditions were not included, was whether there was any evidence obtained that the old items were being suppressed and the new items prioritised. Clearly this was the case, with a significant difference in search efficiency between the standard preview trials and the jump trials, and standard preview search slopes being less than a third of the jump slopes. This confirms that having old items jump to new locations when the new items were added was sufficient to disrupt the preview benefit substantially (see also Kunar et al., 2003). The implication is that the new items were being prioritised for search in the standard preview conditions.

However, the main goal of Experiment 1 was to determine whether participants would spontaneously adopt different inhibitory strategies if applying inhibition helped improve their search (most of the time), compared to if it would have no benefit (most of the time). The results showed that there was a robust preview benefit, even in conditions in which, 80% of the time, inhibiting the old items would not have been useful – presumably here because the jumping of the old items served to abolish or reset the suppression of previewed items. Moreover, search efficiency (in terms of search slopes) on standard preview trials did not differ between conditions in which inhibition was predominantly useful (80% standard preview trials) or not useful (80% jump trials). This suggests that participants were not applying inhibition strategically.

Several possibilities might account for these findings. First, it might be that participants have no choice but to inhibit old items when they are looking out for new items. This might seem at odds with the findings from Watson and Humphreys (2000), in which detecting a probe dot was poor for probes presented at old item locations, when participants were engaged in a search task on the majority of trials. When all the trials were probe dot trials, there was no difference between detection of probes at old item locations, compared with probes at new item locations. However, note that in this case, when all trials were probe trials, there was *never* any need to inhibit the old items and new items never had to be prioritised over the old. It might be that whenever a task involves search for new items, the default is to inhibit old items, irrespective of whether the inhibition is advantageous or not. According to this account, inhibitory processing of old items is the default state and is mandatory whenever new items must be prioritised.

Second, numerous studies have suggested that there is a location-based inhibitory component involved in generating the preview benefit with stationary stimuli (e.g., Olivers et al., 1999; Osugi et al., 2009; Watson & Humphreys, 2000). However, there is evidence that a single change in location (i.e., a jump) might not always be sufficient to disrupt the inhibition created during the preview of the old items (Kunar et al., 2003). Even though the ‘jumps’ were essentially random relocations, and the configuration of the old items was disrupted (cf. Kunar et al., 2003; Watson, 2001), it is possible that a single jump was not able to fully abolish the preview benefit, leading participants to continue to apply inhibition to the old elements.

Third, a single jump might not have been noticed by our participants. Change blindness studies (O’Regan, Rensink, & Clark, 1999; Rensink, 2000; Simons & Levin, 1997) demonstrate that people are very poor at noticing changes that occur when the transients that would normally be associated with such changes are rendered less visible. This is typically achieved by interleaving a blank screen (i.e., an artificial eye blink) between the changed images (e.g., Cole, Kentridge, &

Heywood, 2004), presenting the changes during a real eye blink (O’Regan, Deubel, Clark, & Rensink, 2000), or by presenting competing transients (‘mudsplashes’, see O’Regan et al., 1999) at the time when the change occurs. In terms of time-based selection, Watson and Kunar (2010) showed that shape changes in old items, that would normally disrupt the preview benefit, are rendered less effective if the changes are masked by moving occluders. When the change was not directly visible, it had less of a disruptive influence. In Experiment 1, it is possible that participants did not notice that the old items had changed their locations because the jumps were effectively masked by the onset of the new set of (relevant) search items. That is, the transients associated with the onset of the new items might have acted as ‘mud splashes’ (O’Regan et al., 1999), which masked the motion of the old items. If participants were not aware of the jumps in the old items, then they might not have had a sufficiently strong explicit signal for changing their inhibitory strategy across the two different blocks of trials.

In order to test these possibilities, in Experiment 2 it was made much more obvious that the old items changed their locations before the new items arrived. Furthermore, although not approaching significance, numerically, the search rate on standard preview trials in the 80% jump condition was over twice as slow as standard preview trials in the 80% standard preview condition (11.40 ms/item vs. 4.49 ms/item), which would be consistent with the strategic application of inhibition. Hence, Experiment 2 also provided a useful confirmation of the robustness of the current findings.

Experiment 2: Salient Multi-Location Jumps

Experiment 2 was similar to Experiment 1, except that the old items jumped locations four times during the preview period, and a fifth time when the new items appeared. If the lack of strategically controlled inhibition in Experiment 1 was due to participants not noticing the changes to the old items, or due to a single jump not being sufficiently disruptive, then evidence should now obtained for the strategic application of inhibition.

Method

Participants. Participants were 12 students at the University of Warwick (11 female, 1 male), aged between 18 and 23 years (*M* = 18.8, *SD* = 1.47) and participated in exchange for course credit or payment. They did not take part in Experiment 1.

Stimuli, apparatus, and procedure. The apparatus and procedure were identical to those of Experiment 1. The stimuli were similar, except that on jump trials, the previewed items jumped five times before the new items appeared, and the largest display size was 16 items. On a jump trial, the previewed items appeared for 800 ms, they then jumped to new locations and remained visible for 300 ms, before jumping to another set of new locations and so on. On the fifth jump, the new items were added and the display remained unchanged until participants responded. On standard preview trials, the previewed items appeared for 800 ms, after which the new items were added to the display.

Results

Reaction times. Trials with RTs less than 200 ms or greater than 10,000 ms were removed as outliers (0.49% of the data). Mean correct RTs for the jump and standard preview trials are shown in Figure 9 and search slope statistics in Table 3.

As in Experiment 1, search data were calculated using a 2 × 2 × 3 repeated-measures ANOVA, which revealed a significant main effect of trial type *F*(1,11) = 17.83, MSE = 3963.15, $p < .005$, $\eta_p^2 = .62$, and display size *F*(2,22) = 64.53, MSE = 4900.26, $p < .001$, $\eta_p^2 = .85$. The main effect of block was not significant, $F < 1$, $\eta_p^2 < 0.1$. RTs on standard preview trials were shorter than on jump trials, and RTs increased as the display size increased. There was also a significant Block × Trial Type interaction *F*(1,11) = 9.79, MSE = 4603.21, $p < .05$, $\eta_p^2 = .47$. Jump trial RTs were shorter in the 80% jump block and standard preview trial RTs were shorter in the 80% standard preview block.

The Trial Type × Display size interaction was borderline significant *F*(1,11) = 3.27, MSE = 4775.80, $p = .057$, $\eta_p^2 = .23$. This is based on a non-directional test. Given that we would expect a preview benefit to occur in the standard preview condition but not in the jump condition, there is some justification for treating this as a directional test which would have been significant at the .05 level. The Block × Display size interaction did not approach significance *F*(2,22) = 2.26, MSE = 2999.48, $p = .13$, $\eta_p^2 = .17$, nor did the Block × Trial Type × Display size interaction, $F < 1$. As in Experiment 1, planned follow-up comparisons compared the two standard preview and two jump conditions individually.

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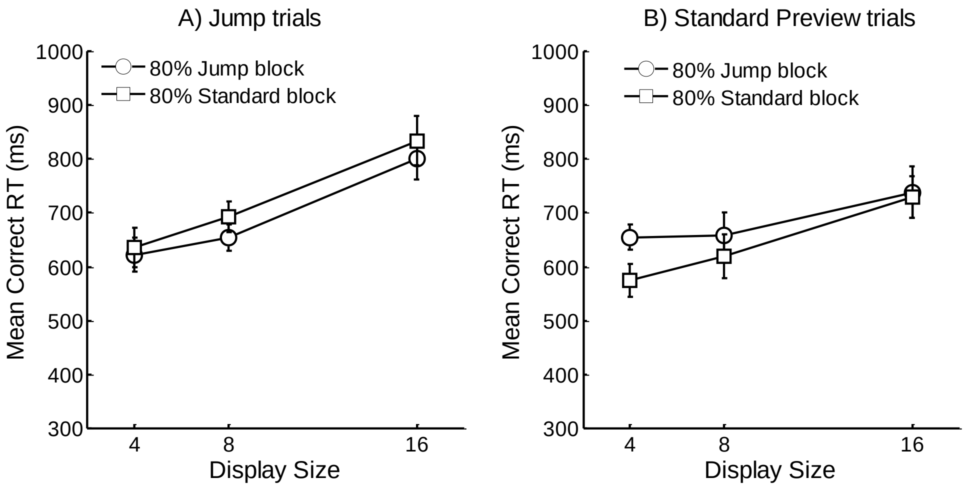

Figure 9. Mean correct RTs for jump trials (Panel A) and standard preview trials (Panel B) as a function of block and display size for Experiment 2. Error bars represent standard errors. If inhibition was being applied strategically, we would expect more efficient search for standard preview trials in the 80% Standard block than in the 80% Jump block

Table 3. *Search slope statistics for Experiment 2.*

	80% Jump block		80% Standard preview block	
	Jump Trials	Standard Trials	Jump Trials	Standard Trials
Slope (ms/item)	15.48	7.41	16.79	13.07
Intercept	548.21	614.62	564.11	519.16
R^2	0.97	0.91	0.99	0.99

Jump trials only: RTs increased with display size, $F(2,22) = 39.76$, MSE = 5934.16, $p < .001$, $\eta_p^2 = .78$, however, neither the main effect of block, $F(1,11) = 1.01$, MSE = 14153.72, $p = .34$, $\eta_p^2 = .08$, nor the Block × Display Size interaction were significant, $F < 1$, $\eta_p^2 < 0.1$.

Standard preview trials only: As with the jump trials, RTs increased with display size, $F(2,22) = 25.62$, MSE = 3741.76, $p < .001$, $\eta_p^2 = .70$, however, neither the main effect of block, $F(1,11) = 1.03$, MSE = 31615.17, $p = .33$, $\eta_p^2 = .08$, nor the Block × Display Size interaction proved significant, $F(2,22) = 1.75$, MSE = 4436.64, $p = .20$, $\eta_p^2 = .14$. Moreover, the numerical trend was for more efficient search in the 80% jump block than in the 80% standard preview block (7.4 ms/item vs. 13.1ms/item respectively), which is the opposite of what would be expected if inhibition was being applied strategically.

Error rates. Error rates were low overall (1.53%) and are shown in Table 4. A 2 (block) × 2 (trial type) × 3 (display size) repeated-measures ANOVA showed that the main effect of display size was marginally significant $F(2,22) = 2.89$, MSE = 3.41, $p = .08$, $\eta_p^2 = .21$. However, all other main effects and their interactions were non-significant, Block × Display Size, $F(2,22) = 2.49$, MSE = 5.17, $p = .11$, $\eta_p^2 = .19$, Block × Trial Type × Display Size $F(2,22) = 2.54$, MSE = 2.64, $p = .10$, $\eta_p^2 = .19$, remaining Fs < 1, $\eta_p^2 < 0.1$. The overall error rate on catch trials was low (4.39%), and these errors were not analyzed further.

Table 4. *Mean percentage error rates for Experiment 2.*

	Display size		
	4	8	16
80% Jump block			
Jump trials	0.35	1.39	2.78
Standard trials	0.69	1.39	1.39
80% Standard block			
Jump trials	2.08	0.69	1.39
Standard trials	1.74	1.04	2. 25

Discussion

The main aim of Experiment 2 was to determine whether a strategic use of inhibition would emerge when the changes to the old items were made more salient, by having the old items jump several times. Despite these changes, there was no evidence that old items were being inhibited strategically. As in Experiment 1, search slopes of the standard preview trials did not differ between the two blocks of 80% jump and 80% standard preview trials. Again, search on jump trials was less efficient than on standard preview trials, suggesting that the stimulus jumps had been effective in disrupting the preview benefit. Taken together, Experiments 1 and 2 suggest that inhibition is not spontaneously withheld even when, 1) items move location, rendering any old item inhibition ineffective, and 2) when location changes are more salient and should be noticed easily.

Note that the old items in Experiments 1 and 2 moved location before the new items arrived and this would have had the effect of disrupting any location-based inhibition of those items. However, previous work has shown that old items can also be excluded by inhibition applied at the level of feature maps, for example, the item’s colour (Watson & Humphreys, 1998; Andrews et al., 2011; Braithwaite et al., 2003, 2004). In this way, old items remain deprioritised (even if they move), without the need for the involvement of complex tracking procedures (Watson & Humphreys, 1998), which are likely to be of low capacity (Pylyshyn & Storm, 1988). Accordingly, it is possible that participants might have continued to apply inhibition, because the old items maintained their colour throughout the jump period, allowing a potential role for colour-based inhibition to remain effective. Experiment 3 assessed this possibility by changing both the colour and the locations of the previewed items before the new items arrived.

Experiment 3: Disrupting Both Feature and Location-Based Inhibition

Even if participants realized that location-based inhibition was ineffective on 80% of the trials, they might still have tried to inhibit the previewed items because the colour of the old items remained constant throughout the preview period. Furthermore, this maintenance of colour could have encouraged them to continue to apply both location- and feature-based based inhibition, even when the old items jumped to new locations on the majority of trials. This possibility was tested in Experiment 3 by having the old items change both their locations and their colour during the preview period. This aim of using this procedure was to disrupt both location- and feature-based inhibition.

Importantly, the colour change of each old item was independent of the colour changes of other items (i.e., the intermediate preview displays were of mixed colours). This procedure should make it more difficult to group the old items (Jiang, et al., 2002) into a single set, based on a common colour (see also Duncan & Humphreys, 1989). In turn, this should prevent participants from being able to apply inhibition to a single colour-feature map, and increase the likelihood that feature-based inhibition would be disrupted, due to the associated changes of activity within multiple colour maps (Watson & Humphreys, 1998). Taken together, these aspects of the design should produce maximal disruption to both location- and feature-based inhibition, as well as providing highly-noticeable changes in terms of participants' subjective experience. As in the previous experiments, the proportion of jump trials and standard preview trials was manipulated in an 80:20 ratio, across two different blocks of trials.

Method

Participants. Twelve students from the University of Warwick (6 male, 6 female) aged between 19 and 45 years (*M* = 24.4, *SD* = 7.74) and participated in exchange for course credit or payment. They did not participate in the previous experiment.

Stimuli, apparatus, and procedure. The stimuli and procedure were similar to those of Experiment 2, except that each preview item also changed colour each time it jumped to a new location. Thus, a preview jump trial consisted of a set of pink squares, within which each square then jumped to a new location (after 800 ms), at the same time changing to a new colour, independently within the set. The possible colours consisted of: light green [RGB = 50, 205, 50; CIExy = .323, 442; lum = 39 cd/m^2] , orange [RGB = 255, 265, 0; CIExy = .451, 454; lum = 79 cd/m^2], yellow [RGB = 238, 238, 0; CIExy = .441, 448; lum = 66 cd/m^2], olive green [RGB = 142, 142, 56; CIExy = .356, 352; lum = 26 cd/m^2] and bright red [RGB = 238, 0, 0; CIExy = .564, 318; lum = 19 cd/m^2]. The colour change was randomized individually for each item, with every item having the same probability of changing into one of the five possible colours. After a further 300 ms, the items jumped and changed their colour again. On the fifth jump, all items returned to the initial pink colour, and at the same time the new (blue) items were added, together with the target, if presented. Having the items change back to their start colour ensured that the final display on jump trials matched that of the standard preview condition and hence, allowed performance in the two trial types to be compared directly. The standard preview condition was identical to that of Experiment 2.

Results

Reaction times. Trials with RTs less than 200 ms or greater than 10,000 ms were removed as outliers (0.01 % of the data). Mean correct RTs for trials in the jump and standard preview blocks are shown in Figure 10, and search slope statistics are shown in Table 5. Mean correct RTs were analyzed using a 2 (Block type: 80% jump or 80% standard preview) × 2 (Trial Type: jump or standard preview) × 3 (Display size) repeated-measures ANOVA. Standard preview trials had shorter RTs than the jump trials, $F(1,11) = 12.03$, MSE = 8715.81, $p < .01$, $\eta_p^2 = .52$, and RTs increased as the display size increased $F(2, 22) = 53.72$, MSE = 9923.85, $p < .001$, $\eta_p^2 = .83$. In addition, there was a significant interaction of Block × Trial Type $F(1, 11) = 32.62$, MSE = 2150.44, $p < .001$, $\eta_p^2 = .75$, indicating that the RTs for the standard trials were longer overall in the 80% Jump block. A Trial Type × Display Size interaction revealed that the jump trials were affected more by the display size than the standard preview trials $F(2, 22) = 15.99$, MSE = 3019.19, $p < .001$, $\eta_p^2 = .59$ However, there was no main effect of block $F(1, 11) = 2.92$, MSE = 23228.80, $p = .12$, $\eta_p^2 = .21$, and neither the Block × Display Size, nor the three-way Block × Trial Type × Display Size interaction reached significance, both *F*s < 1. Two planned comparisons compared the two standard preview and two jump conditions individually, similarly to the previous experiments.

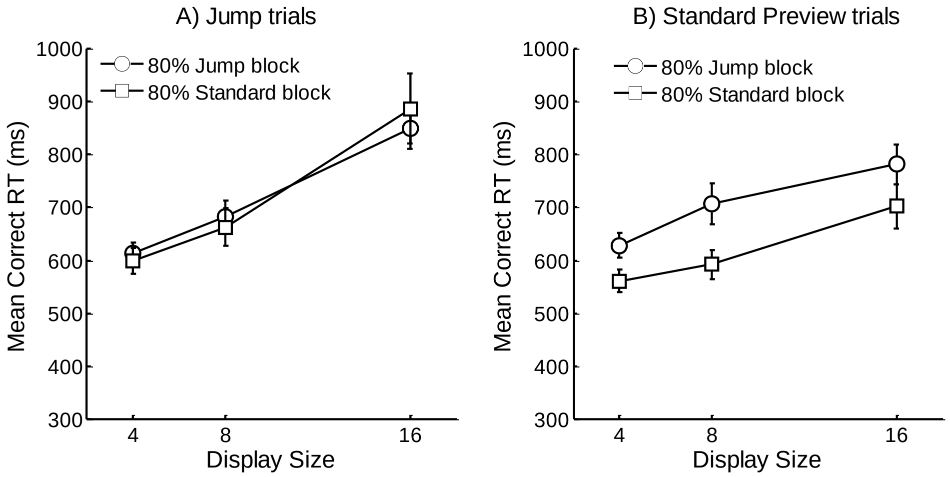

Figure 10. Mean correct RTs for Jump trials (Panel A) and standard preview trials (Panel B) as a function of block and display size for Experiment 3. Error bars represent standard errors. If inhibition was being applied strategically, we would expect more efficient search for standard preview trials in the 80% standard block than in the 80% jump block.

Table 5. *Search slope statistics for Experiment 3*

	80% Jump Block		80% Standard Preview Block	
	Jump Trials	Standard Trials	Jump Trials	Standard Trials
Slope (ms/item)	19.88	12.33	24.65	12.06
Intercept	530.13	590.77	486.31	505.72
R^2	0.99	0.96	0.99	0.99

Jump trials only: RTs increased with display size, $F(2, 22) = 57.26$, MSE = 7820.29, $p < .001$, $\eta_p^2 = .84$, however, neither the main effect of block, $F < 1$, $\eta_p^2 < 0.1$, nor the Block × Display Size interaction approached significance, $F(2, 22) = 1.48$, MSE = 4042.89, $p = .25$, $\eta_p^2 = .12$.

Standard Preview trials only: RTs increased with display size, $F(2, 22) = 26.08$, MSE = 5122.59, $p < .001$, $\eta_p^2 = .70$, and RTs were shorter overall in the 80%

standard preview block than in the 80% jump block, $F(1,11) = 9.40$, MSE = 14688.32, $p < .05$, $\eta_p^2 = .46$. However, of most relevance, search efficiency, as measured by the Block × Display Size interaction, did not differ between the two types of block ($F < 1$), with slopes of approximately 12 ms/item for both blocks.

Error rates. Error rates were low overall (1.44%) and are shown in Table 6. A 2 (Block: 80% Jump or 80% Standard) × 2 (Trial type: Jump or Standard) × 3 (display size) repeated-measures ANOVA revealed that there were no significant main effects or their interactions; block, $F(1, 11) = 3.02$, MSE = 8.98, $p = .11$, $\eta_p^2 = .22$ and display size, $F(2, 22) = 2.42$, MSE = 5.52, $p = .11$, $\eta_p^2 = .18$, all remaining *F*s < 1, $\eta_p^2 < 0.1$. The overall error rate on catch trials was 4.17% and these were not analyzed further.

Table 6. *Mean percentage error rates for Experiment 3.*

	Display size		
	4	8	16
80% Jump block			
Jump trials	1.22	0.52	1.91
Standard trials	0.69	0	1.39
80% Standard block			
Jump trials	0.69	2.08	2.78
Standard trials	1.91	1.56	1.91

Discussion

Experiment 3 aimed to determine if the strategic use of inhibition would emerge when the old items changed both their locations and their colours throughout the preview period. As in the previous experiments, search efficiency was reduced in the jump trials compared with the standard preview trials, demonstrating that the colour and location manipulation abolished the preview benefit. However, of most relevance, there was again no reliable difference between search efficiency on the standard preview trials in the 80% standard preview and 80% jump blocks. Although there was no evidence for a difference in search slopes, there was evidence that overall RTs were shorter in the 80% standard preview block than in the 80% Jump block. It is also the case that a preview benefit is sometimes exhibited in overall RTs, rather than search slopes (e.g., Al-Aidroos et al., 2012; Blagrove & Watson, 2010). However, specifically in the present work, I suggest treating this difference with some caution. This is because an overall difference in RT can also reflect differences in arousal, alerting, and warning signal effects (see Watson & Humphreys, 1997). It is possible that the onset of the preview items act as a warning or alerting signal for the onset of the search display. Here, the presentation of the preview display in a Standard Preview trial might act as a more reliable warning signal for the onset of the search display, than the more complex multi-jump preview displays in the jump trials. When a block contains mostly standard preview trials, participants might be more sensitive to the preview-based warning signal than when a block contains fewer standard preview trials. This would lead to a reduction in overall RTs in the 80% standard preview block. Hence, in the present work, I prefer to place most interpretational emphasis on the search slope measure of the preview benefit rather than on overall RT differences.

In summary, participants continued to apply inhibition to the old items, even when: 1) it would only have been effective on 20% of the trials and, 2) it was clear that the old items changed their locations and colours before the new items arrived. It follows that the constant colour of the old items throughout the preview period in Experiments 1 and 2 was unlikely to be responsible for the continued application of inhibition, even when the inhibition would clearly be ineffective on the majority of trials.

Comparison of Experiments 2 and 3

In order to increase statistical power and to compare any potential differences between Experiments 2 and 3 directly, the data from Experiments 2 and 3 were combined, adding ‘Experiment’ as a between-subjects factor. Mean combined correct RTs for trials in the jump and standard preview blocks are shown in Figure 11 with the combined search slope statistics and error rates shown in Tables 7 and 8.

Reaction times. The overall pattern of results was similar to that of the individual analyses for Experiments 2 and 3. There was a significant main effect of trial type, $F(1, 22) = 27.42$, MSE = 6339.48, $p < .001$, $\eta_p^2 = .55$, and of display size, $F(2, 44) = 122.51$, MSE = 7412.06, $p < .001$, $\eta_p^2 = .84$, but no effect of block, $F(1, 22) = 1.44$, MSE = 8.98, $p = .24$, $\eta_p^2 = .06$. In addition, the main effect of experiment was also non-significant, $F < 1$. The Block × Trial Type interaction was significant, $F(2, 44) = 122.51$, MSE = 7412.06, $p < .001$, $\eta_p^2 = .84$, as was the Trial Type × Display Size interaction, $F(2, 44) = 15.09$, MSE = 3897.47, $p < .001$, $\eta_p^2 = .41$. No other main effects or their interaction were significant, all Fs < 2.08, ps > 0.13, η_p^2s < 0.06. Importantly, the absence of a Block × Display Size interaction suggests that there is no strategic control when location-based or both location-based and feature-based inhibition is disrupted. Planned comparisons assessed the two standard preview and the two jump conditions individually.

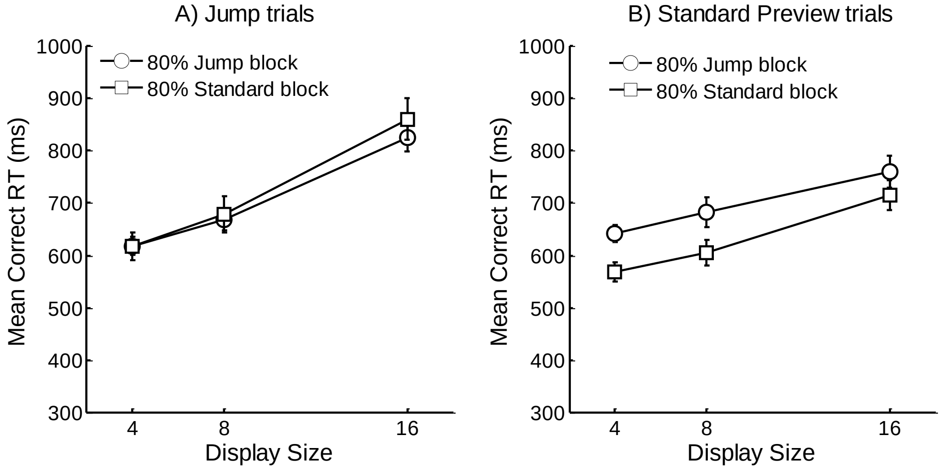

Figure 11. Mean correct RTs for jump trials (Panel A) and standard preview trials (Panel B) as a function of block and display size for Experiment 2 & 3 combined. Error bars represent standard errors. If inhibition was being applied strategically, we would expect more efficient search for standard preview trials in the 80% Standard preview block than in the 80% jump block.

Table 7. *Search slope statistics for Experiments 2 and 3 combined.*

	80% Jump block		80% Standard preview block	
	Jump trials	Standard trials	Jump trials	Standard trials
Slope (ms/item)	17.68	9.87	17.61	12.57
Intercept	539.17	602.7	542.66	512.44
R^2	0.98	0.99	0.99	0.99

Jump trials only: There was no significant main effect of block, $F < 1$, while the main effect of display size was significant, $F(2, 44) = 96.97$, MSE = 6877.21, $p < .001$, $\eta_p^2 = .82$. The Block × Display Size interaction was not reliable, $F(2, 44) = 1.21$, MSE = 3419.87, $p = .31$, $\eta_p^2 = .05$, and neither was the Display Size × experiment interaction, $F(2, 44) = 2.45$, MSE = 6877.32, $p = .09$, $\eta_p^2 = .10$. In addition, the between-subjects main effect of experiment, the Block × Experiment, and the Block × Display Size × Experiment interaction did not reach significance, *F*s < 1, η_p^2s < 0.1.

Standard preview trials only*:* There was a significant effect of block, indicating longer overall RTs in the 20% standard block, $F(1, 22) = 6.59$, MSE = 23151.56, $p < .05$, $\eta_p^2 = .23$. The main effect of display size was also significant, $F(2, 44) = 50.97$, MSE = 4432.21, $p < .001$, $\eta_p^2 = .70$. The between-subjects effect of experiment did not prove to be significant, nor did the Block × Display Size, Block × Experiment, or Display Size × Experiment interactions, all *F*s < 1, η_p^2s < 0.1. The Block × Display Size × Experiment interaction was also not significant $F(2, 44) = 1.73$, MSE = 4366.05, $p = .19$, $\eta_p^2 = .07$.

Error rates. Errors were analyzed in the same way as the RT data. There was a significant main effect of display size, $F(2, 44) = 5.17$, MSE = 4.47, $p < .05$, $\eta_p^2 = .19$, indicating that error rate increased with display size. There was no significant main effect of block, $F(1, 22) = 1.62$, MSE = 12.72, $p = 0.22$, $\eta_p^2 = .07$, nor Block × Trial Type, $F(1, 22) = 1.05$, MSE = 5.16, $p = .32$, $\eta_p^2 = .05$, Block × Display Size × Experiment, $F(2, 44) = 1.97$, MSE = 7.65, $p = .15$, $\eta_p^2 = .08$, and Block × Display Size × Trial Type × Experiment, $F(2, 44) = 2.65$, MSE = 3.60, $p = .08$, $\eta_p^2 = .11$, interactions. The Block × Display Size, Block × Experiment, Trial Type × Experiment, Block × Trial Type × Experiment, Trial Type × Display Size interactions, Display Size × Experiment, Trial Type × Display Size × Experiment, and Block × Trial Type × Display Size interactions were all non-significant, Fs < 1, η_p^2 s < 0.1.

Table 8. *Mean percentage error rates for Experiments 2 and 3 combined.*

	Display size		
	4	8	16
80% Jump block			
Jump trials	0.78	0.95	2.34
Standard trials	0.69	0.69	1.39
80% Standard block			
Jump trials	1.39	1.39	2.08
Standard trials	1.82	1.30	2.08

Discussion

The findings suggest that: 1) having the items change both location and colour was no more disruptive to the preview benefit than having them simply change location, and 2) location and colour changes in the previewed items were no more effective at prompting the strategic use of inhibition than location changes alone. Taken together, the results from Experiments 1 to 3 show that, even when inhibition is disrupted on the majority of trials, people continue to apply it.

So far, the effectiveness of applying inhibition has been manipulated by disrupting the inhibition applied to the old items (i.e., via changes in their location and colour). Participants appeared insensitive to these disruptions and continued to apply inhibition. However, given that the blocks consisted of an 80:20 mix of different trials, participants might have chosen to adopt a single inhibitory strategy, because it would still have been effective in improving search efficiency, even if only on a minority of trials. Furthermore, there was no way for participants to be able to predict whether a jump or standard preview trial was to appear next and so, they would not have been able to modulate their inhibition on a trial-by-trial basis. Experiment 4 examined whether participants will modulate their application of inhibition if given advance information regarding the type of trial that will appear.

Experiment 4: Cued Location-Based Disruptions of Inhibition

In Experiments 1-3, participants continued to apply inhibition throughout both standard preview and jump blocks. However, even though cognitive resources are consumed by applying inhibition, alternative strategies might have created even greater cognitive costs. For example, participants did not know whether a jump or a standard preview trial was going to occur until sometime into the actual trial. By that stage, it might have been difficult or costly to reconfigure their attentional set (i.e., apply or withhold inhibition). Thus, a simple strategy of always applying inhibition might have appeared the easiest and most efficient approach. Furthermore, participants might have placed more decisional weight on the trials in which inhibition would have been helpful, and might have been unaware of the full extent of the 80:20 and 20:80 ratio of trials (i.e., on which inhibition would have been useful). If this is the case, then participants might apply inhibition strategically if they know in advance of each trial, whether the application of inhibition would be effective or not. In Experiment 4, this was probed by providing participants with advance information directly before each trial as to whether the trial would be: 1) a standard preview trial (in which inhibition would be useful), or 2) a jump trial (in which any inhibition would be disrupted, and therefore not effective). Specifically, directly before each trial participants were presented with an 80% valid visual cue, which informed them whether the next trial would be a jump trial or a standard preview trial (see Figure 12).

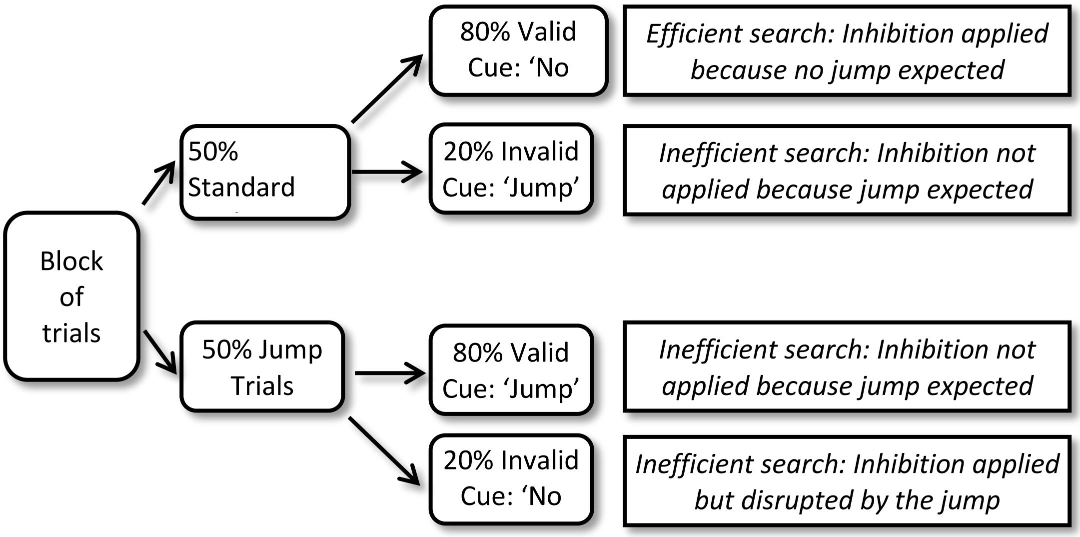

Figure 12. Summary of the design of Experiment 4 (rounded boxes) and search efficiency predictions if participants apply inhibition strategically (square boxes).

If participants applied inhibition strategically, we would expect search to be more efficient on validly cued standard preview trials (participants would expect a standard preview trial and apply inhibition), than on invalidly cued standard preview trials (participants would expect a jump trial and not apply inhibition). In contrast, on jump trials, cue validity should have little effect. This is because on validly cued jump trials, participants would not apply inhibition (i.e., because they were expecting a jump). On invalidly cued jump trials, participants would expect a standard preview trial and apply inhibition, but the inhibition would be rendered ineffective because of the jump (as in Experiment 1).

Method

Participants. Twelve students from the University of Warwick (3 male, 9 female) aged between 21 and 37 years (*M* = 25.25, *SD* = 4.71) participated in exchange for payment. They did not take part in the previous experiments.

Stimuli, apparatus, and procedure. The apparatus and procedure were similar to those of Experiments 1-3. However, in Experiment 4, each trial was preceded with the words (the cue) ‘Jump’ or ‘No Jump’ presented for 1500 ms displayed at the screen center. Following the cue there was a blank screen (500 ms), followed by a central fixation dot (750 ms), after which the preview/search displays were presented. Consistent with previous experiments, there were two blocks with 180 search trials and 18 catch trials. Whereas blocks in the preceding experiments contained an unequal proportion (80:20 and 20:80) of jump and standard preview trials, in the current experiment both blocks were identical. Each block consisted of 50% jump trials and 50% standard preview trials. For both types of trials, the pre-trial cue was 80% valid. That is, 80% of jump trials were cued validly as *jump* trials, and 20% were cued invalidly as *No Jump* trials. Similarly, 80% of the standard trials were cued validly as *No Jump* trials and 20% were cued invalidly as *Jump* trials.

The stimuli were the same as in Experiment 1, because the multiple jumps or colour changes as used in Experiments 2 and 3 would have provided additional cues of trial type, prior to the final search display. This could have discouraged participants from following the written cues, and would have confounded trials that were invalidly cued.

Results

Reaction times. There were no outliers in the data (RTs less than 200 ms or greater than 10,000 ms). Mean correct RTs for jump and standard preview trials are shown in Figure 13 and Table 9 shows the search slope statistics. Mean correct RTs were analyzed using a 2 (Cue Validity: Valid or Invalid) × 2 (Trial Type: Jump or Standard Preview) × 3 (Display Size) within subjects ANOVA. Standard preview trials were faster than jump trials, $F(1,11) = 106.03$, MSE = 3326.79, $p < .001$, $\eta_p^2 = .91$, and RTs increased with display size, $F(2,22) = 63.39$, MSE = 5511.80, $p < .001$, $\eta_p^2 = .85$. RTs also increased more as display size increased on jump trials than on standard preview trials, $F(2,22) = 29.45$, MSE = 2654.61, $p < .001$, $\eta_p^2 = 29.45$. There was no significant effect of validity, nor was there significant interactions of Validity × Trial Type, Validity × Display Size, and Validity × Trial Type × Display Size, all Fs < 1. As above, to confirm these results for the two trial types individually, two separate planned comparisons were carried out.

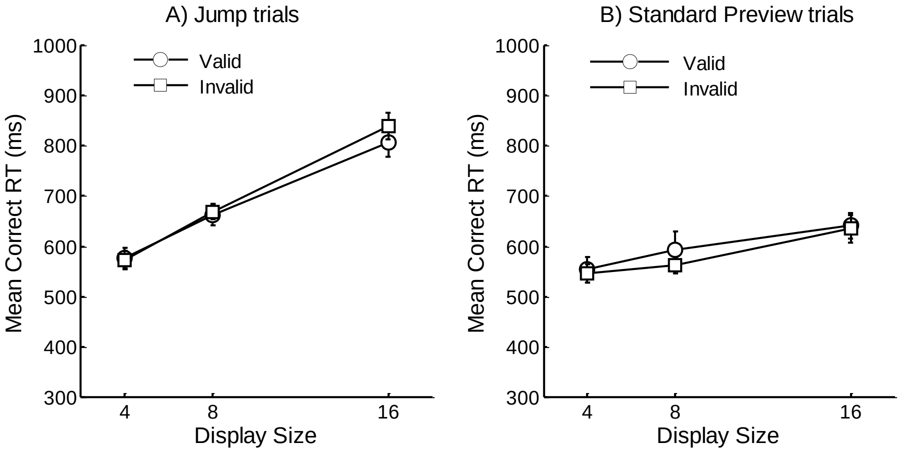

Figure 13. Mean correct RTs for jump trials (Panel A) and standard preview trials (Panel B) as a function of block and display size for Experiment 4. If inhibition was being applied strategically, we would expect that for standard preview trials, search

would be more efficient on validly cued (cued 'No Jump') trials than on invalidly cued trials (cued 'Jump').

Table 9. *Search slope statistics for Experiment 4*

	Valid trials (80%)		Invalid trials (20%)	
	Jump trials	Standard trials	Jump trials	Standard trials
Slope (ms/item)	18.99	7.13	22.11	7.61
Intercept	504.67	529.68	487.56	510. 24
R^2	0.99	0.98	0.99	0.97

Jump trials. RTs increased as display size increased, $F(2,22) = 67.01$, MSE = 5654.65, $p < .001$, $\eta_p^2 = .86$. However, neither the main effect of cue validity, nor the Cue Validity × Display Size interaction reached significance, Fs < 1, η_p^2 s < 0.1.

Standard preview trials. RTs increased with display size, $F(2,22) = 19.38$, MSE = 2511.77, $p < .001$, $\eta_p^2 = .64$. However, there was no significant effect of cue validity and cue validity did not interact with display size, both Fs < 1, η_p^2 s < 0.1.

Error rates. Overall error rates were low (0.99%) and are shown in Table 10. A three-way repeated-measures ANOVA showed that there was a borderline significant effect of trial type, $F(1, 11) = 4.42$, MSE = 11.47, $p = .06$, $\eta_p^2 = .29$. However, the main effects of validity, display size, and all interactions were non-significant, all Fs < 1, η_p^2s < 0.1. On catch trials, the overall error rate was 3.01% and these data were not analyzed further.

Table 10. *Mean percentage error rates for Experiment 4.*

	Display size		
	4	8	16
Valid trials			
Jump trials	0.69	0.87	1.91
Standard trials	0.52	0.17	0.52
Invalid trials			
Jump trials	1.39	1.39	3.47
Standard trials	0.69	0.00	0.69

Discussion

One possibility for why participants did not apply inhibition strategically throughout Experiments 1 to 3 is that there was no information available to them directly before each trial indicating whether or not inhibition would be useful. Given that inhibitory processing would still have been useful overall (even if only on a minority of trials), participants might have chosen to apply it on every trial. Furthermore, even though the presence of changes in the previewed items would have been very salient on a trial-by-trial basis (especially in Experiments 2 and 3), the extent of the 20:80 and 80:20 trial distribution might not have been as salient. This is especially the case if participants had weighted their decisional focus or overall strategy on trials in which inhibition would have helped task performance. To test this, in Experiment 4 participants were explicitly cued in advance of each trial as to whether it would be a jump or a standard preview trial.

If inhibition was applied in a strategic manner then we would expect to find a difference in search performance, when comparing validly cued standard preview trials (in which participants should have applied inhibition to the preview items) with invalidly cued standard preview trials (in which participants should have withheld inhibition). However, there was no hint that this was the case, with search slopes on validly cued standard preview trials being 7.13 ms/item, compared with 7.61 ms/item for invalidly cued standard preview trials. As in previous experiments, search on jump trials was much less efficient than on standard preview trials (~20 ms/item vs. ~7 ms/item), confirming that changing the locations of previewed items when new elements were added was sufficient to abolish a preview benefit. The find of a relatively large difference in search slopes between the standard preview and jump trials also confirms that there was enough ‘room’ for standard preview search to become less efficient, if participants had chosen not to apply inhibition on the validly cued standard preview trials.

Overall, the findings confirm the conclusions obtained from Experiments 1 to 3 that participants appear to apply inhibition in time-based visual selection with little or without any strategic modulation. Moreover, the results of Experiment 4 show, 1) that this is not simply because participants were unaware of changes, 2) nor was it because there were unsure of the overall distribution of trials in which inhibition would have been helpful, and 3) the lack of strategic inhibitory control was not due to insufficient time for participants to readjust their attentional sets within a trial.

Of note in Experiments 1 to 4, participants had to search through the display in order to find the target item. Search was relatively inefficient, with search slopes on Jump trials of approximately 20 ms/item, which equates to a search rate of around 40 ms/item. Participants could respond as soon as they had found the target item. For a classic serial search (Treisman & Gelade, 1980), this would lead to participants searching through approximately half of the display items on each trial. Hence, the actual search rate through stimuli is approximately half (i.e., the search slope is double) of that obtained on target present trials. It is possible that inhibition might be applied by default in any time-based selection tasks in which a relatively inefficient search has to be made. This type of behaviour might well be adaptive, if the cost of applying inhibition is relatively low compared to the potential cost of missing a predator in complex (i.e., inefficient) search conditions. To examine this possibility, in Experiment 5 the global ‘search environment’ was changed by introducing trials in which the target was easily detected without the need for search processes.

Experiment 5: Inhibition in Salient Preview Search Contexts

Experiment 5 assessed whether inhibition is applied strategically when target detection can be performed without having to search the display on a minority or majority of occasions. It is possible that inhibition is applied by default (a safe strategy) only when target detection requires effortful search. If a majority of trials do not require the engagement of search processes to find the target then this might trigger participants to stop applying inhibition.

In outline, the standard preview trials were the same as those presented in Experiments 1 to 4, consisting of a preview display of pink squares, followed by the addition of a search display containing blue circles and a blue square target item. However, the *jump trials* were replaced with *salient trials*. On a salient trial, pink squares appeared for 1000 ms, followed by the addition of a *single* blue square target. Thus, on salient trials, the target would be easily detected, because it would be a singleton blue item which was accompanied by a unique luminance onset within the display. Accordingly, on salient trials, there would be no need to inhibit the old previewed items, because the target would pop-out (Treisman & Gelade, 1980) from the display.

If top-down inhibition operates by default, then it should be applied whenever the previewed items are presented – here, we should expect no difference between blocks of trials with many salient trials, compared with few salient trials.

However, if inhibition is subject to the observer's control, then it might not be applied if it is expected that the subsequent search will be easy (i.e., the target will be obvious and minimal, if any, search will be needed to locate it).

Method

Participants. Twelve students (6 male, 6 female) from the University of Warwick aged 20 to 26 years (*M* = 23.41, *SD* = 1.92) participated for course credit or payment. They did not participate in any of the previous experiments.

Stimuli, apparatus, and procedure. The stimuli, apparatus, and procedure were similar to those of Experiment 1-4, except that jump trials were replaced by salient trials. Thus one block of trials consisted predominantly of 80% standard preview trials and 20% salient trials and the other block consisted of 20% standard preview trials and 80% salient trials. A salient trial consisted of the presentation of pink squares displayed for 1000 ms, after which a single blue square target was added to the display. There were no additional distractors in the second set of items. Thus, the display sizes for salient trials consisted of 3, 5, and 9 items in total (see Figure 14). The standard preview trials were identical to those in Experiment 1.

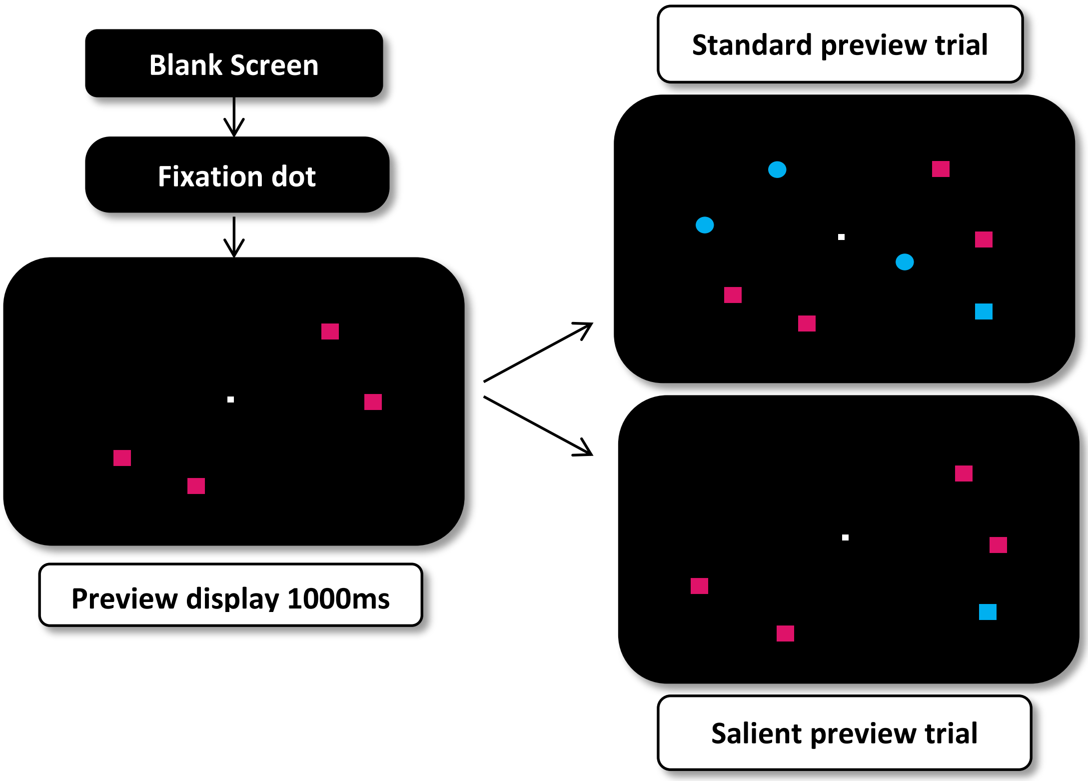

Figure 14. Example trial sequence from Experiment 5 where white represents pink and grey represents blue (not drawn to scale). The task was to indicate the location (left/right of center) of the blue square which appeared amongst the second set of items. On a *standard preview* trial, the new items were added to the preview items. On a *salient preview* trial, only the single blue square was added. The mostly standard block consisted of 80% standard preview trials and 20% salient trials. This ratio was reversed for the mostly salient block.

Results

Reaction times. Trials with RTs less than 200 ms or greater 10,000 ms were removed as outliers (0.26 % of the data). Mean correct RTs for salient and standard preview trials are shown in Figure 15, and the mean search slope statistics are shown in Table 11. As the display sizes for the salient and standard preview trials differed (3, 5, and 9 items vs. 4, 8, and 16 items), two separate 2 (Block: 80% salient or 80%

standard preview) × 3 (Display size) ANOVAs were performed for each trial type in order to compare search efficiency in each block.

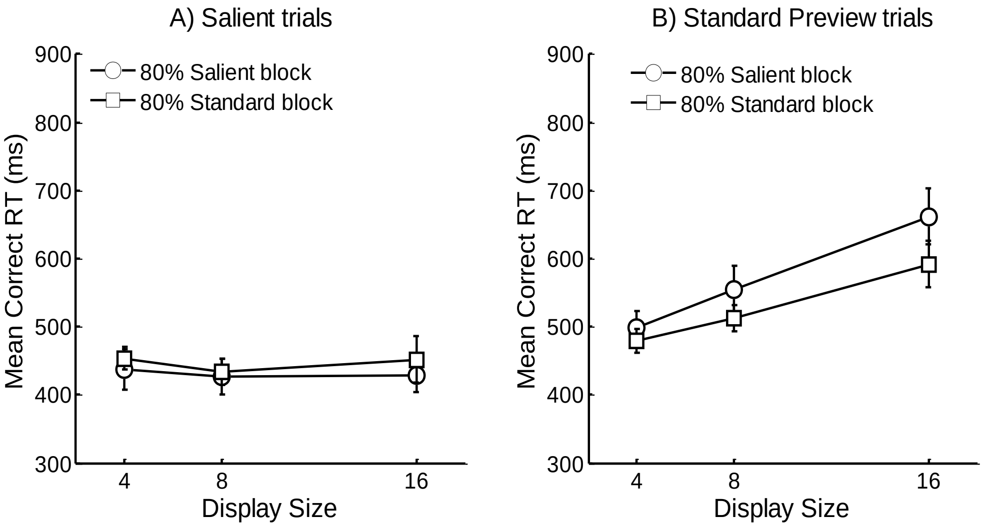

Figure 15. Mean correct RTs for salient trials (Panel A) and standard preview trials (Panel B) as a function of block and display size for Experiment 5. Error bars represent standard errors. If inhibition was being applied strategically we would expect more efficient search for standard preview trials in the 80% standard preview block than in the 80% salient block.

Table 11. *Search slope statistics for Experiment 5.*

	80% Salient Block		80% Standard preview block	
	Salient Trials	Standard Trials	Salient Trials	Standard Trials
Slope (ms/item)	-1.17	13.57	0.32	9.49
Intercept	437.34	445.29	444.67	439.18
R^2	0.48	0.99	0.01	0.99

Standard preview trials: For the standard preview trials, there was a marginally significant effect of block $F(1,11) = 4.29$, MSE = 8178.49, $p = .062$, $\eta_p^2 = .28$, and a significant effect of display size $F(2,22) = 67.64$, MSE = 1761.18, $p < .001$, $\eta_p^2 = .86$. However, of most relevance was a significant Block × Display Size interaction $F(2,22) = 4.18$, MSE = 912.58, $p < .05$, $\eta_p^2 = .28$, indicating that the display size affected the RTs of standard preview trials more in the 80% salient block than in the 80% standard preview block.

Salient trials: There were no significant main effects or their interaction; block, $F(1,11) = 2.19$, MSE = 2048.30, $p = .17$, $\eta_p^2 = .17$, display size, Block × Display size, both Fs < 1, η_p^2 s < 0.1.

Error rates. Error rates were low overall (1.41%) and are shown in Table 12. Again, due to the difference in display sizes, separate 2 (Block: 80% Salient or 80% Standard Preview) × 3 (Display Size) ANOVAs were performed for each trial type.

Table 12. *Mean percentage error rates for Experiment 5*

Salient trials			
Condition		Display size	
	3	5	9
80% Salient block	0.69	0.69	1.74
80% Standard block	0.00	0.00	2.08
Standard preview trials			
Condition		Display size	
	4	8	16
80% Salient block	1.39	5.56	3.47
80% Standard block	1.56	0.87	1.91

Standard preview trials: There were more errors overall in the 80% salient block than the 80% standard preview block, $F(1,11) = 5.01$, MSE =14.53, $p < .05$, $\eta_p^2 = .32$. However, neither the main effect of display size, $F(2,22) = 1.12$, MSE = 15.89, $p = .32$, $\eta_p^2 = .09$, nor the Block × Display Size interaction approached significance, *F*(2,22) = 2.37, MSE =15.37, *p* = 12, η_p^2 = 17. The overall error rate on catch trials was 4.16 %, and these data were not analyzed further.

***Salient trials**:* Errors increased as the display size increased, *F*(2,22) =4.30, MSE =4.54, *p* < .05, η_p^2 = .28. However, there was no significant main effect of block, *F* < 1, η_p^2 < 0.1.or a significant Block × Display Size interaction, *F*(2,22) = 1.13, MSE = 1.91, *p* = .34, η_p^2 = .09.

Comparing Standard Preview trials in Experiments 1 and 5

Reaction times. In order to examine whether performance on preview trials in the salient block in Experiment 5 differed from standard preview trials in other experiments, I compared them to those in Experiment 1 using a 2(Block: 80% standard preview block or 80% jump block) × 3(Display Size: 4,8, or 16) mixed ANOVA with experiment as the between-subject variable. There was no main effect of experiment, *F* < 1, η_p^2 < 0.1. This is likely because both trial types were standard preview trials. There was a main effect of display size, *F*(2,44) = 14.33, MSE = 4236.61, *p* < .001, η_p^2 = .39. There was no Block × Display size interaction, *F*(2,44) = 1.90, MSE = 4013.04, *p* = .169, η_p^2 = .08. No other main effect of interaction proved significant, all *F*s < 1, η_p^2 s < 0.1.. The absence of the three-way Block × Display Size × Experiment interaction would suggest that the difference observed between standard preview trials in the two block types between the two experiments is not significant. However, given that the effect in Experiment 5 is relatively small, any differences could have been masked by between-subject variability in the two experiments. Watson and Maylor (2005) argue that a within-subject analysis (comparing preview efficiency to a baseline efficiency) is sufficient and the most sensitive analysis as to whether the preview benefit has occurred. Thus, the lack of an interaction between Experiments 1 and 5 does not compromise the presence of the effect in Experiment 5.

Errors. There was no between-subjects effect of experiment, $F(1,22) = 2.25$, MSE = 19.37, $p = .148$, $\eta_p^2 = .09$. There was no Display Size × Experiment interaction, $F(2,44) = 1.22$, MSE = 4.91, $p = .305$, $\eta_p^2 = .05$. No effects or their interactions proved significant, all *F*s < 1, η_p^2 s < 0.1.

Discussion

The main purpose of Experiment 5 was to determine whether inhibition would be applied strategically, if the target was salient on a minority/majority of trials. Search slopes on salient trials were essentially flat, confirming the prediction that salient trials would produce efficient target detection. However, of most interest, and in contrast to Experiments 1 to 4, a difference in performance was now found between the standard preview trials across the two blocks of trials in which the ratio of standard to salient trials was manipulated. Specifically, when the block contained a minority of salient trials, RTs on standard preview trials were marginally faster overall, and search slopes were flatter than when the block of trials contained a majority of salient trials. This suggests that when the majority of trials within a search task do not require attentional search, participants do not apply (or are less likely to apply) inhibition to old, previewed distractors.

Experiment 6: Testing Alternative Accounts

Although the results of Experiment 5 are compatible with an account that suggests the strategic application of inhibition, there remain alternative explanations. First, it is possible that increasing the number of easy pop-out searches within a block of trials encouraged participants to change their style of search. Specifically, a greater ratio of pop-out trials might encourage participants to adopt a more passive style of visual search compared with a more active search style. For example, Smilek et al. (2006) found that actively instructing participants to adopt a passive style of search produced more efficient search (shallower search slopes) than instructing participants to adopt an active style of search. However, this account seems unlikely, because if more passive search results in increased search efficiency, then we would expect that search would have been more efficient in the 80% Salient block of trials than in the 80% standard preview block of trials. However, the opposite was found in Experiment 5, with search in the 80% standard preview block being *more* efficient than search in the 80% salient block.

An alternative version of this account might, however, still hold. If passive search is less influenced by top-down preview inhibition, or if adopting a passive search strategy interferes with the deployment of top-down inhibition, then search would become *less* efficient in the 80% salient block of trials. By this account, adopting a passive attentional set might prevent the adoption of a more active and top-down inhibitory set against the previewed items. This account has some links to the finding that maintaining an attentional set for secondary load tasks can reduce the preview benefit (Humphreys et al., 2002).

A further alternative account can be developed on the basis of intertrial priming. Previous work has shown that when the target and distractor features do not change over consecutive trials, RTs can decrease (e.g., Becker, 2008ab; Lamy, Antebu, Aviani & Carmel, 2008; Maljkovic & Nakayama, 1994). Recall that in the standard preview trials, participants searched for a blue square among blue circles and pink squares. On the salient trials, participants only needed to search for a blue luminance-onset square. Now, in the 80% standard preview block, there would have been many trials on which the standard preview trial target and distractor identities would have been repeated over consecutive trials. Such repetition of target and distractor features might have led to a reduction in RTs/improved search efficiency as the number of repeats increased. In contrast, when only 20% of the trials were standard preview trials, there would have been fewer repeats of the target-distractor identities and so the improvement by priming would have been much less. According to this account, the improved search efficiency in the 80% standard preview block (i.e., compared with the 80% salient block) represents a difference in the amount of target-distractor intertrial priming, rather than reflecting a difference in the application of inhibition to the previewed distractors. Going somewhat against this account, previous findings show that priming effects due to repetition of target and distractor features over consecutive trials usually produce a benefit in overall reaction times, and have little effect on search slopes (e.g., Geyer, Müller, & Krummenacher, 2006). Instead, in Experiment 5, any such repetition priming produced a marginal effect on overall RTs, but more importantly, there was also a significant reduction in search slope.

Nonetheless, to address these potential alternatives in Experiment 6, the conditions of Experiment 5 were repeated, except that rather than presenting preview displays, all the stimuli were presented simultaneously. That is, standard preview trials were replaced with standard FEB trials, which had no preview gap. FEB trials are used in preview search studies as a search efficiency baseline that does not involve the use of inhibition (Watson & Humphreys, 1997, 1998). If changes in search strategy or differences in inter-trial priming can account for the results of Experiment 5, then we should obtain a similar pattern of results when all the stimuli are presented at the same time, given that the stimuli are identical to those of Experiment 5.

Method

Participants. Twelve students from the University of Warwick (all female) aged 18 to 19 (*M* = 18.17, *SD* = 0.39) participated for course credit. They did not take part in any of the previous experiments.

Stimuli, apparatus, and procedure. The stimuli, apparatus and procedure were the same as in Experiment 5, with the exception that all the search stimuli were presented simultaneously.

Results

Reaction times. There were no outliers (trials with RTs less than 200 ms or greater 10,000 ms) in the data. Mean correct RTs for the salient and standard FEB trials are presented in Figure 16, and mean search slope statistics in Table 13. As in Experiment 5, two separate 2 (Block: 80% Salient trials or 80% Standard FEB trials) × 3 (Display Size) ANOVAs were conducted for each trial type, due to differences in display sizes (3, 5, and 9 items on Salient trials vs. 4, 8, and 16 items on Standard FEB trials).

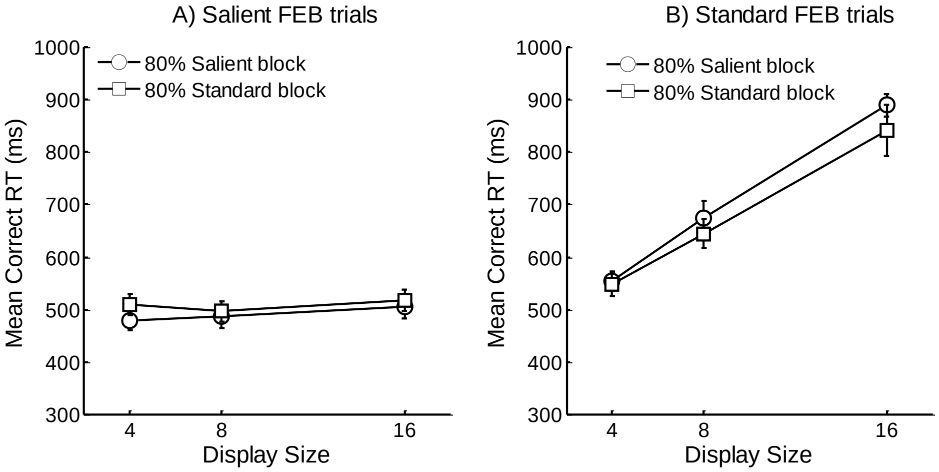

Figure 16. Mean correct RTs for salient FEB trials (Panel A) and Standard FEB trials (Panel B) as a function of block and display size for Experiment 6. Error bars represent standard errors.

Table 13. *Search slope statistics for Experiment 6.*

	80% Salient FEB Block		80% Standard FEB Block	
	Salient Trials	Standard Trials	Salient Trials	Standard Trials
Slope (ms/item)	4.30	27.86	1.99	24.52
Intercept	465.58	446. 59	496.22	448.93
R^2	0.99	0.99	0.31	1

Standard FEB trials: There was a significant effect of display size, *F*(2,22) = 86.66, MSE = 7093.17, $p < .001$, $\eta_p^2 = .89$. However, neither the main effect of block, *F*(1,11) = 1.97, MSE = 7555, $p = .19$, $\eta_p^2 = .15$ nor the Block × Display Size interaction, $F < 1$, $\eta_p^2 < 0.1$, were significant. Thus, there was no evidence that search was faster overall or more efficient in the 80% Standard FEB block of trials compared with the 80% Salient trials block.

Salient trials: RTs increased at a rate of approximately 3 ms/item as display size increased, *F*(2,22) = 4.08, MSE = 685.99, $p < .05$, $\eta_p^2 = .27$. However, neither the main effect of block, *F*(1,11) = 1.69, MSE = 3296.43, *p* = .22, η_p^2 = .13 nor the Block × Display Size interaction, *F*(2,22) = 1.54, MSE = 444.87, *p* = .24, η_p^2 = .12 proved significant.

Error rates. Error rates were low overall (1.18%), and are presented in Table 14. Errors were analyzed using two separate 2 (Block: 80% Salient or 80% Standard FEB trials) × 3 (Display Size) ANOVAs for each trial type. The overall error rate on catch trials was 4.63%, and catch errors were not analyzed further.

Table 14. *Mean percentage error rates for Experiment 6*

	Salient FEB trials		
Condition	Display size		
	3	5	9
80% Salient FEB block	0.35	0.52	0.52
80% Standard FEB block	1.39	0.69	2.78
	Standard FEB trials		
Condition	Display size		
	4	8	16
80% Salient FEB block	1.39	2.78	4.17
80% Standard FEB block	1.22	1.39	1.56

***Standard FEB trials**:* There were no significant main effects of block, *F*(1,11) = 2.61, MSE = 13.28, *p* = .13, η_p^2 = .19, or display size, *F*(2,22) = 1.33, MSE = 11.03, *p* = .29, η_p^2 = .11. The Block × Display Size interaction was also non-significant, *F* < 1, η_p^2 < 0.1.

***Salient trials**:* There were more errors in the 80% standard FEB block than in the 80% salient block, *F*(1,11) = 5.50, MSE = 4.38, *p* < .05, η_p^2 = .33. However, there was no significant effect of display size or a significant Block × Display Size interaction, both *Fs* < 1, η_p^2 s < 0.1.

Comparison of Experiments 5 and 6

In order to examine whether performance in standard trials differed across preview and FEB search contexts in experiments 5 and 6, I examined the standard trials from these experiments together with ‘Experiment’ as a between-subjects factor.

A 2(Block: 80% Standard or 80% Salient) × Display Size (4,8 or 16 items) – within-subjects ANOVA revealed a main effect of block, $F(1,22) = 6.09$, MSE = 7866.79, $p < .05$, $\eta_p^2 = .22$, and a main effect of display size, $F(2,44) = 143.99$, MSE = 4427.17, $p < .001$, $\eta_p^2 = .50$, and significant between-subjects effect of experiment, $F(1,22) = 13.18$, MSE = 55338.49, $p < .005$, $\eta_p^2 = .38$. This was expected, since Experiment 6 represented FEB trials, and Experiment 5 represented preview trials. There was also a significant Display Size × Experiment interaction, $F(2,44) = 21.77$, MSE = 4427.17, $p < .001$, $\eta_p^2 = .49$, suggesting that RTs were longer for larger display sizes in the FEB experiment than the in the preview experiment. The Block × Display Size interaction was significant, $F(2,44) = 3.48$, MSE = 1846.27, $p < .05$, $\eta_p^2 = .14$, suggesting longer RTs with increasing display size in the 80% salient search context. There was no Block × Experiment, and no Block × Display Size × Experiment interaction, both Fs < 1, η_p^2 s< 0.1. The lack of this three-way interaction differed to that of the individual analysis of Block × Display Size in Experiments 5 and 6, which suggested a differential interactions across experiments (presence of an interaction in Experiment 5 and absence of an interaction in Experiment 6). This lack of interaction is likely to be due to the Block × Display Size effects observed in Experiment 5 being relatively modest, and thus between-subject variability could have masked the effect. The within-subject comparison in

Experiment 5 remains the most sensitive analysis as to the presence of the effect (see Watson & Maylor, 2005).

Errors. Error rates for standard trials in experiments 5 and 6 were analysed with a 2(Block: Salient or Standard) × 3(Display size: 4,8 or 16 items) ANOVA with experiment as the between-subjects variable. There was a significant effect of experiment, $F(2,44) = 6.14$, MSE = 7.17, $p < .05$, $\eta_p^2 = .22$. More errors were made in the FEB experiment (Experiment 6) than in the preview experiment (Experiment 5). There was no effect of condition, $F(1,22) = 2.52$, MSE = 6.64, $p = .126$, $\eta_p^2 = .10$, display size, $F(2,44) = 1.36$, MSE = 5.52, $p = .269$, $\eta_p^2 = .06$, nor a Condition × Experiment, $F(1,22) = 2.71$, MSE = 6.64, $p = .114$, $\eta_p^2 = .11$, Display Size × Experiment, $F(2,44) = 1.36$, MSE = 7.47, $p = .269$, $\eta_p^2 = .06$, Display Size × Condition × Experiment, $F(2,44) = 1.00$, MSE = 4.46, $p = .376$, $\eta_p^2 = .04$, and Condition × Display Size interaction, $F < 1$, $\eta_p^2 < 0$.

Discussion

The main purpose of Experiment 6 was to test whether a shift to a passive search strategy, or intertrial priming effects could account for the results of Experiment 5, rather than being due to the strategic application of inhibition. This was achieved by repeating the conditions of Experiment 5, except that all stimuli appeared simultaneously rather than via the two-stage preview procedure. Both the passive search strategy and the intertrial priming accounts predict that we should observe a difference in search efficiency for the 80% standard preview block compared with the 80% salient block, for standard preview search trials. Experiment 5 showed that these predictions do not fit the findings. Taken together, the results of Experiment 6 suggest that neither the passive account nor the intertrial priming account can explain the results of Experiment 5. Instead, the difference in search efficiency across the 80% salient block and 80% standard preview in Experiment 5 is likely to reflect some strategic deployment of inhibition applied to the previewed distractors. One might ask why there was no evidence for a priming effect in Experiment 6. The most likely explanation is that target-distractor priming might be weaker when there is a mix of both salient and non-salient search tasks within a single block of trials (cf. Maljkovic & Nakayama, 1994; Geyer et al., 2006).

The current results are also suggestive regarding the possible level of modulation of inhibition indicated in Experiment 5. Given that all the stimuli in Experiment 6 appeared simultaneously, there was no opportunity for participants to inhibit a subset of the stimuli. Hence, search performance in Experiment 6 is equivalent to what would be obtained if participants had not inhibited *any* of the previewed items in Experiment 5. In other words, the conditions in Experiment 6 were equivalent to the full-element-baseline (FEB) conditions, often presented in previous studies of time-based selection.

With this in mind, if participants in Experiment 5 had not inhibited any of the preview stimuli, then search should be approximately the same as that obtained in Experiment 6. However, considering the 80% standard preview trial condition of Experiment 5 (in which inhibition was reduced), search was still substantially more efficient than in the equivalent condition of Experiment 6, in which inhibition could not have been applied. In addition, a combined analysis of preview trials across Experiments 5 and 6 suggested this differential effect across blocks in the two experiments was not detected, which is likely due to a relatively small effect in Experiment 5. This suggests that, even when there were a large number of trials on which search was easy and inhibition was not necessary (salient trials), people reduced their level of inhibition, but they did not choose to abandon it altogether.

This reduction might reflect a weaker application of inhibition to all items in the field, or that inhibition might be applied in an all-or-none fashion, but the number of trials on which inhibition was applied was modulated. In the latter case, participants might be matching probability of applying inhibition to the proportion of trials in which it would be useful. Differentiating between these possibilities would require an analysis of the RT distributions, for which there is insufficient data in the present study.

General Discussion

Overview and Summary of Findings

In six experiments, it was investigated whether top-down inhibition in time-based visual selection conditions is applied to old irrelevant items strategically, or by default, regardless of the subsequent level of benefit. This was accomplished by comparing preview performance in conditions in which it was advantageous to apply inhibition with conditions in which inhibiting old items would have no benefit. In Experiments 1-4, the effects of inhibition was disrupted and varied how obvious the disruption was. In Experiment 5, the target was made salient enough so that it could be detected efficiently, without the aid of inhibitory processing or effortful search. Experiment 6 served as a test of alternative accounts of the results from Experiment 5 and provided an indication of what search would be like if no elements were being inhibited.

Given that visual marking is claimed to be a top-down and resource-demanding process (Watson & Humphreys, 1997), we might expect that it would be applied maximally in conditions in which inhibition would be helpful and withheld in conditions when inhibiting old items would be of little use. The alternative account is that, in conditions of time-based selection, inhibition of old items is the default behaviour and is not sensitive to the relative cognitive costs associated with applying it.

In conditions in which effortful search is required, our findings suggest that top-down inhibition operates mostly by default, and seems to be prone to little, if any, strategic modification (Experiments 1 to 4). In contrast, in situations in which the majority of targets can be detected without effortful search, there was evidence that participants applied inhibition strategically (Experiment 5). However, even in those situations, inhibition was not abandoned altogether, but was still applied to some degree (either weakly, or on a reduced number of trials).

Although there is no statistical basis for concluding that no strategy at all was applied in Experiments 1-4 (i.e., accepting the null hypothesis), the effect sizes demonstrated by partial-eta squared were always very small ($\eta_p^2 < 0.1$). Therefore, had there been any modulation, it would have been to an irrelevant degree. Since null hypothesis significance testing depends on the sample size, one might argue that the samples in the current study were not sufficient to detect an effect. However, the sample size of 12 participants has shown to be powerful enough to detect large effects in visual marking in many previous studies since are based on within-subject comparisons with conditions consisting of a large number of trials (e.g., Watson & Humphreys, 1997, 1998). Moreover, this sample size was sufficient to detect even a small effect in Experiment 5, suggesting that the sample size and set-up of the experiments in Chapter 2 were appropriate to detect an effect, had there been any in Experiments 1-4.

Strategic Application of Top-Down Processes

Although top-down processes have been traditionally considered to be easily withheld and modified, the results show that people may not necessarily recruit them in a strategic way. Consistent with this, past research suggests that there may be a strong bias or preference towards certain search strategies, even if those strategies might not be optimal for performance (Bacon & Egeth, 1994; Leber & Egeth, 2006). For example, Bacon and Egeth (1994) found that participants switched to a feature-based search strategy, if a singleton-detection strategy was not efficient. However, when either strategy could be used to complete the goal, participants showed a preference for the singleton-detection strategy. This was the case, even when the singleton detection strategy was susceptible to greater distraction and hindered performance. Similarly, Leber and Egeth (2006) demonstrated that if participants were trained in either one of these two strategies, they continued to use the same strategy, even if it led to worse performance. Both studies suggest that participants do not evaluate the effectiveness of the search strategies they are deploying, based on task demands, as long as their goal is reached.

It is possible that these effects are due to an implicit use of high-level cognitive processes operating without conscious intention, but in a goal-directed fashion, as recent research has shown for working memory (Hassin, Bargh, Engell, & McCulloch, 2009; Maljkovic & Nakayama, 1994), inhibitory control in executive functions (Van Gaal, Ridderinkhof, Johannes, Scholte, & Lamme, 2008; Van Gaal, Ridderinkhof, Johannes, Scholte, & Lamme, 2010), space-based attention (Zhou & Davis, 2012) and object-based attention (Norman, Heywood, & Kentridge, 2013).

There was, however, some evidence for the strategic application of inhibition in Experiment 5. This shows that inhibition is modified in some situations, as the inhibitory account of visual marking proposes. As noted earlier, participants might have modulated inhibitory processing by applying inhibition more weakly, or they might have applied inhibition on a reduced proportion of trials. However, an alternative explanation is that inhibition was withdrawn completely, and the resulting benefit was the result of a residual anticipatory set for the target stimuli. Consistent with this, previous research has found evidence for the involvement of dual attentional sets in preview search – an inhibitory set directed towards irrelevant items, and an anticipatory based on expectations of target features (Braithwaite & Humphreys, 2003; Watson & Humphreys, 2005). A greater proportion of ‘pop-out’ salient trials might have amplified, or served to maintain a feature-based anticipatory set, even if the inhibitory attentional set was withdrawn. Indeed, the relative contribution of an anticipatory set, in addition to the inhibitory set in the preview benefit, remains an area of investigation. Note that the current data cannot distinguish between these different possibilities, but also that the accounts outlined above need not be mutually exclusive.

The current results demonstrate the nature of cognitive control and voluntary action in time-based visual selection. In summary, there might be two reasons for applying effortful cognitive operations even when they produce little benefit. First, goal-directedness seems to be the key principle underlying the implementation of attentional strategies. Therefore, an inhibitory template against currently visible items is likely to be activated, when the goal is to find a target item which is anticipated, but has not yet appeared. In contrast, when the goal itself is changed, such as in Watson and Humphreys' (2000) study, when a probe dot always fell on the locations of old items and prioritizing new information was never needed, inhibition was abolished. Therefore, accomplishing the goal is likely to be crucial to strategic modification, rather than the actual efficiency of the strategy. Second, as this process seems to be carried out fairly implicitly, participants might not be fully aware of the costs of applying inhibition. Accordingly, despite visual marking being resource demanding, participants might have continued to apply it even in conditions in which there was little overall advantage to be gained. In this sense, the strategy would seem adaptive because the relatively small, possibly imperceptible cost of applying inhibition might be trivial, compared with the cost of missing potentially important new information.

Visual Marking as a Top-Down Inhibitory Process and the Effect of Location Changes

Given that there seems to be a consistent preview effect in all of the experiments, do the results demonstrate top-down control at all, or could they be due to bottom-up, automatic onset capture? With regards to the different accounts of the preview benefit, the present data provide additional support for a role of top-down inhibition (Watson & Humphreys, 1997). If onset capture was entirely responsible for driving the preview benefit, we would have expected no difference between the standard preview trials in any of the experiments. Since there was a difference between the efficiency of standard preview trials in Experiment 5, depending on their proportion amongst the easier salient trials, we can conclude that this result is due to some form of top-down regulation. Experiment 6 provides confirmation that such an effect is not observed when all items appeared simultaneously. However, this effect in Experiment 5 is likely to be very modest, as evidenced by the effect sizes and the between-experiment comparison of Experiments 1 and 5 and Experiments 5 and 6, respectively.

With regard to effect of old item location changes, in Experiments 1 and 2, standard preview search differed significantly from the jump preview conditions (approximately 9 ms/item in the Standard preview conditions compared with approximately 20 ms/item in the Jump conditions). Thus, a change of location in the preview items disrupted the preview benefit. Moreover, if we assume that only the new items are selected in standard preview trials, then an overall doubling of search slopes on Jump preview trials suggests that the old item location changes totally abolished the preview benefit. This finding confirms Watson and Humphreys' (1997) proposal that the preview benefit is based (at least partially) on the inhibition of the locations of old distractors (also shown in probe-dot procedures, e.g., Olivers

& Humphreys, 2002; Osugi et al., 2009; Watson & Humphreys, 2000). It follows that old item location changes should disrupt the inhibition applied to those items, unless perhaps the configuration of the old items remains constant and the change in location is relatively modest (e.g., 1 degree of visual angle; Kunar et al., 2003).

Implications

The default recruitment of high-level cognitive processes, without the evaluation of their necessity, may have corollaries in terms of adding extra load and compromising the efficiency of working memory. It may also predict and account for potential failures of attention. As noted earlier, recent work has shown that, in addition to location-based inhibition, the features of old items (e.g., their colour), can also be inhibited via visual marking processes, and even with stationary old items (Andrews et al., 2011; Braithwaite et al., 2003, 2004; Olivers & Humphreys, 2003). One of the consequences of such feature-based inhibition is that any new items that share the inhibited feature become much harder to detect (or are more easily missed) than items that do not possess the feature (Braithwaite & Humphreys, 2003, 2007). This feature-based inhibition has been linked to inattentional blindness phenomena (Most et al., 2001; Most, Scholl, Clifford, & Simons, 2005, see also Andrews et al., 2011), in which otherwise salient items can be missed by the visual system in certain circumstances. In terms of the present work, if individuals are prone to applying inhibition, then this could lead to amplified inattentional blindness, with potentially, the associated serious consequences for failing to notice new information that has common features with the old (e.g., the appearance of hazards whist driving). These issues would be worth exploring further in relation to understanding and engineering safe, efficient behaviour in the real world.

In sum, the findings from Chapter 2 show that observers generally do not evaluate the effectiveness of applying an inhibitory template in time-based visual selection, as long as it is a function of current behavioural goals. Search tasks and contexts in which the target is often salient can produce a shift to a more strategic application of prioritization processes; however, even then the shift is relatively modest. These results carry theoretical and methodological implications of how attentional mechanisms function and highlight the nature of top-down control, as well as potential challenges to our attentional system in complex, dynamic visual environments.

Whereas Chapter 2 focused on the properties of endogenous control of inhibition in time-based visual selection, Chapter 3 will investigate how exogenous or environmental factors may constrain the efficiency of time-based visual selection. In Chapter 3, I consider how external factors, such as complex stimuli or perceptual groups, may influence the effectiveness of the inhibition in time-based visual selection.

Chapter 3

Perceptual Grouping Constrains Top-down Inhibition in Time-based Visual Selection

Synopsis

Attentional efficiency for new objects is enhanced if irrelevant distractors can be separated in time and excluded via top-down inhibition (the preview benefit; Watson & Humphreys, 1997). As described in Chapter 2, difficult search conditions prompt observers to consistently apply top-down inhibition in time-based visual selection, even when it provides no benefit. The experiments in this chapter investigate how exogenous stimulus properties may impact the efficiency of time-based visual selection. Specifically, Chapter 3 investigates whether complex distractors formed by perceptual groups can be inhibited effectively. Experiments 7 and 8 showed that with Kanizsa-type stimuli, or with non-Kanizsa-type stimuli that required spatial grouping, a preview benefit reached a plateau at small display sizes. This suggests that perceptual grouping, rather than inference of an illusory shape may be a crucial constraint in inhibiting a large number of old distractors. Experiment 9 demonstrated that local changes to individual elements of perceptual groups eliminated the preview benefit. Overall, the findings in the present chapter suggest that: i) perceptual grouping reduces the capacity to ignore old distractors, ii) this reduction is independent of the presence of illusory contours, and iii) local changes to elements of a perceptual group feed back to the inhibitory template, abolishing any inhibition

for that group. The findings are discussed in terms of constraints of time-based visual selection, the effectiveness of perceptual groups and illusory contours in guiding search, and possible mediating mechanisms at smaller display sizes such as onset capture or VWM.

Introduction

One enduring issue in attentional research is how organized perceptual input is processed attentionally. Perceptual grouping enables humans to perceive parts of the same object as a discrete unit, by establishing an interrelation of elements forming a certain shape. According to seminal work by Gestalt psychologists in the early 20th century (e.g., Koffka, 1935), this is likely to occur within early stages of the visual system. Subsequent empirical research has been somewhat supportive of these early predictions (e.g., Kimchi & Peterson, 2008; Kimchi & Razpurker-Apfeld, 2004; Moore & Egeth, 1997; Shomstein, Kimchi, Hammer, & Behrmann, 2010), but there are also findings that suggest that attention is required for the formation of certain perceptual groups (e.g., Driver, Davis, Russell, Turatto, & Freeman, 2001; Trick & Enns, 1997). If perceptual grouping is indeed resource demanding then grouping stimuli into perceptual units may reduce the resources available to other attentional processes. In this chapter, I will present experimental evidence relating to whether the need to perceptually group stimuli reduces the capacity of top-down inhibition in time-based selective attention. Inhibitory processes are central for the successful operation of attentional selection. Less is known, however, regarding the factors that might constrain the inhibition of distracting information. The primary goal is to examine the efficiency of top-down inhibition of distractors that are constructed of multiple elements which can be grouped to form single objects. The extent to which attention modulates perceptual grouping will be considered, and whether perceptual groups precede attentional processes.

The Capacity of the Preview Benefit

Despite being a resource-limited mechanism, past RT-based studies have demonstrated that visual marking has the capacity to exclude at least 30 old items (Jiang, Chun, & Marks, 2002b), with no upper limit established yet. Furthermore, up to at least 15 new items can be searched (Theeuwes et al., 1998). However, other work has started to uncover limits with respect to some performance measures. For example, Emrich, Ruppel, Al-Aidroos, Pratt, and Ferber (2008) found that eye movements were only prioritised for approximately 4 new items after which both old and new became equivalent, despite RTs indicating a standard, full preview benefit (see also Watson & Inglis, 2007). In terms of capacity and the influence of stimulus grouping, Watson and Kunar (2012) found that the capacity to prioritise and respond to all new items is about 6-7 items. Moreover, this can depend on the colour homogeneity of the displays, which influences the ease with which the old items can be grouped and rejected together. Specifically, when all the old items were of a common colour, the capacity for prioritizing all new items capacity increased. However, note that this grouping benefit was observed with relatively simple stimuli containing a strong grouping feature (common colour; Braithwaite, Humphreys, Hulleman, 2005). It remains an open question as to what happens when stimulus grouping requires more effort and attentional resources. One the one hand, grouping might increase the ability to ignore old items by allowing them to be grouped and suppressed as a single entity or group of entities. On the other hand, allocating resources to stimulus grouping might reduce the resources available to inhibit the old stimuli resulting in a reduced preview benefit.

Perceptual Groups in Memory and Attention

Studies of VWM have shown that its capacity can decrease when storing complex shapes (Alvarez & Cavanagh, 2004; Eng, Chen, & Jiang, 2005; Luria, Sessa, Gotler, Jolicoeur, & Dell'Acqua, 2010; but see Awh, Barton, & Vogel, 2007; Jackson, Linden, Roberts, Kriegeskorte, & Haenschel, 2015). Nevertheless, some research has shown that the storage capacity of working memory does not change when complex objects are perceptual groups that form illusory contours (Anderson, Vogel, & Awh, 2013). This suggests that, for example, an 'item' can be defined as a set of grouped elements. Nevertheless, even though working memory capacity of the number grouped elements (stored as discrete units) is the same as the number of ungrouped elements, attentional demands may vary due to the processes required to group the stimuli. Much research suggests that perceptual groups can be formed in the absence of attention (e.g., Kimchi & Peterson, 2008; Kimchi & Razpurker-Apfeld, 2004; Moore & Egeth, 1997; Shomstein et al., 2010). However, it might be that there exists a continuum of attentional demands that certain perceptual groups require (Driver et al., 2001; Kimchi & Razpurker-Apfeld, 2004). Note that, even unique perceptual groups that have been extensively researched, such as the Kanizsa-illusory figure, yield contrasting results as to whether they impose attentional demands for the visual system (Grabowecky & Treisman, 1989; Li, Cave, & Wolfe, 2008) or not (Davis & Driver, 1994, 1998). Whether perceptual groups are more distracting and difficult to suppress is a relevant question for attentional research, as performance might substantially differ from that found with simple stimuli. Trick and Enns (1997) tested subitizing for two types of perceptual groups: element clusters and shape formations. Subitizing refers to the ability to enumerate (determine the number present) up to approximately 4 items rapidly and in parallel and without needing to count them (Kaufman, Lord, Reese, & Volkmann, 1949). Beyond four items enumeration becomes much slower and error prone (Kaufman et al., 1949). Trick and Enns (1997) found that element clusters, as well as line-drawn shapes could be subitized, whereas those that formed shapes without line terminations could not. This was the case when target shape formations had to be distinguished from other shape formation distractors. They concluded that clusters and shapes with line terminations do not demand attention while objects that form shapes do. Thus, shape formations, such as illusory conjunctions impose differential demands in being suppressed.

Aims of the Experiments in Chapter 3

In the present chapter, the potential influence of stimulus grouping on the ability to successfully ignore old stimuli was investigated. One possibility is that stimulus grouping might help old objects to be inhibited. This follows because grouped objects can act as discrete items within VWM and do not reduce storage capacity (Anderson et al., 2013). Furthermore, some attentional research indicates that perceptual groups do not pose attentional demands (Kimchi & Peterson, 2008; Kimchi & Razpurker- Apfeld, 2004; Moore & Egeth, 1997; Shomstein et al., 2010), which should essentially preserve the capacity of top-down inhibition for perceptually grouped distractors. In other words, grouped items may be inhibited as if they were single elements. Alternatively, if grouping elements requires attentional resources (e.g., Trick & Enns, 1997; Li et al., 2008), this might diminish resources available for inhibiting distractors, and hence decrease the ability to prioritise new items.

To assess these possibilities, Experiment 7 examined time-based selection in conditions in which individual stimuli could be grouped to induce a subjective experience (i.e., Kanizsa-type figures). This experiment also provided an opportunity to contribute to the debate regarding early (Davis & Driver, 1994, 1998) or late formation of illusory contours (Grabowecky & Treisman, 1989; Li et al., 2008). Experiment 8 assessed inhibition for grouped stimuli which did not result in the perception of illusory contours. Experiment 9 evaluated the extent to which grouped stimuli could be suppressed when changes to the local elements of the group were made. Small local changes in the elements might be disruptive if the identity of the entire object is vital for the inhibitory template, or irrelevant if inhibition is based on individual elements and insensitive to more global properties (cf. Watson & Humphreys, 2002; 2005; Watson, Braithwaite, & Humphreys, 2008).

Experiment 7: Inhibition of Illusory Perceptual Groups

Kanizsa-based figures are one of the best demonstrations of how the human visual system groups separate elements into a coherent object that induces a subjective experience from incomplete, fragmented stimulation (Fahle & Koch, 1995). The main aim of Experiment 7 was to determine to what extent perceptual groups that induce a subjective experience, such as Kanizsa-type figures, can be inhibited. Following Li et al. (2008), we used a visual search task consisting of a vertical target and horizontal distractor Kanizsa-type rectangles. Similar to past time-based selection studies, there were three main conditions. As in the standard preview trials in Chapter 2, in the preview condition half of the distractors were presented before the second set was added. The target was only ever present within the second set. Performance in this preview condition was compared with that from the associated HEB and FEB conditions. If the generation of illusory stimuli consumes substantial attentional resources (e.g., Li et al., 2008; Trick & Enns, 1997), we would expect search performance in the preview condition to be similar to that in the FEB.

Alternatively, illusory contours may be generated early by the visual system and thus not require resources (e.g., Davis & Driver, 1994, 1998), permitting inhibition to operate effectively. In this case, search performance in the preview condition should match that of the HEB. Specifically, the task in Experiment 7 was to find a vertically oriented Kanizsa-type rectangle among horizontally oriented Kanizsa-type rectangles. In the preview condition, half of the distractor stimuli (i.e., horizontal Kanizsa-type rectangles) were presented prior to the search task.

Method

Participants. Participants consisted of 18 undergraduates (17 female) from the University of Warwick who received course credit or payment for participating. They did not participate in any of the previous experiments. Their ages ranged from 18-25 years (*M* = 20.17, *SD* = 2.18). All participants reported normal or corrected to normal visual acuity in this and the remaining experiments.

Stimuli and apparatus. Stimuli were presented on a 22” LCD panel at a resolution of 1680 × 1050 pixels. A custom written computer program generated the stimuli and recorded participants’ responses. The target was a vertical rectangle defined by Kanizsa-type illusory contours, and the distractors were horizontal Kanizsa-type rectangles placed against the white background of the computer monitor. Four black pacman shapes formed the Kanizsa-type rectangles that measured 25.2 × 37.8 mm (2.53º × 3.79º of visual angle). Each pacman had a diameter of 16.8 mm (1.69º). Search displays were generated by placing the stimuli randomly into the cells of an invisible 6 × 6 matrix, with an equal number of Kanizsa-shaped rectangles presented on the right and left side of the display. The number of items in the final search display of the preview and FEB conditions was 4, 8, or 16 items. An example of a preview search trial is illustrated in Figure 17. The HEB contained 2, 4 or 8 items. The target when present, was positioned in the two furthest leftward or rightward columns. The monitor was positioned at eye level, with viewing distance approximately 60 cm, although participants' head movements were not constrained.

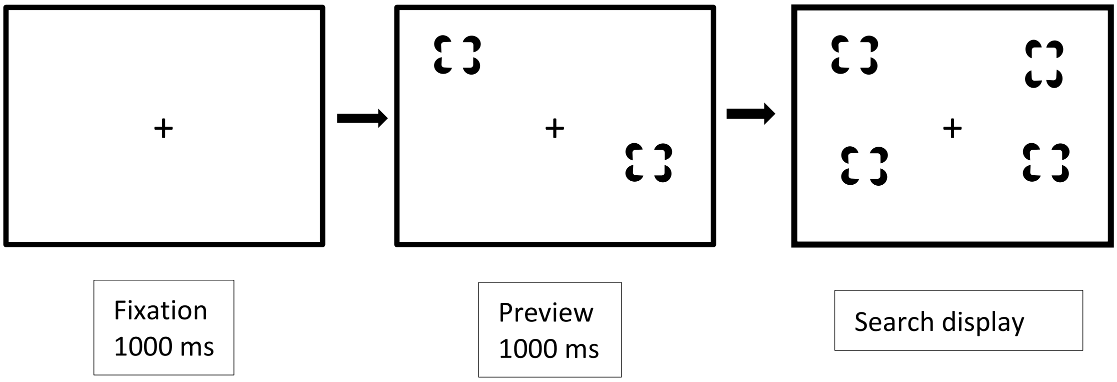

Figure 17. Schematic of a preview search trial in Experiment 7. The target is defined as a vertically oriented Kanizsa-type rectangle.

Design and procedure. The design and procedure were essentially the same as in previous visual marking experiments (Watson & Humphreys, 1997). There were three main conditions: a half-element baseline (HEB), a full-element baseline (FEB) and a preview condition. A trial in the FEB condition consisted of a blank screen for 500 ms, followed by a fixation cross for 750 ms, after which a search display of 4, 8, or 16 items was presented for 1000 ms. Search displays remained visible until the participant indicated the location of the target by pressing the Z or M keys on a standard computer keyboard. The response triggered the next trial. Error responses were indicated by visual feedback. The HEB was essentially the same as the FEB, but consisted of display sizes of 2, 4, or 8 items. In the preview condition, half of the Kanizsa-type rectangles for a particular display size were presented for 1000 ms before the remaining half, containing the target, was added. The fixation cross remained visible throughout the entire trial. Participants were told to try and ignore the distractors present in the preview set, as the target would always appear in the second set of distractors.

Each condition (HEB, FEB, Preview) contained 120 target trials. There were also 12 (10%) catch trials on which there was no target present. Participants responded to these trials by pressing the space bar on the keyboard. As in the experiments in Chapter 2, the purpose of these trials was to ensure that participants do not search only half of the display, by concluding that the target is on the opposite side if not present on the display side they have searched (see e.g., Al-Aidroos et al., 2011; Blagrove & Watson, 2010; for previous uses of this method). Trials within a block were presented in a random order and condition order was counterbalanced across participants. Directly before each block of experimental trials was a practice block consisting of 12 trials for each condition.

Results

As in previous visual marking studies, search efficiency was compared in the preview condition with the two baseline conditions. In the FEB and preview conditions, slopes were calculated using the actual display size. In the HEB condition, slopes were calculated using twice the true number of items. The search rate in the HEB then represents the time needed to search through only the new items in the preview condition. Therefore, if search in the preview condition corresponds to that of the HEB, the old items have been fully excluded from search. However, if search rates in the preview condition match those of the FEB, the old items have not been ignored and were included in subsequent search.

Reaction times. Trials with RTs less than 200 ms or greater than 10s were removed as outliers (0.01% of the data). The rationale for these cut-off points was the same as in Chapter 2. Using means with cutoffs provides greater power when analyzing reaction times in comparison to using medians (Ratcliff, 1993). Thus, means with cutoffs were used in all the remaining experiments in Chapter 3. Overall mean correct RTs as a function of display size are presented in Figure 18 and descriptive statistics for the search slopes in Table 15. Initially the data were analyzed using a 3(Condition: HEB, FEB, Preview) × 3(Display Size) repeated-measures ANOVA. This revealed a significant main effect of condition *F*(2,34) = 42.92, MSE = 41023.37, $p < .001$, $\eta_p^2 = .72$, display size *F*(1.14,19.38) = 226.86, MSE = 47031.34, $p < .001$, $\eta_p^2 = .93$, and a Condition × Display Size interaction, *F*(3,50.99) = 10.48, MSE = 9494.61, $p < .001$, $\eta_p^2 = .38$. As shown in Figure 18, preview search performance appeared to be similar to that of the HEB for small display sizes of 4 and 8 items whereas it was closer to FEB performance at display sizes of 16 items.

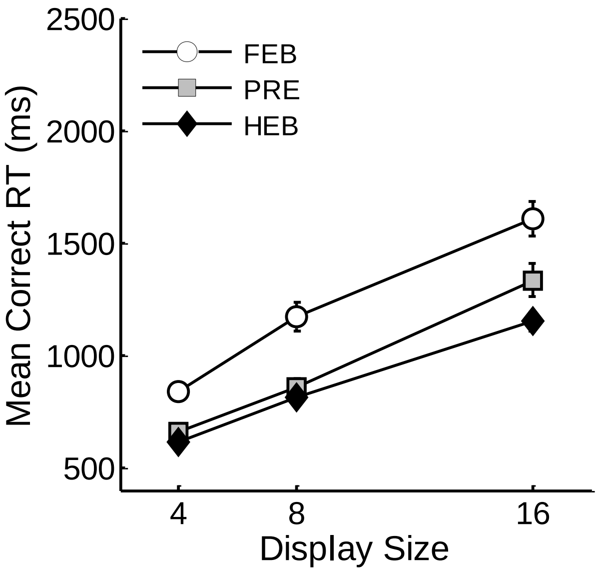

Figure 18. Mean correct reaction times (RTs) as a function of condition and display size for Experiment 7. HEB = Half element baseline, PRE = Preview condition, FEB = Full element baseline. Error bars indicate ±1SE

Table 15. *Search slope statistics for Experiment 7.*

Descriptive characteristic	HEB	FEB	Preview
Slope (ms/item)	44.69	63.03	56.91
Intercept	442.22	619.48	420.08
R^2	0.99	0.99	0.99

Following previous work, I compared performance in the preview condition with each of the two baselines in order to determine if a preview benefit had occurred. In addition, given the apparent difference between performance at large and small display sizes, I also assessed search performance at the smaller (4 to 8) and larger (8 to 16) display sizes individually.

HEB vs. Preview. Overall RTs were longer in the Preview condition than in the HEB, $F(1,17) = 9.59$, MSE = 23785.68, $p < .01$, $\eta_p^2 = .36$, and increased with display size, $F(1.04,17.69) = 200.98$, MSE = 33157.56, $p < .001$, $\eta_p^2 = .92$,. The Condition × Display Size was also significant, $F(1.25,21.25) = 10.92$, MSE = 8203.22, $p < .005$, $\eta_p^2 = .39$, indicating that search was less efficient overall in the preview condition than in the HEB. Considering only small display sizes (4 to 8 items), RTs were shorter for a display size of 4 than 8, $F(1,17) = 204.63$, MSE = 3556.32, $p < .001$, $\eta_p^2 = .92$, however, neither the main effect of condition, $F(1,17) = 3.82$, MSE = 10136.62, $p = .067$, $\eta_p^2 = .18$, nor the Condition × Display size interaction proved significant, $F < 1$, $\eta_p^2 < 0.1$. Considering the large display sizes (8 to 16 items), RTs were longer for a display size of 16 than 8 items, $F(1,17) = 186.77$, MSE = 16052.18, $p < .001$, $\eta_p^2 = .36$. Overall RTs were longer in the preview condition than in the HEB, $F(1,17) = 9.47$, MSE = 25057.28, $p < .01$, $\eta_p^2 = .92$, and RTs increased more from 8 to 16 items in the preview condition than in the HEB, $F(1,17) = 14.20$, MSE = 5883.53, $p < .005$, $\eta_p^2 = .46$.

FEB vs. Preview. Overall RTs were shorter in the preview condition than in the FEB, *F*(1,17) = 38.29, MSE = 46404.27, $p < .001$, , $\eta_p^2 = .72$, increased with display size, *F*(1.21,20.48) = 179.25, MSE = 44849.85, $p < .001$, $\eta_p^2 = .93$, and the Condition × Display size interaction was also significant *F*(2,34) = 5.09, MSE = 8742.74, $p < .05$, $\eta_p^2 = .38$. Considering the small display sizes (4 to 8), RTs were faster overall in preview condition than in FEB, *F*(1,17) = 47.87, MSE = 23011.23, $p < .001$, $\eta_p^2 = .74$, and faster for a display size of 4 than of 8 items *F*(1,17) = 106.04, MSE = 12367.99, $p < .001$, $\eta_p^2 = .86$. There was also a significant Condition × Display Size interaction, *F*(1,17) = 11.95, MSE = 7067.09, $p < .005$, $\eta_p^2 = .41$ indicating more efficient search in the preview condition. At the large display sizes (8 to 16), overall RTs were shorter in the preview condition than in the FEB, *F*(1,17) = 31.16, MSE = 50391.45, $p < .001$, $\eta_p^2 = .65$, and increased between 8 and 16 items, *F*(1,17) = 185.20, MSE = 20186.19, $p < .001$, $\eta_p^2 = .92$. However, the Condition × Display Size interaction did not approach significance, *F*(1,17) = 1.04, MSE = 7304.89, $p = .323$, , $\eta_p^2 = .06$, suggesting that search efficiency between the two conditions was statistically equivalent.

Error rates. Overall error rates were low (2.75 %) and as shown in Table 16, the general pattern of errors was consistent with the RT data. A two-way repeated measures ANOVA, with condition (HEB, FEB, preview) and display size as factors revealed that there were more errors in the Preview and FEB conditions than in the HEB, *F*(2,34) = 12.28, MSE = 5.43, $p < .001$, $\eta_p^2 = .42$, the number of errors increased with display size, *F*(2,34) = 24.74, MSE = 11.39, $p < .001$, $\eta_p^2 = .59$, and there was a significant Condition × Display Size interaction, *F*(4,68) = 8.09, MSE = 7.42, $p < .001$, $\eta_p^2 = .32$.

Table 16. *Mean percentage error rates for Experiment 7*

	Display size		
Condition	4	8	16
HEB	0.97	1.53	1.94
FEB	1.11	2.64	5.83
Preview	0.97	1.53	8.19

Given that most errors were found in the preview condition but that different search patterns were found at small and large display sizes, I conducted an analysis for each display size separately to clarify if there were any speed/accuracy trade-offs. For small display sizes of 4 and 8, neither the main effects of condition, $F(2,34) = 2.51$, MSE = 1.87, $p = .096$, $\eta_p^2 = .13$, or display size, $F(1,17) = 3.83$, MSE = 5.45, $p = .067$, $\eta_p^2 = .18$, nor the Condition × Display Size interaction, $F < 1$, $\eta_p^2 < 0.1$. reached significance. At large display sizes (8 and 16), there was a significant main effect of condition, $F(2,34) = 12.22$, MSE = 8.09, $p < .001$, $\eta_p^2 = .42$, display size, $F(1,17) = 28.77$, MSE = 11.02, $p < .001$, $\eta_p^2 = .63$, and a significant Condition × Display Size interaction, $F(2,34) = 8.71$, MSE = 10.13, $p < .005$, $\eta_p^2 = .34$; there was a greater number of errors in the preview condition at the largest display size followed by the FEB and HEB conditions.

The overall error rate on catch trials was low (2.62%), confirming that participants were searching over the whole display. Given the small number of catch trials, these data were not analyzed further.

Discussion

Experiment 7 demonstrates that the capacity of inhibitory time-based visual selection is reduced when perceptual groups form illusory contours. Specifically, based on search slope measures, a preview benefit was present for relatively small display sizes, but absent at larger display sizes. Note that with discrete, non-grouping stimuli full preview benefits have been shown with much larger display sizes (e.g., up to 15 old items, Theeuwes et al., 1998). One prediction was that the formation of illusory surfaces and grouping of stimulus elements might enhance and support inhibition. This is because grouping of elements would reduce the overall number of discrete stimuli and might provide an (illusory) surface for inhibition to be applied. The alternative was that stimulus grouping/illusory surface formation requires attentional resources (e.g., Trick & Enns, 1997) which reduces the resources available for inhibiting the old items. The data supported the latter account.

These findings lend support to high-level accounts for both visual marking (Watson & Humphreys, 1997) and the detection of subjective figures (e.g., Grabowecky & Treisman, 1989; Li et al., 2008). For instance, a pure automatic onset capture account of visual marking (Donk & Theeuwes, 2003, 2005) predicts that new items would attract attention irrespective of complexity and display size. In contrast, reduced performance is predicted by a resource-limited inhibitory account in situations where other processes consume attentional resources, leaving fewer resources available for the coordination and application of inhibition (Watson & Humphreys, 1997; Humphreys et al., 2002). Li et al., (2008) have suggested that grouping costs might be the underlying cause of relatively slow search for subjective figures, as grouping may require attention (Driver et al., 2001) and Kanizsa-figures require grouping (Fahle & Koch, 1995). Hence in the present work, grouping processes associated with the Kanizsa stimuli may have left fewer resources available for inhibiting the old items. Consistent with this possibility is the finding that the preview benefit was intact at small display sizes but absent at the largest. This pattern would be expected if grouping costs increase as the number of stimuli that have to be grouped increase. In addition to suppression being reduced, the search slopes in the FEB numerically replicate those of Li et al. (2008), suggesting that illusory conjunctions do not guide attention.

Note that although the search slopes did not differ between the preview and FEB conditions at the larger display sizes, overall RTs were nonetheless shorter in the preview condition. A similar effect occurred in Chapter 2 (Experiment 3), where there was an overall RT difference between standard preview trials in the two conditions (80% jump and 80% standard). However, as it was argued in Chapter 2, such reductions in overall RTs do not necessarily reflect the exclusion of old distractors (which would produce a search slope difference). Instead, such overall differences could be the result of changes in alertness, the presence of a warning signal or arousal effects (see Watson & Humphreys, 1997). That is, the onset of the preview items might have a role in preparing and alerting subjects to the upcoming search display with a consequent overall reduction in their response initiation time.

Experiment 8 considered the role of the formation of illusory contours in reducing the preview benefit compared to simple grouping effects. Specifically, I assessed whether a preview benefit occurs when all distractors and the target were formed from spatially grouped pacman which do not elicit a subjective figure. We might expect a smaller reduction in preview performance when illusory contour formation cannot occur, if illusory contour formation consumes attentional resources.

Experiment 8: Inhibition of Non-Illusory Perceptual Groups

Experiment 7 demonstrated that the presence of illusory figures constrained top-down inhibition in time-based selective attention. Another possibility which has not been explored in previous studies with Kanizsa-type stimuli, is that inefficient search patterns for Kanizsa-type figures (e.g., Li et al., 2008; Grabowecky &

Treisman, 1989; but see Davis & Driver, 1994, 1998) might be caused by the action of general grouping processes irrespective of whether or not illusory contours are present (e.g., Fahle & Koch, 1995). Thus, the results of Experiment 7 might have been due to perceptual grouping of pacman into single objects, independent of whether or not illusory contours/surfaces were also formed. This would suggest that time-based selection is compromised whenever stimuli have to be attentionally grouped. To examine this possibility, Experiment 8 tested whether the number of the old distractors that can be inhibited in the preview condition would increase when spatial grouping within target and distractor shapes is required, but does not induce illusory contours or surfaces within the stimuli.

Method

Participants. A total of 18 participants, aged 18 to 20 years (*M*=18.72, *SD*=0.75) completed the experiment for course credit or payment. They had not been participants in any previous experiments.

Stimuli, apparatus and procedure. The stimulus displays, apparatus, and procedure were similar to those of Experiment 7, except that the distractor pacman were randomly oriented so that they did not induce an illusory percept. In addition, the pacman forming the target were all oriented leftward (see Figure 19).

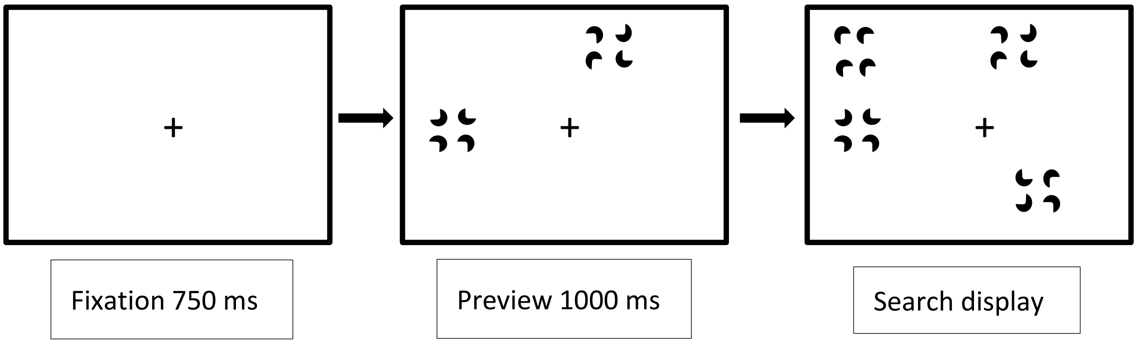

Figure 19. Schematic of a preview search trial in Experiment 8. The target is defined as vertically clustered pacman aligned in the same leftward direction.

Results

A total of 0.14% of outlier RTs that were less than 200 ms or greater than 10s were excluded from the analysis.Mean correct RTs as a function of display size for each of the three conditions are presented in Figure 20, and search slope statistics in Table 17.

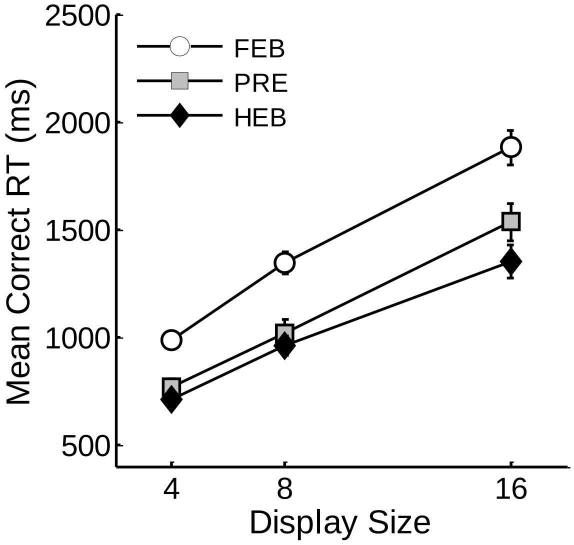

Figure 20. Mean correct reaction times (RTs) as a function of condition and display size for Experiment 8. HEB = Half element baseline, PRE = Preview condition, FEB = Full element baseline. Error bars indicate ±1SE

Table 17. *Search slope statistics for Experiment 8.*

Descriptive characteristic	HEB	FEB	Preview
Slope (ms/item)	52.72	73.47	64.20
Intercept	518.7	720.29	509.17
R^2	0.99	0.99	1

A 3(Condition: HEB, FEB, Preview) × 3 (Display size: 4, 8, 16 items) within-subjects ANOVA revealed significant main effects of condition, $F(2,34) = 26.87$, MSE = 85173.76, $p < .001$, $\eta_p^2 = .61$, display size, $F(1.41,23.97) = 261.18$, MSE = 44179.47, $p < .001$, $\eta_p^2 = .94$, and a significant Condition × Display Size interaction, $F(2.91,49.43) = 6.21$, MSE =17344.91, $p < .001$, $\eta_p^2 = .27$, indicating a difference in search rates across the conditions. Following Experiment 7, performance in the preview condition was compared with both baselines and over a range of display sizes.

HEB vs. Preview. There was a marginal effect of condition, $F(1,17) = 4.12$, MSE = 62550.55, $p = .058$, $\eta_p^2 = .20$, a significant effect of display size, $F(2,34) = 283.05$, MSE =16237.69, $p < .001$, $\eta_p^2 = .94$, and a significant Condition × Display size interaction indicating that overall, search in the preview condition was less efficient that in the HEB, $F(1.26, 21.49) = 5.05$, MSE =15406.95, $p < .05$, $\eta_p^2 = .23$. Considering only the small display sizes (4 to 8). Overall RTs were longer for larger display sizes, $F(1,17) = 137.39$, MSE = 8247.92, $p < .001$, $\eta_p^2 = .89$. However, neither the main effect of condition, $F(1,17) = 2.49$, MSE = 21928.41, $p = .133$, $\eta_p^2 = .13$, nor the Condition × Display Size interaction, $F < 1$, $\eta_p^2 < 0.1$, were significant. At the larger display sizes there was a marginally significant effect of condition, $F(1,17) = 4.30$, MSE = 59898.34, $p = .054$, $\eta_p^2 = .20$, and RTs increased with display size, $F(1,17) = 220.19$, MSE = 16850.81, $p < .001$, $\eta_p^2 = .93$. There was also a significant Condition × Display Size interaction, $F(1,17) = 5.63$, MSE = 12869.78, $p < .05$, $\eta_p^2 = .25$, indicating that, at large display sizes, search was less efficient in the preview condition than in the HEB.

FEB vs. Preview. Overall RTs were faster in the preview condition, $F(1,17) = 23.53$, MSE = 101612.09, $p < .001$, $\eta_p^2 = .58$ and increased with display size, $F(2,34) = 241.79$, MSE = 26369.39, $p < .001$, $\eta_p^2 = .93$. There was no Condition × Display Size interaction, $F(2,34) = 2.51$, MSE = 15845.67, $p =.097$, $\eta_p^2 = .13$. Given past results and the findings from Experiment 7, we would expect search in the preview condition to be more efficient than in the FEB and so there is some justification for treating this comparison as directional, in which case it would be significant at the .05 level.

At the smaller display sizes, overall RTs were shorter in preview search, *F*(1,17) = 24.54, MSE = 54765.33, $p < .001$, $\eta_p^2 = .59$, and increased with display size, *F*(1,17) = 69.09, MSE = 23975.51, $p < .001$, $\eta_p^2 = .80$. The Condition × Display Size interaction was also significant, *F*(1,17) = 5.86, MSE = 8096.91, $p < .05$, $\eta_p^2 = .26$, indicating more efficient search in the preview condition than in the FEB. Considering the larger display sizes (8 and 16), preview search produced shorter overall RTs, *F*(1,17) = 20.45, MSE = 99003.31, $p < .001$, $\eta_p^2 = .55$, and RTs increased with display size, *F*(1,17) = 334.55, MSE = 15013.83, $p < .001$, $\eta_p^2 = .95$. However, Condition × Display Size interaction did not approach significance, $F < 1$, $\eta_p^2 < 0.1$, suggesting that the absence of a preview benefit at the larger display sizes.

Error Rates. Error rates were low overall (4.23%) and showed a similar pattern to the RT data (see Table 18). Overall errors decreased across the Preview to HEB conditions, *F*(2,34) = 4.86, MSE = 20.56, $p < .05$, $\eta_p^2 = .22$, and error rate increased with display size, *F*(2,34) = 42.93, MSE = 17.75, $p < .001$, $\eta_p^2 = .72$. Errors increased the most with display size in the preview condition, followed by FEB, and then HEB, *F*(4,68) = 4.86, MSE = 9.64, $p < .005$, $\eta_p^2 = .22$. As in Experiment 7, we conducted additional analyses for small and large display sizes separately. At small display sizes, errors increased with display size, *F*(1,17) = 4.72, MSE = 6.99, $p < .05$, $\eta_p^2 = .22$.

Table 18. *Mean percentage error rates for Experiment 8*

	Display size		
Condition	4	8	16
HEB	0.97	1.25	5.14
FEB	1.94	3.61	9.72
Preview	1.11	2.92	11.39

However, neither the main effect of condition, $F < 1$, nor the Condition × Display Size interaction, $F(2,34) = 1.39$, MSE = 5.39, $p = .26$, $\eta_p^2 = .08$, proved significant. At large display sizes, more errors were made in FEB and preview condition than in the HEB, $F(2,34) = 6.31$, MSE = 22.75, $p < .01$, $\eta_p^2 = .27$, and error rates increased at the largest display size, $F(1,17) = 43.91$, MSE = 21.26, $p < .001$, $\eta_p^2 = .72$. There was also a significant Condition × Display Size interaction, $F(2,34) = 3.95$, MSE = 12.58, $p < .05$, $\eta_p^2 = .19$, indicating that errors increased most in the preview condition at large display sizes. The overall error rate on catch trials was low (4.78%) and these data were not analyzed further.

Discussion

The overall pattern of findings from Experiment 8 was similar that of Experiment 7. The capacity of inhibition for perceptually grouped objects was limited to a relatively small number of items in both experiments. This suggests the perception of illusory contours in Experiment 7 neither hindered nor helped with the inhibition of the old, previewed stimuli. It is noteworthy that in all conditions, search functions were similar to those in Experiment 7 (that is, they were relatively inefficient). Thus, it would seem that the perception of illusory contours has little impact even in standard visual search task conditions. This is, to our knowledge, the first study to compare visual search for a grouped non-illusory pacman target among grouped non-illusory pacman distractors, raising a question of whether inefficient search for illusory contours found in previous studies (Grabowecky & Treisman, 1989; Li et al., 2008) is associated with costs of perceptually grouping pacman.

In Experiment 9, I consider how local changes in the grouped elements may influence the preview benefit obtained at small display sizes. This is relevant as it would clarify whether inhibition is applied to the individual pacman or holistically to the grouped representation. If applied to individual pacman, then local rotational changes should not be disruptive (Watson & Humphreys, 1998), whereas if the representation of the object is important for the benefit to be maintained, then local changes should abolish the effect. Thus, Experiment 9 tested whether the configuration of the grouped elements is important for maintaining the preview benefit at small display sizes, and whether local changes to the individual elements that alter the representation of the object abolish the preview benefit.

Experiment 9: Changes to Previewed Stimuli

Previous research has demonstrated that changes to the shape or object identity of previewed items disrupts the preview benefit, whereas changes to surface properties, such as stimulus colour or luminance, do not (Watson & Humphreys, 2002, 2005; Watson et al., 2008; but see also Osugi et al., 2010 for findings when the semantic meaning is preserved). In Experiment 9, I examined the effect of making changes to the individual elements that form a grouped stimulus. In the preview condition, the placeholders were initially misaligned and so did not elicit a subjective contour. They were subsequently rotated to form subjective contours when the second set of items was added. Thus, the final search display in the preview condition was comprised of illusory stimuli similar to those of Experiment 7. A past study with rotating old distractors has shown that local rotation does not abolish the preview benefit, albeit it reduces it to partial rather than full (Watson & Humphreys, 1998). Using this method, I was able to test whether inhibition is applied to the elements (pacman) separately, in which case local rotation should produce at least a partial preview benefit. Alternatively, inhibition could be applied to the grouped elements forming a single representation, in which case local rotation would abolish the benefit because the identity of the percept would be changed (e.g., Watson &

Humphreys, 2002). That is, the local rotation of the elements would result in the formation of an emergent illusory surface that was previously absent.

Method

Participants. There were 18 participants (6 male), aged 18-25 years (*M*=19.77, *SD*=1.66), that participated for course credit or payment. They had not participated in any of the previous experiments. All had normal or corrected to normal vision.

Stimuli, apparatus, and procedure. The stimuli, apparatus and procedure were similar to those of Experiment 7, except that here, in the Preview condition, previewed pacman were initially presented with a random rotation. After 1s, the pacman rotated so as to form Kanisza figures, simultaneously with the onset of the second set of search items. The second set of items in the preview condition, as well as in the HEB and FEB, remained the same as in Experiment 7, consisting of horizontal Kanizsa-type rectangles and a vertical Kanizsa-type rectangle target. An example of a preview trial in Experiment 7 is shown in Figure 21.

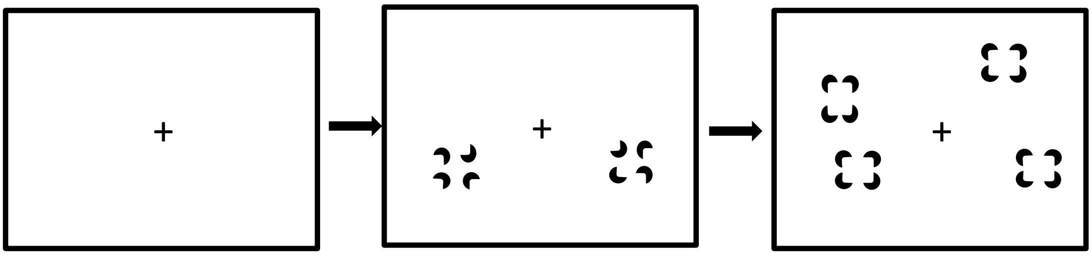

Figure 21. Schematic of a preview search trial in Experiment 9. The target is defined as a vertically oriented Kanizsa-type rectangle.

Results

RTs less than 200 ms or greater than 10s were removed from the analysis as outliers (0.08 % of the data). Figure 22 shows the mean correct RTs as a function of display size for each of the three conditions. Search slope statistics are shown in Table 19.

Reaction times. A two-way within-subjects ANOVA indicated that the RTs were fastest overall in the HEB condition, $F(2, 34) = 51.75$, MSE = 44306.64, $p < .001$, $\eta_p^2 = .75$, and that RTs increased with display size $F(1.19, 20.17) = 208.88$, MSE = 68172.95, $p < .001$, $\eta_p^2 = .93$. RTs increased more with display size in the FEB and Preview than in the HEB condition $F(4,64)=7.92$, MSE=12437.43, $p < .001$, $\eta_p^2 = .32$. As shown in Figure 22, RTs were slower overall and search slopes steeper than in the HEB, moreover, preview performance was almost identical to performance in the FEB condition. To confirm this, two further ANOVAs were conducted to test for differences between the preview condition and each of the two baselines.

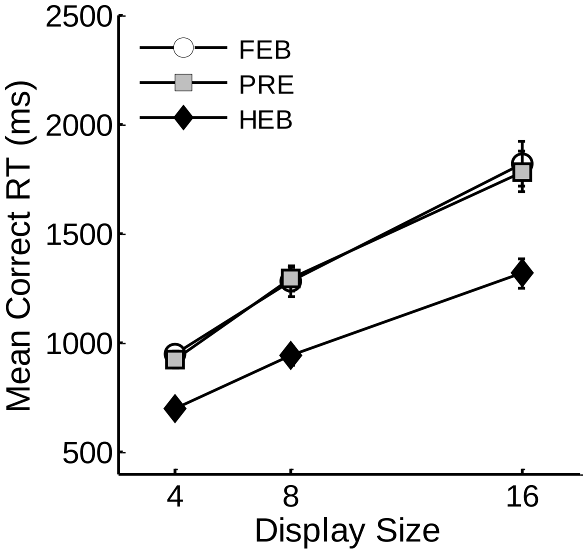

Figure 22. Mean correct reaction times (RTs) as a function of condition and display size for Experiment 9. HEB = Half element baseline, PRE = Preview condition, FEB = Full element baseline. Error bars indicate ±1SE

Table 19. *Search slope statistics for Experiment 9.*

Descriptive characteristic	HEB	FEB	Preview
Slope (ms/item)	50.93	72.23	70.45
Intercept	510.63	676.30	677.42
R^2	0.99	0.99	0.99

HEB vs. Preview. RTs were longer overall in the preview condition than in the HEB, *F*(1, 17) = 69.97, MSE = 46985.70, $p < .001$, $\eta_p^2 = .81$, and increased with display size *F*(1.32, 22.43) = 194.72, MSE = 38873.93, $p < .001$, $\eta_p^2 = .92$. In addition, RTs increased more with display size (indicating less efficient search) in the preview condition than in the HEB, *F*(2, 34) = 10.16, MSE =13399.02, $p < .001$, $\eta_p^2 = .37$.

FEB vs. Preview. RTs increased with display size, $F(1.27,21.52) = 165.72$, MSE = 65683.86, $p < .001$, $\eta_p^2 = .91$. However, neither the main effect of condition, nor was there a Condition × Display Size interaction, all Fs < 0, η_p^2s< 0.1.

Error rates. The overall error rate was low (3.16%). Mean error percentage rates are presented in Table 20. More errors were made overall in the FEB and Preview conditions than in HEB, $F(2,34) = 6.19$, MSE = 11.65, $p < .01$, $\eta_p^2 = .27$, and the error rate increased with display size $F(2,34) = 29.87$, MSE = 12.40, $p < .001$, $\eta_p^2 = .64$. Errors increased more with display size in the FEB and preview condition, $F(4,68) = 5.09$, MSE = 6.98, $p < .001$, $\eta_p^2 = .23$. Catch trial errors were also low (4.93%) and were not analyzed further.

Table 20. *Mean percentage error rates for Experiment 9*

	Display size		
Condition	4	8	16
HEB	1.25	1.39	3.06
FEB	0.83	2.08	7.36
Preview	1.81	2.64	8.06

Discussion

In Experiment 9, the preview condition did not differ from the FEB at any display size, indicating that inhibition at small display sizes was destroyed when the pacman rotated. Given that the local rotation of individual elements should have at least partially preserved the benefit (Watson & Humphreys, 1998), these results suggest that inhibition is applied to the representation of the grouped object as a whole, rather than to individual elements. Instead, changes in orientation of the elements meant identity change, which fully disrupted the benefit, consistent with previous studies (Watson & Humphreys, 2002). This means that once grouped, the identity of the object as a whole is vital for maintaining an inhibitory template.

General Discussion

The results from the experiments in this chapter suggest that perceptual grouping dramatically reduces the number of distractors that can be suppressed, thus reducing attentional efficiency in time-based visual selection. The primary conclusions are that inhibition in time-based visual selection: a) can be applied to complex objects that require perceptual grouping, b) is reduced in capacity when applied to perceptually grouped objects, c) is independent of whether or not the grouped elements elicit an illusory figure, and d) is disrupted when local changes are made to the individual elements, suggesting that the inhibitory template is applied at the level of perceptually grouped objects as discrete units, rather than to the individual inducers.

Perceptual Grouping and Visual Marking

The visual world is rich with information, and perceptual mechanisms organize this information to enable a greater amount of coherent information to be processed and a clearer structure of the world to be perceived. These perceptual mechanisms can sometimes facilitate attentional processes. For instance, grouping distractors by similarity can enhance the selection of a target by allowing the grouped distractors to be discarded in one go (Duncan & Humphreys, 1989). However, the present work demonstrates that perceptual grouping of multiple elements into a single objects does not always result in improved selection. It is likely that the processes involved in grouping stimuli consume resources which are also required to inhibit those stimuli. The result is that inhibition of old stimuli is compromised resulting in a reduced ability to select new stimuli. Indeed, in the current conditions there was little evidence of any inhibition present at the largest display size.

In addition, the phenomenal visual experience of a subjective figure did not add or reduce any further resources from distractor inhibition. Nevertheless, there was *some* influence of the presence of a subjective figure. Specifically, when changes to local elements resulted in the creation of a subjective figure, inhibition was abolished even at the small display sizes. Changing the old distractors from non-illusory to illusory perceptual groups altered their identity and eliminated inhibition at small display sizes. This indicates that global, grouped representations were inhibited, rather than the individual elements. It also implies that apart from location-based inhibition (Watson & Humphreys, 1997, 2000), some feature-based information about the object is also coded into the inhibitory template (Braithwaite et al., 2003, 2004). The importance of shape changes in non-grouped stimuli are documented in previous studies of visual marking (e.g., Watson & Humphreys, 1997, 2002). Changes to old objects that do not distort their meaning, such as luminance, or colour (Watson & Humphreys, 2002, 2005; Watson et al., 2008) and even semantics (from Japanese symbols to pictorial symbols retaining the same meaning; see Osugi et al., 2010) preserve the preview benefit. The current findings are thus consistent with the proposal that the preview benefit reflects an adaptive mechanism that is sensitive to ecologically relevant changes in the environment (Watson & Humphreys, 1997, 2002). The current work shows that the visual marking mechanism is also sensitive to shape changes that occur as a result of inter-element stimulus grouping.

Alternative Accounts for Visual Marking of Small Display Sizes

The present data provide support for inhibitory accounts of visual marking (Watson & Humphreys, 1997), and are inconsistent with a pure onset capture (Donk & Theeuwes, 2001, 2003) or temporal segregation (Jiang et al., 2002a) account, according to which a full preview benefit should be obtained in all the three experiments in the present study. Although a full explanation of the preview benefit by onset capture as proposed by Donk and Theeuwes (2001, 2003) is incompatible with the current findings, a role for onset capture might be consistent with performance at the smaller display sizes. For example, Yantis and Jonhson (1990; Yantis & Jones, 1991) showed that the onset of a limited number (approximately four *perceptually new* objects) could capture attention automatically. Thus, the preserved preview benefit observed at the small display sizes might reflect the operation of such an automatic capture mechanism. However, it is difficult to reconcile this onset account with the elimination of the preview benefit by local rotation in Experiment 9 at even small display sizes. If the preview benefit were the result of automatic attentional capture by new onsets, then the local rotation of existing elements should have had little, if any, influence. Instead, local rotation of the elemental stimuli abolished the preview benefit at all display sizes.

A second possibility is that the benefit at small display sizes is mediated by VWM (Al-Aidroos et al., 2012). A recent study has suggested that VWM might mediate the preview benefit for display sizes falling within its capacity (Al-Aidroos et al., 2012), with inhibitory processes playing a role when larger numbers of items are present. Given that Kanizsa-type illusory figures can be stored in VWM as discrete units (Anderson et al., 2013), it is possible that the preview benefit with perceptual groups at small display sizes is supported by VWM rather than via inhibitory processes. The role of VWM could be assessed by comparing performance in the preview condition in which grouped distractors are present with the working memory capacity of individual participants (Al-Aidroos et al., 2012). The role of these alternative accounts in filtering perceptual groups as distractors remains a question for future research. Nevertheless, this discussion does not negate the central finding that perceptual grouping of stimulus elements reduces the capacity of top-down inhibitory mechanisms for suppressing old items at large display sizes.

The Capacity of the Preview Benefit and Attentional Load Theory

It is noteworthy that the relationship between perceptual demands and attentional efficiency has previously been studied with respect to attentional load theory (Lavie, 1995; Lavie, Hirst, de Fockert, & Viding, 2004; Lavie, 2005). Lavie (2005) defines perceptual load as either the number of distracting items, or the demands of processing the perceptual representation. Attentional load theory proposes that high perceptual load reduces distractor interference in attentional selection, while low perceptual load increases interference. The results from this chapter are inconsistent with the predictions of attentional load theory, as overall attentional efficiency declined drastically with perceptually demanding stimuli. This raises the possibility that attentional load theory may apply to space-based attention, but is not generalizable to time-based attention. Attentional load theory proposes that distractors are only processed if a task is not perceptually demanding so that there is available capacity that can spill over, and allow them to ‘intrude’ (Lavie, 1995, 2005). In contrast, in time-based selection distractors are actively processed and inhibited, and this is central for improving the selection of newly arriving stimuli. The influence of perceptual load on attentional efficiency may therefore depend on the mechanism used (or not used) for distractor rejection. Determining which attentional mechanisms are used for selection in different tasks and how perceptual load influences these specific mechanisms is an important problem for understanding how efficiently attention is allocated.

On the Attentional Demands of Perceptual Grouping

The current findings also contribute to the debate regarding the attentional demands of perceptual grouping. The results of Chapter 3 are in line with those studies that suggest that some forms of perceptual grouping require resources (e.g., Trick & Enns, 1997; Mack & Rock, 1998). If perceptual grouping was possible at early visual stages, we would not expect the number of distractors to reduce the capacity of top-down inhibition in visual marking. Indeed, we might expect that the ability to group distractors would make them easier to suppress. Similarly, the formation of illusory surfaces might provide a stronger representation for inhibition to be applied to. Clearly, this was not the case.

However, the results do not preclude the possibility that perceptual grouping is a continuum varying in resource demands (e.g., Trick & Enns, 1997; Driver et al., 2001; Kimchi & Razpurker-Apfeld, 2004). This entails that there might be more and less demanding forms of perceptual grouping for inhibiting distractors in time-based visual selection. Indeed, when discrete moving stimuli maintain their relative positions and can be grouped into a single representation, a full preview benefit can be obtained (Watson, 2001). In contrast, when moving stimuli do not maintain their relative positions and make grouping more demanding, the preview benefit is abolished unless there is a colour difference between the old and new items (Watson & Humphreys, 1998). Nevertheless, here it is shown for the first time that there can be a negative influence of grouping elements into multiple groups and of illusory surfaces in time-based selection conditions.

Attention and Perceptual Grouping of Kanizsa-Type Contours

The results lend support to high-level accounts of the formation of illusory contours (e.g., Grabowecky & Treisman, 1989; Li et al., 2008), and are inconsistent with low-level accounts (e.g., Davis & Driver, 1994, 1998). I extend these results by showing for the first time that resources recruited when perceiving Kanizsa-type figures are likely to result from perceptual grouping, and not the inference of the illusory figure. This pattern was observed in both visual search performance, and in the preview search task.

The assumption of participants inferring illusory contours is present in other visual search tasks using Kanizsa-type stimuli (e.g., Davis & Driver, 1994, 1998; Li et al., 2008). However, it is worth noting that the formation of illusory contours in the current task is an assumption rather than an empirical prediction, as the perception of the illusory shape was not explicitly tested. In order to complete the task in Experiments 7 and 9, participants did not need to infer illusory contours. Instead, they may have been guided by the patterns of the pacmen similarly as in Experiment 8.

Limitations

One limitation in Experiments 7-9 is that the inter-stimulus separation was not held constant. Consequently, elements in large display sizes might have been more difficult to distinguish and perceptually group in comparison to those in small display sizes. The greater element density could potentially account for a lack of a preview benefit at large display sizes. However, had the inter-stimulus separation been held constant, it would have resulted in a differentially sized visual areas for small and large display sizes, producing another confound.

Conclusions

Although lab-based examples of visual illusions can be viewed as a product of our visual system, in natural environments this ability serves an adaptively vital function. Using luminance cues to detect object boundaries is crucial for object recognition in low-luminance environments, such as at night, in shadow, or to detect camouflaged or occluded objects. Perceptual groups also occur when elements do not induce a phenomenal experience, but can be perceived separately – such as a flock of birds, a basket of apples, or a car convoy.

Here it is shown for the first time that perceptual grouping can be a limiting factor in time-based visual attention. The results of the present study suggest that when such perceptual groups occur, attentional prioritization of new items is likely to be efficient only when there are a relatively small number of grouped items to be ignored. When larger number of distractors are present the preview benefit becomes severely reduced. Such environments will thus be more susceptible to distractor interference, which is beyond the control of the observer.

Chapter 3 showed that complex stimuli, such as perceptual groups, can considerably reduce the effectiveness of the preview benefit. The topic of Chapter 3 is complementary to Chapter 2, which examined how internal top-down inhibitory settings of the observer are modulated by the context of the task. These chapters established some fundamental endogenous and exogenous characteristics of time-based visual selection. Chapter 4 will examine how top-down inhibition in time-based visual selection develops in middle to late childhood. Currently, the development of the preview benefit has been examined from adulthood to old age (Watson & Maylor, 2002). However, the development of the preview benefit in childhood is missing from the current literature. Thus, the aim of Chapters 4 and 5 will be to establish at what age the preview benefit becomes fully functional, and whether it operates in a way similar to that present in adults. As discussed in Chapter 1, examining the development of attention can illuminate some underlying processes that appear unitary in adulthood (Astle & Scerif, 2009). Chapter 4 will examine the development of time-based visual selection with stationary stimuli from the age of 6 to adulthood.

Chapter 4

The Development of Time-based Visual selection in Children

Synopsis

Two experiments used the preview task to examine the ability of children aged 6 to 12 years to enhance processing of new items using temporal information. The findings showed that, from 6 years onwards, children are able to successfully ignore old visual information in order to prioritise selection of new stationary stimuli. This ability could be instantiated within 500 ms and maintained for at least 1500 ms. However, a number of 6-year-showed a deficit in the ability to ignore old stimuli, indicating greater individual differences in this age group. This suggested that children also use top-down inhibitory resources in preview search for stationary items, and that this ability develops until the age of 8 years. Efficient performance in time-based attention demonstrated an association with executive function measures in adults only (switching and response inhibition combined), providing behavioural evidence for a developmentally-constructed functional connection. The findings are discussed in terms of the development of time-based attentional selection, and improvement of attention in early school years and adolescence.

Introduction

Traditionally, the field of attention has focused on the ability to select objects based on their spatial location, and perhaps unsurprisingly, this aspect of attention has also been the focus of developmental studies. Some findings relating to the development of space-based attention in childhood have already been discussed in Chapter 1. For example, previous work has examined children's performance in visual search tasks (e.g., Donnelly et al., 2007; Trick & Enns, 1998), their ability to use cues for spatial orienting (e.g., Jakobsen et al., 2013; Schul et al., 2003), and implicit learning through space-based contextual cueing (Couperus, Hunt, Nelson, & Thomas, 2011). Overall, previous findings suggest that children's attentional ability is primarily characterized by greater distractibility (Hommel et al., 2004), and that until the age of around 8 years, children have difficulties controlling their attention volitionally across space (Ristic & Kingstone, 2009).

Whilst past studies enable us to understand how the developing brain is increasingly able to control attention in the spatial domain, they do not inform our understanding of attentional control and development in the temporal domain. Clearly, our visual world is not stationary, but rather, consists of a continuous flow of changing surroundings, events, and the appearance of new information that must be dealt with. Thus, establishing the developmental trajectory of temporal selection as a means of guiding attention is vital for characterizing children's attention in the real world.

Development of Time-Based Visual Selection

Studies investigating the use of inhibition in time-based selection have mostly considered young adults. However, those few that have examined the effects of age have shown that older adults have a preserved ability to exclude old stationary items from future search (Kramer & Atchley, 2000; Watson & Maylor, 2002). At the other end of the age range, Mason, Humphreys and Kent (2003, 2004) found facilitated preview search when comparing a group of ADHD and typically-developing children. Although not designed as developmental studies, they noted that the preview benefit might be stronger when children were older, suggesting the possibility of a developmental trajectory.

Broadly speaking, there are two reasons why inhibitory time-based selection might develop over time, rather than being present from an early age. First, although adult cognition is characterized by modular and specialized functions (Fodor, 1983; Pylyshyn, 1999), early and intermediate stages of development are characterized by domain-general learning processes (e.g., statistical learning) . These processes become domain-specific over time due to repeated experience and different brain regions becoming more specialized (Karmiloff-Smith, 1997, 1998). Thus, multiple regions in the brain compete to process inputs, through which specific mechanisms become established in certain domains (e.g., language, social cognition, memory, etc.) with increasing practice and apparent relevance. For example, inhibitory mechanisms may initially be relatively domain-general, becoming more specialised and domain-specific in the adult end-state (Karmiloff-Smith, 1998). In the case of time-based visual selection, although a general executive inhibitory function may be accessible to children from the age of 6 years (e.g., Klenberg, Korkman, & Lahti-

Nuuttila, 2001), it may not yet be sufficiently specialized in the visual attention modality to filter old distractors in time.

This may be particularly likely given that inhibition in time-based attention can be used intentionally and strategically, depending on task demands (e.g., Watson & Humphreys, 2000), potentially with a late developmental onset. This possibility would align such development with the trajectory of executive functions, which appear to be unitary in the early childhood years (e.g., Tsujimoto, Kuwajima, Sawaguchi, 2007; Wiebe, Espy, & Charak, 2008; Hughes, Ensor, Wilson, & Graham, 2009) and increasingly specialized across middle childhood and adolescence (e.g., Huizinga, Dolan, & van der Molen, 2006; Lehto, Juujarvi, Kooistra, Pukkinen, 2003). A second possibility is that because prioritizing novel objects in time is based on a resource-demanding process, (Watson & Humphreys, 1997; Humphreys et al., 2002; Olivers & Humphreys, 2002), any smaller resource capacity in childhood may not be sufficient for effective implementation.

Aims of the Experiments in Chapter 4

The main aim of the work presented in this chapter was to examine time-based selection for stationary items over the age range of 6 years to adulthood. Using the preview paradigm, three aspects important to attentional development can be addressed: 1) the ability to use temporal appearance to select goal-relevant information, 2) the ability to filter out stationary distractors, and 3) the development of top-down inhibitory processes. All of these aspects are incorporated in a single paradigm, informative about each at different developmental stages. Establishing whether children can anticipate temporal information is crucial to demonstrate whether (or when) in development children are able to use foreknowledge, predict future events, and use the appearance of anticipated information to modulate perception, decision making, and preparation for action.

In Experiment 10, time-based selection for stationary stimuli was examined from 6 years of age to adulthood, and its relationship with individual differences in executive functions (EF). Experiment 11 examined the influence of age on: 1) how long it takes to inhibit information, and 2) how long the information can be ignored for. Finally, I present a single measure to compare the magnitude and effectiveness of underlying inhibitory function across different age-groups.

Experiment 10: The Development of Time-Based Selection for Stationary Stimuli

In Experiment 10, the preview paradigm was used to determine the developmental trajectory of time-based selection for stationary stimuli. Experiment 10 also examined the relationship between preview search performance for stationary stimuli and individual measures of EF and STM, in order to illuminate any shared mechanisms. The EF tasks consisted of measures of response inhibition, switching, and a combination of inhibition and switching. STM tasks consisted of verbal and visuo-spatial STM measures.

Method

Participants. Participants comprised of 24 *6-year-olds* (10 male, age 5-6, *M* = 6 years, 3 months, *SD* = 3.3 months); 24 *8-year-olds*[1] (11 male, age 7-8, *M* = 8 years, 1 month, *SD* = 3.78 months), 24 *12-year-olds* (17 male, age 11-12, *M* = 12

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[1] One school declined to disclose dates of birth. Therefore, the mean age of the 6- and 8-year olds is based on a subset of the sample for which precise age data was available (16 out of 24 6-year- olds and 10 out of 24 8-year-olds).

years, 4 months, *SD* = 3.67 months), and 24 *adults* (4 male, age 18-29, *M* = 19 years, 8 months, *SD* = 32.2 months). Two 6-year-olds did not complete a full set of baselines, and were replaced by two additional participants. Children were recruited from local schools in three UK counties: West Midlands, Warwickshire, and Oxfordshire, and adults were students at the University of Warwick. All children and adults had normal or corrected-to-normal vision. Fourteen *6-year-olds* and ten *8-year-olds* were recruited via an opt-in procedure; the remaining children were recruited via an opt-out procedure with the Head Teacher's agreement. Adult participants were newly recruited for the purpose of this study and did not participate in any of the previous preview search experiments. Adult participants signed informed consent forms, while children gave their assent. Children received stickers for their participation while adults were given course credit or paid for participation. Ethical approval was obtained from the Psychology Research Ethics Board at the University of Warwick.

Search tasks. Displays were presented and response s recorded by custom programs running on a Samsung 550P5 15-inch LCD (1366 × 768 pixels, 60 Hz) laptop. The target was a light blue [RGB=68,164,176] square (8 mm × 8 mm), the distractors were light blue circles (10 mm diameter) and pink [RGB=211,103,126] squares, presented against a black background. Stimuli were placed into the cells of an invisible 6×6 grid, with center-to-center grid spacing of 28 mm (±5 mm random jitter). The target location was restricted to columns 1, 2, 5, or 6 to avoid left and right side location ambiguity. The number of blue and pink items on each side of the display was equal. There were three search conditions: a preview search task, a half-element baseline (HEB), and a full-element baseline (FEB). All trials consisted of a blank screen (500 ms), followed by a central white [RGB=180,180,180] fixation dot

(2 mm × 2 mm), after which the stimuli were added. In the preview condition, 2, 4, or 8 pink squares were presented for 1000 ms (the preview items), after which 1, 3, or 5 blue circles and one blue square target were added to the display to give a final display size of 4, 8, or 16 items. Participants were instructed to ignore the previewed items and find the target amongst the new items when they appeared. In the FEB, all search items appeared at the same time. In the HEB, only the second set of (blue) items were presented; hence the display size was 2, 4, or 8 items. Participants responded by pressing the left- or right-shoulder button of a USB gamepad to indicate target presence on the left or right of the display. Response errors were indicated by visual feedback by displaying the word ‘incorrect’ on the screen.

Executive function tasks. Components of executive functions were measured using the extended version of Shape School (Espy, 1997), adapted for older children, adolescents, and adults (Ellefson, Blagrove & Espy, in preparation) which provides a measure of inhibition and switching performance. The task is administered in a colourful story-book format. Stimuli, consisting of cartoon shape figures with faces, arms, and legs, vary in colour (red or blue), shape (square or circle), and ‘performance cues’. These comprised expression cues for the *Inhibition* condition (happy mouth vs sad mouth), and presence/absence of a hat for the *Switching* condition; inhibition and switching performance (and their corresponding cues) were combined for the *Both* condition. There were four conditions overall, administered in fixed order (Control, Inhibition, Switching, Both). In all test conditions, there were 48 figures, arranged in eight lines of six. Subjects processed each figure successively, according to the specific condition instructions, as quickly and as accurately as they could.

In the *Control* condition, participants named the colour (red/blue) of each stimulus to ensure accurate recognition and naming, and to establish a baseline speed. In the *Inhibition* condition, there were 24 ‘happy’ figures and 24 ‘sad’ figures, randomly interspersed, with happy figures having ‘finished their work’ and being ‘ready to go for lunch’, whereas for sad figures, this instruction was reversed. The task was to name the colour of happy figures only (i.e., those ready for lunch), and suppress responses for sad figures (i.e., those not ready for lunch). In the *Switching* condition, half of the stimuli wore hats and half were hatless. Here, hat-wearing figures were named according to shape (square or circle), and hatless figures, according to colour (red or blue); thus switching occurred between two response sets (colour versus shape). The *Both* condition measured inhibition and switching performance within the same trial block, with *Inhibition* and *Switching* cues combined (i.e., stimuli had happy or sad faces, and were also hat-wearing or hatless). Thus, participants needed to name happy figures only (suppressing responses for sad figures; Inhibition), according to their hat-status (Switching). Hat-wearing happy figures were named by shape (square or circle) and the hatless figures by colour (red or blue). There were 24 happy figures (12 hat-wearing) and 24 sad figures (12 hat-wearing), arranged randomly. Prior to each condition, children completed a practice set of six figures to check for adequate rule acquisition. RTs to complete each condition and errors were recorded by the researcher. For each condition, the dependent variable was the efficiency of responding, computed as Efficiency = [number of correct – number of errors]/total time

Working Memory Test-Battery for Children (WMTB-C). The digit recall and block recall tasks to measure verbal and spatial working memory, respectively (Pickering & Gathercole, 2001). In the *digit recall*, participants heard a sequence of digits and had to recall them verbally in identical order. In the *block recall*, participants viewed a board with 9 blocks placed randomly. The experimenter tapped a sequence of blocks, and participants had to tap the blocks in the same order. In both tasks, the length of the sequences increased until an accuracy criterion of below 2/3 for the current sequence.

Design and procedure. Children completed two counterbalanced sessions. One session contained the search tasks and the other contained the EF tasks. Adults completed all tasks in a single session. The search tasks consisted of six blocks of 36 trials (two for each of the preview, FEB and HEB conditions), presented in a counterbalanced ABCABC design to give a total of 216 trials. Participants completed a practice session of 10 trials for each condition to familiarize themselves with the tasks. Four additional practice trials preceded each block to remind participants of the task when blocks alternated. Between blocks was a self-paced break. The experimenter administered the Shape-School Extended task, and recorded the participants' responses and RTs.

Results

Search tasks. RTs less than 200 ms or greater than 10s were removed as outliers. The rationale for these cut-off points is provided in Chapter 2. This resulted in the removal of 0.31, 0.23, 0.10, and 0% of trials for the *6-*, *8-*, *12-year-olds* and adults respectively. In addition, one *12-year-old* completed one rather than two blocks of trials for each of the search tasks. Thus, this participant's data was based on average RTs and error rates from a single block for each condition. As discussed in the previous chapters, using means with cutoffs provides greater power when analyzing reaction times in comparison to medians (Ratcliff, 1993). Thus, means were used to describe the data throughout Chapter 4.

Reaction times: Figure 23 shows the mean correct RTs a function of display size, age, and condition, with search slope statistics in Table 21. As in previous studies, the size of the preview benefit was assessed by comparing preview performance with the FEB and HEB (Watson & Humphreys, 1997).

A 3(Condition: FEB, HEB, Preview) × 3 (4, 8, or 16 items) repeated measures ANOVA with age as the between-subject variable was conducted. There was a significant effect of condition, $F(2,184) = 125.96$, MSE = 73966.96, $p < .001$, $\eta_p^2 = .58$, display size, $F(2,184) = 150.54$, MSE = 39717.75, $p < .001$, $\eta_p^2 = .62$, and a between-subjects effect of age, $F(3,92) = 67.27$, MSE = 698224.72, $p < .001$, $\eta_p^2 = .69$. Bonferroni-adjusted pairwise comparisons revealed that all age groups differed in performance ($p < .001$), apart from 12-year-olds and adults. There was also a significant Condition × Display Size interaction, $F(4,368) = 75.72$, MSE = 18880.05, $p < .001$, $\eta_p^2 = .45$, Condition × Age interaction, $F(4,368) = 6.26$, MSE = 73966.96, $p < .001$, $\eta_p^2 = .17$, Age × Display Size Condition × Display Size, $F(12,368) = 6.38$, MSE = 18880.05, $p < .001$, $\eta_p^2 = .17$.

To provide a more fine-grained analysis of these effects and similarly to Watson and Maylor (2002), the preview benefit was further assessed by using individual analyses for each age group. Hence, data were analyzed using two separate 2 (Condition: Preview vs. HEB or Preview vs. FEB) × 3 (Display Size: 4, 8, or 16 items) within-subject ANOVAs for each of the four age groups; the outputs of these analyses are presented in Table 22. F or all age groups, preview search RTs were significantly longer than HEB RTs overall, and search was less efficient (as shown by a Condition × Display Size interaction) in the preview condition than in the HEB. In addition, preview search RTs were shorter than FEB RTs, and search was also more efficient in the preview condition than in the FEB. This suggests that all groups were able to successfully ignore old items to some extent. A more fine-grained age-based analysis of the preview benefit will be considered following Experiment 11.

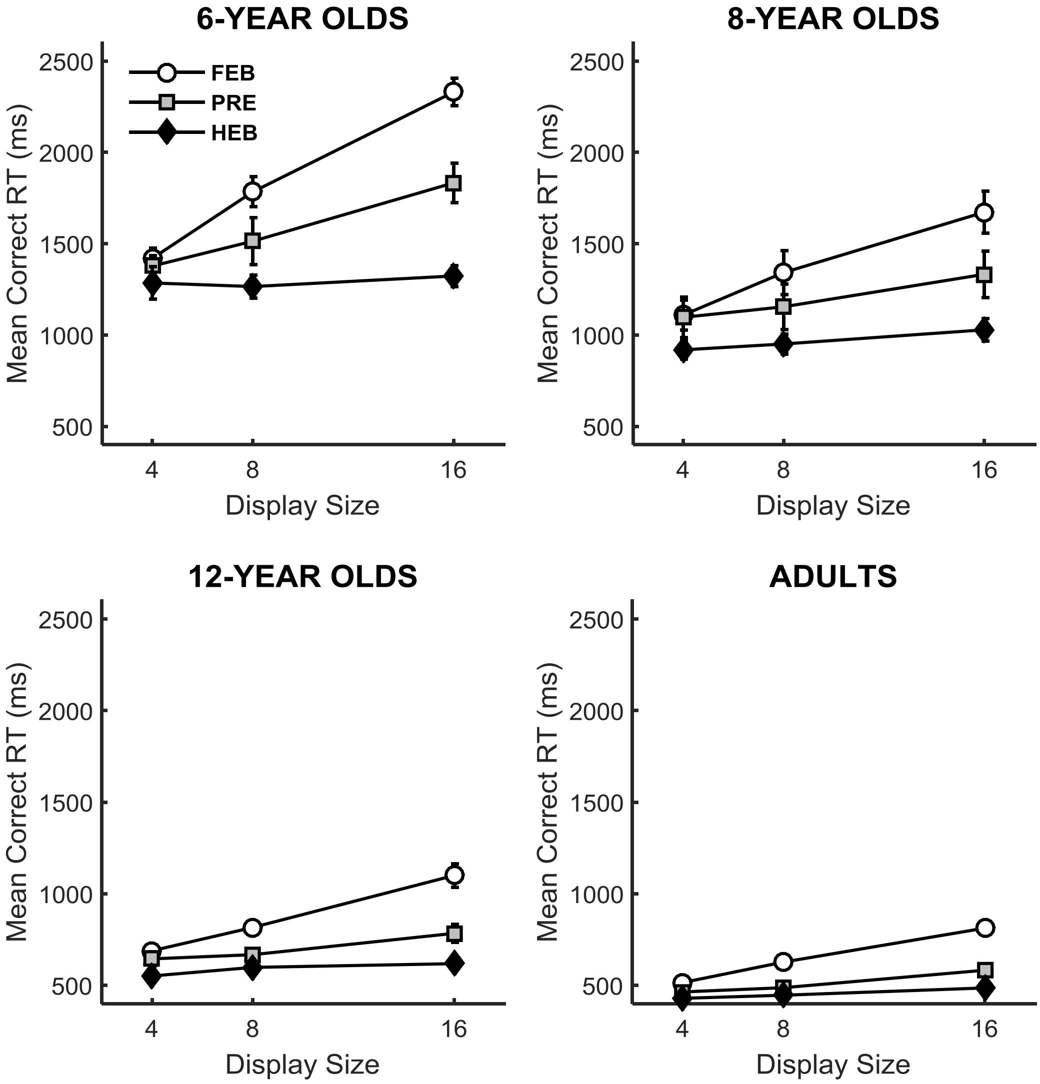

Figure 23. Mean correct reaction times (RTs) as a function of condition, display size and age for Experiment 10. Error bars indicate ±1SE.

Table 21. *Search slope statistics for Experiment 10.*

Group and descriptive characteristic	HEB	FEB	Preview
6-year-olds:			
Slope (ms/item)	3.77	74.79	38.24
Intercept	1256	1147.1	1218.1
R^2	0.61	0.99	0.99
8-year-olds:			
Slope (ms/item)	9.22	46.16	20.01
Intercept	879.94	944.02	1007.8
R^2	0.99	0.99	0.99
12-year-olds:			
Slope (ms/item)	5.15	34.44	12.03
Intercept	541.03	546.74	586.34
R^2	0.84	0.99	0.97
Adults:			
Slope (ms/item)	4.76	24.53	10.17
Intercept	409.12	422.60	416.32
R^2	0.99	0.99	0.98

Table 22. *F-values (top row), MSE values (middle row) and* η_p^2 *values (bottom row) for the Analyses from Experiment 10. F-value significance levels are donated as follows:* *** = $p < .001$, ** = $p < .005$, * = $p < .05$

	Preview vs. HEB			Preview vs. FEB		
Age	Condition	Display Size	Condition × Display Size	Condition	Display Size	Condition × Display Size
6-year olds	26.55*** 109183.03 .54	10.97** 97569.85 .32	10.18** 68752.78 .31	34.86*** 75344.73 .60	42.86*** 194350.2 1.65	12.19*** 68982.72 .35
8-year olds	6.91* 2721139.72 .23	25.14*** 23751.60 .52	7.42** 7163.49 .24	27.22*** 42937.86 .54	68.25*** 28773.68 .75	24.19*** 13333.69 .51
12-year olds	31.85*** 13545.69 .58	24.87*** 7296.27 .52	9.04*** 3326.69 .28	86.49*** 11967.52 .79	57.27*** 26400.64 .71	54.24*** 4162.47 .70
Adults	29.39*** 3874.07 .56	52.38*** 1880.78 .69	15.53*** 1186.49 .40	46.26*** 15290.37 .67	104.12*** 7709.49 .82	40.86*** 2360.09 .64

Error rates**:** Error rates were low overall for all age groups; 3.07%, 3.45%, 2.31%, and 0.81% for *6-*, *8-*, *12-year-olds* and adults respectively (Table 23).

A 3(Condition: FEB, HEB, Preview) × 3 (4, 8, or 16 items) repeated measures ANOVA with age as the between-subject variable revealed a significant effect of condition, $F(2,184) = 12.68$, MSE = 18.97, $p < .001$, $\eta_p^2 = .12$, and a Condition × Age interaction, $F(6,184) = 2.56$, MSE = 18.97, $p < .05$, $\eta_p^2 = .08$. There was also a significant between-subjects factor of age, $F(3,92) = 5.44$, MSE = 56.62, $p < .005$, $\eta_p^2 = .15$, indicating that 6- and 8-year olds made more errors than adults overall. No other effect or interaction proved significant, all Fs < 1.

To understand the error patterns in more detail, errors were analyzed individually for each age group, using 3(Condition: HEB, FEB, Preview) × 3(Display Size: 4, 8, 16 items) within-subject ANOVAs. This revealed a significant main effect of condition for *6-year-olds*, $F(2,46) = 7.95$, MSE = 18.83, $p < .005$, *8-year-olds*, $F(2,46) = 4.03$, MSE = 40.76, and *12-year-olds*, $p < .05$, $F(2,46) = 4.98$, MSE = 13.51, $p < .05$. Errors rates tended to be largest in the FEBs and smallest in the HEBs. Of most importance, there were no significant Condition × Display Size interactions, all Fs < 1, with all remaining Fs ≤ 2.79, ps $\geq .18$.

Table 23. *Mean percentage error rates for Experiment 10 as a function of age, condition and display size.*

Group and Condition	Display size 4	 8	 16
6-year-olds			
HEB	1.74	2.95	2.08
FEB	4.34	4.86	5.38
Preview	2.60	2.08	2.78
8-year-olds			
HEB	2.08	1.04	2.08
FEB	3.82	4.34	5.56
Preview	4.17	2.43	5.56
12-year-olds			
HEB	2.60	1.56	2.26
FEB	3.47	3.13	3.47
Preview	1.56	1.74	1.04
Adults			
HEB	1.04	0.87	0.35
FEB	0.69	1.56	1.04
Preview	0.17	1.04	0.52

EF and STM measures. Four *6-year-olds* and one *8-year-old* were excluded from analysis, due to early termination of the Shape-School extended task. As shown in Table 24, EF and STM performance improved generally as age increased. An associated MANOVA revealed a significant effect of age on EF and STM, *F* (18, 232) = 11.78, *p* < .001; Wilk's Λ = .16. Age had a significant effect on all measures: control efficiency (*F*(3,87)= 73.61; *p* < .001); inhibition efficiency (*F*(3,87)= 60.01; *p* < .001), switch efficiency (*F*(3,87)= 62.62; *p* < .001), both efficiency (*F*(3,87)= 60.56; *p* < .001), digit recall (*F*(3,87)= 41.77; *p* < .001), and block recall (*F*(3,87)= 61.67; *p* < .001).

Table 24. *Means and SDs (reported in parenthesis) for EF and STM tasks for 6-year-olds, 8-year-olds, 12-year-olds, and adults for Experiment 10.*

	Control	Inhibition	Switching	Both	Digit recall	Block recall
6-year-olds	1.01 (.26)	1.01 (.24)	.27 (.08)	.40 (.11)	25.75 (3.47)	19.92 (3.16)
8-year-olds	1.27 (.32)	1.37 (.31)	.47 (.17)	.65 (.26)	27.96 (4.97)	23.00 (3.57)
12-year-olds	1.85 (.40)	1.81 (.55)	.68 (.24)	.84 (.23)	30.17 (3.97)	25.71 (3.63)
Adults	2.51 (.43)	2.76 (.59)	1.09 (.27)	1.31 (.27)	40.38 (6.11)	35.54 (5.21)

It was next considered whether individual differences in EF related to individual differences in the efficiency of time-based visual selection. This was achieved by determining the correlation between the EF measures a measure of preview performance called the Preview Efficiency (PE) index (equation 1). The PE index is a single performance measure, independent of overall baseline (HEB and FEB) search rates (Blagrove & Watson, 2010). PE values towards 1 indicate more efficient Preview search, and values towards 0 indicate less efficient of a Preview search; this measure is bounded by 1 and 0.

$$PE = \frac{FEB\ slope - PREVIEW\ slope}{FEB\ slope - HEB\ slope} \qquad (1)$$

Table 25 shows the preliminary rank order, bivariate, and partial correlations across measures of PE, chronological age, efficiency of response inhibition, switching, inhibition and switching combined, and verbal and spatial working memory performance (raw scores from Shape-School Extended and the two WMTB-

C subscales). Values above the diagonal refer to bivariate correlations between measures, while those below refer to correlations between PE and EF measures, partialling out age and baseline naming speed in the Shape School extended Control condition.

When individual differences in age and baseline naming speed were taken into account, the efficiency of preview search was not related to any measure, but significant correlations between the EF measures remained. Given that controlling for age and baseline naming speed abolished correlations with preview efficiency, it is possible that the presence of these correlations were driven differentially in children and adults. Therefore, we repeated the analyses between preview efficiency and EF measures, controlling for baseline naming speed, in children and adults separately (see Table 26). In adults, switching and inhibition combined was moderately correlated with preview search efficiency, $r(21) = .479$, $p < .05$, while no significant partial correlations were obtained for the children.

Table 25. *Relationships between chronological age, Shape School measures (Control, Inhibition, Switching, Both), working memory measures (digit recall and block recall), and Preview efficiency in Experiment 10.*

Values above the diagonal indicate bivariate correlations (Spearman's for age and Pearson's for the remaining variables) across measures, while values below the diagonal indicate partial correlations controlling for chronological age and baseline naming speed (the 'Control' condition in Shape School).

* p < .05, ** p < .01, *** p < .001

	Control	Inhibition	Switching	Both	Digit recall	Block Recall	PE
Age[a]	.849***	.814***	.845***	.827***	.717***	.777***	.233*
Control		.842***	.867***	.824***	.717***	.803***	.243*
Inhibition			.810***	.846***	.769***	.785***	.218*
Switching		.219*		.856**	.694**	.773***	.216*
Both		.432**	.432**		.697***	.734***	.310**
Digit Recall		.382**	.128	.095		.758***	.154
Block recall		.263*	.108	.328	.380**		.216*
PE		-.009	-0.023	.175	-.063		

[a] Correlations with age are based on Spearman's rank-order correlations.

Table 26. *Partial correlation coefficients (baseline naming speed controlled) for preview efficiency and EF and STM measures*

	Children	Adults
Inhibition	-0.73	.260
Switching	-0.34	.157
Inhibition & Switching	.131	.479*
Digit recall	-.102	.188
Block recall	.094	.008

Note. Children's $N = 67$, adults' $N= 24$ participants

* $p < .05$

** $p < .005$

*** $p < .001$

Discussion

The aim of Experiment 10 was to measure selective attention to new objects across four age groups. As expected from previous research, children produced generally less efficient search than adults (Donnelly et al., 2007; Trick & Enns, 1998; Ruskin & Kaye, 1990). However, of most interest, all age groups showed a robust preview benefit suggesting that children as young as six are able to prioritise the selection of new stimuli to some degree. Further exploration of age-related effects will be addressed after Experiment 11. Of note, for all age groups, preview search was not as efficient as HEB search. This is in contrast to the more typical finding in which preview search matches that of the HEB. Whether a full preview benefit (i.e., search equivalent to HEB) or partial preview benefit (i.e., search different from both HEB and FEB) is obtained, often depends on the type of stimuli used (e.g., Blagrove & Watson, 2010; Gibson & Jiang, 2001). For example, salient stimuli often produce a weaker preview benefit – as found here (Gibson & Jiang, 2001). In current experiment, the difference between the preview and HEB is most likely a result of using salient shape-colour stimuli (rather than more complex letters) to make the task suitable for children.

The second main finding was that the size of the preview benefit was related to combined switching and inhibition measures for adults (over and above baseline naming speed). Importantly, there was no relationship between preview efficiency and EF measures for the children. In addition, it is noteworthy that the adult sample had much less power than the combined child sample, since the data from 6-12-year-olds was combined for the analysis. This suggested that the relationships between preview efficiency and EF measures of switching and inhibition are likely to be strong in adulthood.

The lack of a developmental relation between the EF and Preview efficiency did not compromise the presence of the preview benefit in childhood, indicating that EF do not account for the presence of the preview benefit per se. Nevertheless, it is evident that the association between EF and time-based selection in adulthood is not a result of a predetermined connection, but one that is sculpted across development. This is consistent with neuroconstructivist approaches to development (e.g., Karmiloff-Smith, 1997, 2008). Experiment 11 examined potential quantitative differences across development in the inhibitory mechanisms underlying the preview benefit; specifically, whether age differences may emerge as a result of the time-course of stimulus presentation.

Experiment 11: Time-Course of Time-Based Visual Selection

Previous work has shown that the preview benefit in adults typically requires a preview duration of approximately 400 ms (Watson & Humphreys, 1997), and the minimum duration can depend on the valence of the old items (Blagrove & Watson, 2010). Experiment 11 examined whether age has an effect on the speed with which old items can be ignored. It has been argued that participants develop an attentional template of old items during the preview period, which is then used to co-ordinate inhibition to their locations and/or features (Watson & Humphreys, 1997). Setting up and maintaining this inhibitory template requires attentional resources and is susceptible to interference from competing tasks (Humphreys et al., 2002; Pollmann et al., 2003). Given the attentional resource and processing requirements involved in time-based selection, it is possible that children: 1) require more time to ignore old objects, and 2) find it more difficult to maintain such inhibition. Experiment 11 examined these possibilities by manipulating the preview duration between 500 and 1500 ms. If children require more time to inhibit old items and/or find it more difficult to maintain the inhibition, then we would expect selective impairment at preview durations of 500 and 1500 ms respectively.

Method

Participants. Participants comprised 24 *6-year-olds* (14 male, age 5-6, *M*=5 years 8 months, *SD* = 3.39 months), 24 *8-year-olds* (12 male, age 7-8, *M*=7 years 8 months), 24 *12-year-olds* (10 male, age 11-12, *M* = 12 years 3 months, *SD* = 3.29 months), and 24 *adults* (11 male, age 17- 29, *M* = 20 years 4 months, *SD* = 34.29). One 6-year-old did not complete the session and another child was tested instead. Children were recruited via a Head teacher-approved opt-out procedure. Adults were newly recruited for the purpose of this study and did not participate in any of the prior preview experiments Adult participants signed informed consent forms and children gave their assent. Ethical approval was obtained from the Psychology Research Ethics Board at the University of Warwick.

Apparatus and stimuli. Stimuli and apparatus were identical to Experiment 11. However, there were three preview conditions with durations of 500, 1000 and 1500 ms (PRE_{500}, PRE_{1000}, PRE_{1500} respectively) in addition to the FEB and HEB.

Design and procedure. The design and procedure were identical to those of Experiment 11, except that, due to the longer experiment duration, no individual difference measures were taken. The FEB and the HEB were administered to children in one session, with the three preview conditions administered in a different session. The order of the two sessions was counterbalanced across participants, and all conditions were counterbalanced within the sessions. Adults completed the HEB/FEB and the preview conditions as two separate parts of the same experimental session.

Results

Reaction times: Outlier RTs below 200 ms or greater than 10s were removed; 2.96% for the 6-year- olds, 0.25% for the 8-year-olds, 0.19% for the 12-year-olds, and 1.70% for the adults. Mean correct RTs are shown in Figure 24, search slopes in Table 27 and statistical results in Table 28.

A 5(Condition: FEB, HEB, Pre500, PRE1000, PRE15000) × 3 (4, 8, or 16 items) repeated measures ANOVA with age as the between-subject variable showed a significant effect of condition, $F(4,368) = 49.25$, MSE = 72211.18, $p < .001$, $\eta_p^2 = .35$, display size, $F(2,184) = 175.88$, MSE = 37861.49, $p < .001$, $\eta_p^2 = .66$, and a between-subjects effect of age, $F(3,92) = 92.07$, MSE = 1429611.78, $p < .001$, $\eta_p^2 =$

.75. Bonferroni-corrected pairwise comparisons showed that performance became faster with age across all age groups ($p < .001$) until the age of 12. The Condition × Display Size, $F(8,736) = 28.10$, MSE = 23472.77, $p < .001$, $\eta_p^2 = .23$, Condition × Age, $F(12,368) = 8.14$, MSE = 72211.18, $p < .001$, $\eta_p^2 = .21$, Age × Display Size, $F(6,184) = 12.73$, MSE = 37861.49, $p < .001$, $\eta_p^2 = .29$, and Age × Condition × Display Size interaction, $F(24,736) = 5.11$, MSE = 23472.77, $p < .001$, $\eta_p^2 = .14$, all proved significant.

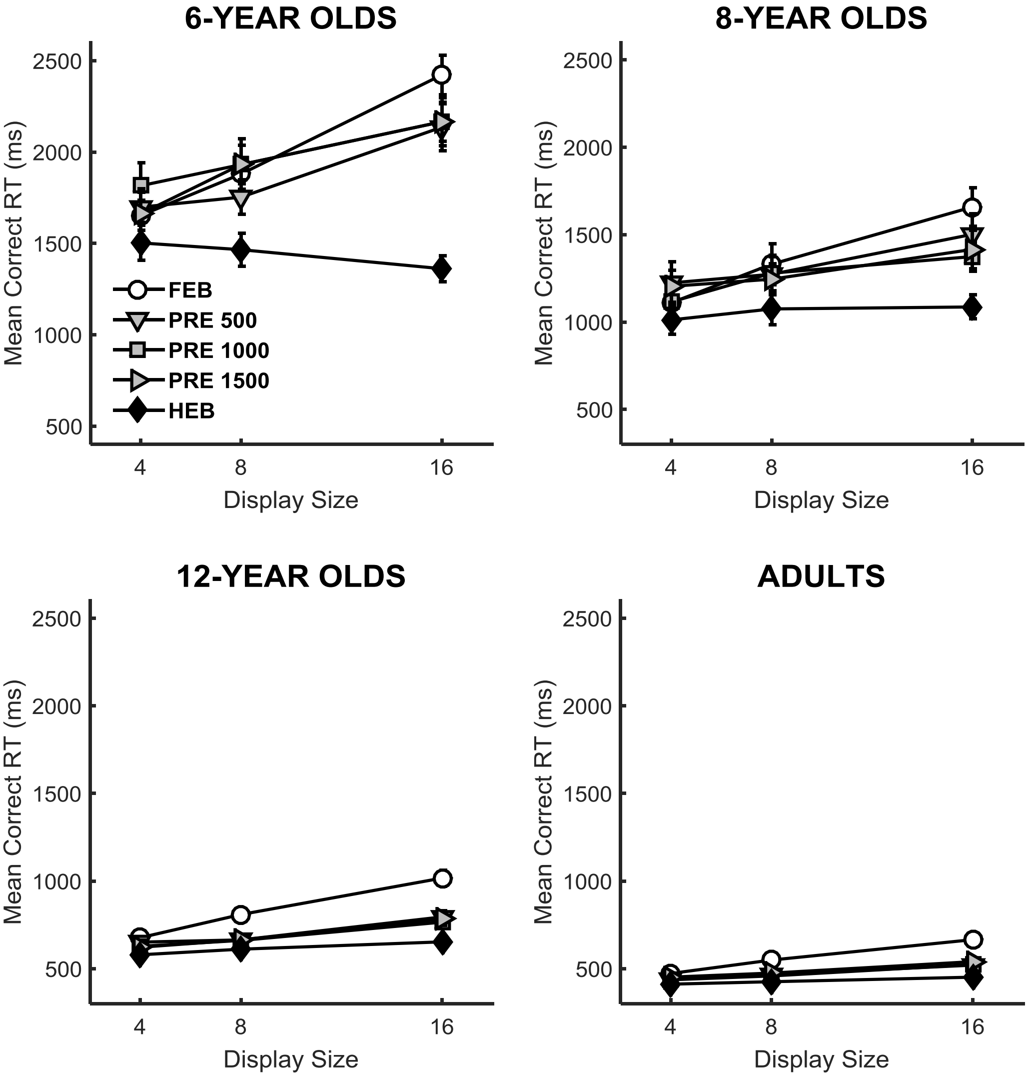

Figure 24. Mean correct reaction times (RTs) as a function of condition, display size and age for Experiment 11. Error bars indicate ±1SE.

Table 27. *Search slope statistics for Experiment 11*

Group and descriptive characteristic	HEB	FEB	PRE$_{500}$	PRE$_{1000}$	PRE$_{1500}$
6-year-olds:					
Slope (ms/item)	-11.95	64.61	38.10	29.2	40.07
Intercept	1553.5	1381.8	1506.8	1698.3	1544.2
R^2	0.99	0.99	0.95	1	0.95
8-year-olds:					
Slope (ms/item)	5.49	45.01	23.93	20.19	18.13
Intercept	1006.5	946.23	1109.6	1068	1119.1
R^2	0.71	0.99	0.98	0.89	0.98
12-year-olds:					
Slope (ms/item)	6.02	28.01	12.61	11.72	13.57
Intercept	558.38	572.94	586.1	575.43	563.18
R^2	0.99	0.99	0.94	0.99	0.99
Adults:					
Slope(ms/item)	3.31	15.85	6.76	7.39	7.48
Intercept	398.70	414.65	412.01	403.99	419.14
R^2	0.99	0.99	1	0.99	0.99

Influence of preview duration. The differences in Preview performance were evaluated by conducting a 3(Preview Duration$_{500,\ 1000,\ 1500}$) × 3 (Display Size: 4, 8, or 16 items) within-subject ANOVA for each age group individually (see Table 28). As expected, RTs increased as a function of display size for all age groups. Overall RTs differed across conditions only for the adults (475, 473 and 489 ms for the PRE$_{500}$, PRE$_{1000}$ and PRE$_{1500}$ conditions respectively). However, of most importance, search efficiency did not differ as a function of preview duration for any age group. This suggests that an inhibitory template could be set up by 500 ms and maintained for 1500 ms for all ages.

Table 28. *F-values (top row), MSE values (middle row) and* η_p^2 *values (bottom row) for the analyses from Experiment 13. F-value significance levels are donated as follows*: *** = *p*<.001, **<.005,* =<.05

resence of the preview benefit. The presence of a preview benefit

Age group	PRE_{500} vs PRE_{1000} vs PRE_{1500} Condition	PRE_{500} vs PRE_{1000} vs PRE_{1500} Display Size	PRE_{500} vs PRE_{1000} vs PRE_{1500} Condition ×Display Size	$PRE_{500,1000,1500}$ vs HEB Condition	$PRE_{500,1000,1500}$ vs HEB Display Size	$PRE_{500,1000,1500}$ vs HEB Condition ×Display Size	$PRE_{500,1000,1500}$ vs FEB Condition	$PRE_{500,1000,1500}$ vs FEB Display Size	$PRE_{500,1000,1500}$ vs FEB Condition ×Display Size
6-year olds	1.14 184701.59 .05	29.31*** 117471.58 .56	1.27 78885.65 .05	21.49*** 194847.09 .48	18.54*** 110040.82 .45	8.04*** 71800.41 .26	1.09 205156.95 .05	63.35*** 104596.01 .74	3.55** 71776.52 .13
8-year olds	2.13 63319.77 .09	31.51*** 52590.86 .58	1.78 32483.51 .07	15.07*** 129885.74 .40	40.18*** 32106.68 .64	3.39** 38566.27 .13	2.18 111050.67 .09	54.82*** 74327.97 .70	6.87*** 23617.73 .23
12-year olds	.84 8212.32 .04	47.03*** 16204.61 .63	1.23 1765.26 .05	11.56*** 9939.88, .33	46.14*** 15760. .67	6.99*** 1814.45 .23	30.22*** 12089.93 .57	82.32*** 22116.05 .78	22.23*** 4705.29 .49
Adults	4.45* 1214.89 .16	163.99*** 1280.25 .88	.86 436.43 .04	27.39*** 1735.49 .54	168.12*** 1274.44 .88	12.76*** 457.46 .36	71.54*** 1806.68 .76	388.69*** 1072.04 .94	40.37*** 692.79 .64

was assessed via a 4(HEB, $PRE_{500,1000,1500}$) × 3(Display Size: 4,8,16) and 4(FEB, $PRE_{500,1000,1500}$) × 3(Display Size: 4,8,16) within-subjects ANOVA for each age group (Table 28). RTs increased with display size, with preview search slopes steeper than in the HEB, but shallower than in the FEB; suggesting a partial, but robust, preview benefit. Overall RTs were longer in preview conditions than in the HEB conditions for all age groups. RTs in the preview condition were shorter than in the FEB condition only for *12-year-olds* and the adults.

Error rates. Error rates were low for all age groups (6.98%, 1.84%, 1.78%, and 2.57% for 6-, 8-, 12-year olds and adults respectively (Table 29).

A 5(Condition: FEB, HEB, Pre500, PRE1000, PRE15000) × 3 (4, 8, or 16 items) repeated measures ANOVA with age as the between-subject variable demonstrated a significant effect of condition, $F(4,368) = 4.47$, MSE = 28.81, $p < .005$, $\eta_p^2 = .05$, display size, $F(2,184) = 13.60$, MSE = 12.64, $p < .001$, $\eta_p^2 = .13$, as well as a between-subjects effect of age, $F(3,92) = 17.46$, MSE = 127.17, $p < .001$, $\eta_p^2 = .36$. Bonferroni-corrected pairwise comparisons indicated that more errors were made by 6-year-olds in comparison to all other age groups (all *p*s < .001). The Condition × Display Size, $F(8,736) = 5.01$, MSE = 15.83, $p < .001$, $\eta_p^2 = .05$, Condition × Age, $F(12,368) = 2.63$, MSE = 28.81, $p < .005$, $\eta_p^2 = .08$, Age × Display Size, $F(6,184) = 13.63$, MSE = 12.65, $p < .001$, $\eta_p^2 = .31$, and Age × Condition × Display Size interaction, $F(24,736) = 3.81$, MSE = 15.83, $p < .001$, $\eta_p^2 = .11$, all proved significant. However, the effect sizes of most of the main effects and interactions were very small.

Errors were further analyzed individually by age group using 5(Condition: HEB, FEB, PRE_{500}, PRE_{1000}, PRE_{1500}) × 3(Display Size: 4, 8, 16 items) within-subject ANOVAs. For the 12-year-olds, overall error rates differed across condition, $F(4,92)$

= 3.59, MSE = 6.55, *p* < .01, and were the highest in FEB. For the adults, errors were greatest in the FEB, *F*(4,92) = 18.12, MSE = 17.01, *p* < .001, and increased with display size, *F*(2,46) = 37.70, MSE = 17.14, *p* < .001. No other main effects or interactions were significant; all *Fs* < 1.74, *ps* >.13. Taken as a whole, the data do not support a speed-accuracy trade-off.

Table 29. *Mean percentage error rates for Experiment 11 as a function of age, display size and condition.*

	Display size		
Group and Condition	4	8	16
6-year olds:			
HEB	7.29	7.29	7.29
FEB	7.07	6.52	6.88
PRE 500 ms	6.63	6.06	6.44
PRE 1000 ms	6.44	6.44	6.06
PRE 1500 ms	6.44	6.63	5.30
8-year olds:			
HEB	2.08	2.08	1.91
FEB	2.95	1.22	2.08
PRE 500 ms	1.91	2.60	1.39
PRE 1000 ms	2.26	1.22	1.91
PRE 1500 ms	1.39	1.74	0.87
12-year olds:			
HEB	1.39	1.39	1.74
FEB	1.39	2.78	1.91
PRE 500 ms	3.65	2.60	1.74
PRE 1000 ms	2.26	0.69	1.56
PRE 1500 ms	1.04	1.74	0.87
Adults:			
HEB	0.87	0.87	1.22
FEB	1.56	1.56	15.10
PRE 500 ms	1.39	2.26	4.69
PRE 1000 ms	0.52	1.04	2.78
PRE 1500 ms	1.04	1.22	2.43

The developmental trajectory of time-based selection revisited. To provide a finer grained analysis of potential age differences in time-based selection, PE values (see equation 1) were calculated for the combined data from the HEB, FEB, and Preview$_{1000}$ conditions of Experiments 10 and 11.

These scores were analyzed with a 4 (age group) × 2 (Experiment) ANOVA, which revealed a significant main effect of age, $F(3,184) = 4.98$, $p < .005$. As shown in Figure 25, the extent to which old items could be excluded increased from around 50% to 70% across the four age groups. Post-hoc Bonferroni-corrected comparisons indicated that the PE index for 6-year-olds was significantly smaller than for 12-year-olds, ($p < .005$) and adults ($p < .05$). Neither the main effect of experiment, nor the Age × Experiment interaction was significant; both *F*s < 1.

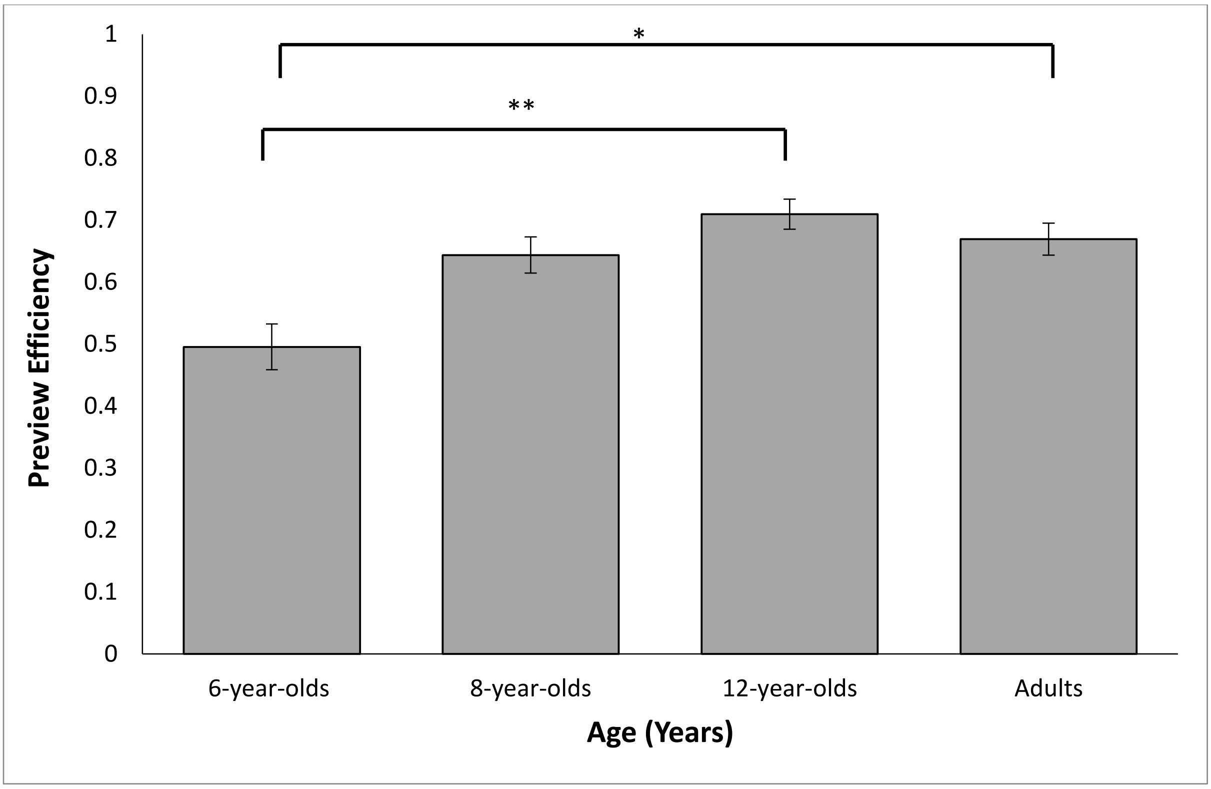

Figure 25. Preview search efficiency (PE) as a function of age for the combined data from Experiments 10 and 11. A value of 0 indicates no preview benefit – none of the old items could be ignored and search was as inefficient as if all items had been presented simultaneously. A value of 1 indicates a full preview benefit – all of the old items could be ignored and selection could be restricted to just the new items.

Intermediate values indicate the ability to partially supress old items and prioritise new items. For example, a PE of 0.5 indicates that approximately half of the new items could be prioritised. Error bars represent ±1SE.

p* < .05, ** *p* < .01, * *p* < .001

A total of 12 6-year-olds children demonstrated a PE index of 0, which indicated that no visual marking had taken place. In each of the older age groups (8 years to adult), there were 2 individuals that had a PE index of 0 and did not show the effect. Since a quarter of 6-year-olds children not being able to apply visual marking, this has likely contributed to the reduced effectiveness of the PE index.

Discussion

In Experiment 11, the effect of reducing and increasing the preview duration across four age groups was assessed. There were three main findings. First, as in Experiment 10, there was a partial but robust, preview benefit for all age groups. Second (again, for all age groups), a preview benefit could be generated within a reduced preview duration (500 ms) and maintained for an extended duration (1500 ms). Finally, a combined analysis based on the preview efficiency (PE) index suggested that the effectiveness of time-based selection was significantly smaller for the 6-year-olds, and generally increased with age. Given that the PE measure controls for general differences in search rate, this result cannot be explained by age-associated differences in overall search speed. Inspecting the PE index has revealed that a quarter of 6-year-olds in the current sample did not demonstrate the preview benefit, indicating that this is likely to account for the reduced overall PE index in the youngest age group.

Previous work has shown that the preview benefit is mediated via a combination of top-down inhibition of old items, attentional capture by signals associated with new stimuli, and stimulus grouping properties (e.g., von Mühlenen et al., 2013; Donk & Theeuwes, 2001, 2003; Jiang et al., 2002). In relation to these mechanisms, a reduced preview benefit for 6-year-olds might best be explained by a reduced ability to inhibit old items. If attentional capture was solely responsible for driving the preview benefit in children, we would expect similar benefits across all age groups, given that reflexive, bottom-up mechanisms develop shortly after birth (e.g., Johnson, Posner, & Rothbart, 1991; Valenza, Simion, Umilta, 1994). Therefore, incomplete development of mechanisms that enable efficient top-down filtering provides a better account of the data.

One further pattern is worth noting here. In Experiment 10, overall Preview search RTs were shorter than in the FEB for all age groups. However, in Experiment 11, despite a robust preview benefit in terms of search slopes for all age groups, overall Preview RTs were only shorter than those in the FEB for the 12-year-olds and adults. In other words, the search slopes evidenced a clear preview benefit, but this was less clear for the overall RTs data. Indeed, for the 6- and 8-year-olds, the overall Preview mean RTs were slower than the FEB for the smallest display size (see Figure 24). A similar pattern was observed by Watson and Humphreys (1998), when adults attempted to ignore moving previewed stimuli.

Watson and Humphreys (1998) suggested that the commitment of attentional resources to task of inhibiting old, moving items led to a slowing of the initial onset of search (i.e., when new items were displayed). When the amount of attentional resources required was reduced, by making the items more discriminable, move more slowly, and allowing participants to have more practice overall Preview RTs reduced. In the present experiment, it is possible that inhibiting old items had consumed most of the attentional resources available for the 6- and 8-year-olds in a similar way, causing initial search of the new items to be delayed. Thus, their overall Preview RTs did not differ from those of the FEB. In contrast, higher resource capacity in 12-year-olds and adults would have resulted in a smaller increase in overall RTs, resulting in a Preview-FEB difference. One might ask why this pattern occurred in Experiment 11 but not also in Experiment 10. One possible explanation is that an increased level of fatigue in Experiment 11 could have caused the difference. For example, in Experiment 11, one session consisted of three preview conditions, which was potentially more demanding for the younger children. In contrast, Experiment 10 comprised a single preview condition, together with HEB and FEB. Increased levels of fatigue in Experiment 11 might have resulted in reduced resources being available.

General Discussion

The aim of the work presented in this chapter was to investigate potential age-related changes in the ability to prioritise new information by the use of temporal cues and expectations in goal-directed attentional processing. In Experiment 10, it was also determined whether individual differences in EF may be related to time-based attentional performance.

This work reported in this thesis is the first to compare developmental trajectories in the ability to use temporal information to guide attention. Overall, all age groups were able to prioritise the selection of new stimuli successfully. This shows that children appear to have a similar ability to filter visual distractors over time as adults. This contrasts with the suggestion that the main attentional difficulty in childhood is due to a reduced ability to filter irrelevant distraction (Hommel et al., 2004). In addition, the duration of previewed information (i.e., longer or shorter) did not seem to influence the ability to suppress old distractors for any age group.

Although qualitatively similar across the age groups, there were nonetheless greater individual differences in the ability to ignore old items between the ages of 6 to 12. It is worth noting that even in the older age-groups, there were a few individuals that demonstrated a lack of a preview benefit. However, a greater number of participants lacking a preview benefit in the 6-year-old age group suggests that this ability has a developmental course. This effect likely results from increasing cognitive resources and improved suppression mechanisms that develop between these ages (Klenberg et al., 2001). If an alternative mechanism such as automatic capture had an exclusive role in producing the preview benefit, we would not expect the effect to be obtained at display sizes of 16 items (8 old and 8 new), where the four-element capacity of automatic capture by abrupt onsets is exceeded (Yantis & Johnson, 1990). In addition, the difficulty for some children to ignore old items is unlikely to be due to deficits in feature-based similarity grouping of old distractors and previous studies have demonstrated that children show sensitivity to Gestalt grouping principles (Enns & Girgus, 1985).

One possibility for greater individual differences occurring in the 6-year-old age group, is because younger children might possess a less modular structure of domain-specialised functions that facilitate cognitive processing. According to neuro-constructivist accounts of developmental cognition, domain-general mechanisms exist in development but their use in specific functions may only appear later through repeated use with certain types of input (Karmiloff-Smith, 1998), which may account for greater individual differences in this age group. For instance, executive inhibition may exist in childhood as a domain-general function, but not be fully applied to time-based visual attention.

The findings from Experiment 10 provide some support for this, in terms of specialisation occurring as increased connectivity between time-based attention and complex EF performance in adults. Furthermore, we can observe reduced inhibitory filtering of old distractors in 6-year-olds. It appears that the effectiveness of top-down inhibition and the associations between the efficiency of time-based visual selection and EF are not established initially, but are constructed during the course of development.

In fact, flexible interaction between different cognitive functions and brain networks characterizes the mature human brain, and here, may account for superior efficiency in suppressing distractors. For instance, Fair and colleagues (2009) analysed fMRI evidence from a number of studies, which suggested that anatomically distant regions in the brain functionally integrate during the ontogenetic course, and are likely to be the organizing principle of adult cognition. The results are consistent with this generalized neural finding, insofar as they apply to attentional performance.

Children's ability to use temporal cues and goals to facilitate voluntary attentional processing is clearly demonstrated here, but importantly, may be reduced for younger age groups. This finding goes beyond simply charting developmental trajectories. The findings have shown that the procedure of successively presenting events in time is a valid and robust way of boosting children's attentional performance in complex tasks. This is especially relevant, given that at any moment, children can only be aware of (and code in their visual working memory) a relatively small amount of information in comparison to adults (Riggs et al., 2006). As such, the ability to filter distractors is particularly important in preventing irrelevant material occupying (age-related) reduced capacity. Therefore, besides improving attentional selection, the availability of this mechanism may be beneficial for other cognitive systems relying on attentional performance, such as memory and learning. It may further be a useful means of improving attention in children that have attentional difficulties. For example, Mason et al. (2003, 2004) have previously shown that children diagnosed with ADHD are able to ignore old distractors and prioritise novel information. Crucially, using a procedure of successively presenting distractors would aid attentional selection in these children, and encourage their use of top-down processes in attentional control.

Limitations

The important issue that merits comment is that the differences observed between younger children, namely 6-year-olds, and adults in performance may not solely be a product of developmental differences in attention. There are a number of task-related factors that may have contributed to children's performance.

Past studies examining developmental attention contend that although differences in reaction times between age-groups are expected based on differences in motor speed alone, it should not affect the interpretation of the attentional variables as they are manipulated in a within-subject design (Trick & Enns, 1998). However, in the context of the preview benefit, a very slow response may have interfered with the maintenance of inhibition by the time the child responded. Another likely factor is that motor abilities (in particular those that involve coordination with gaming devices) may differ among children who regularly play video-games and those that do not. Practice with playing video-games in childhood has also been found to contribute to improvements in attention (Trick, Jaspers, Fayer, & Sethi, 2005; Green & Bavelier, 2006).

Another factor that may have been enhanced in younger children is engagement with the task. A repetitive visual search task with a large number of trials may have been resulted in greater fatigue or loss of motivation in youngest children, despite there being an incentive upon the completion of the task. However, any reduction in the number of trials would have hindered the reliability of the tasks. Such issues involving motivation may be present in any study investigating attention in young children.

Conclusion

In conclusion, the findings from this chapter indicate that the ability to select goal-relevant information temporally is in place by 6 years of age for most children, despite there being a number of 6-year-olds that do not demonstrate a preview benefit at all. This ability to use time for attentional guidance can be generated over short durations (i.e., 500 ms) and sustained (i.e., 1500 ms), consistently across age groups. However, there are large individual differences in the 6-year-old age group, in that a quarter of children in the sample were not able to inhibit the old stimuli, suggesting that this ability has a developmental course.

Chapter 4 demonstrated the developmental trajectory of the preview benefit with stationary stimuli. Past research has suggested that top-down inhibition with stationary stimuli in time-based visual selection is mostly based on inhibiting old locations of the previewed items (Watson & Humphreys, 1997; 2000). The role of location-based inhibition in preview search was also evidenced by Experiments 1 and 2 in Chapter 2. However, the preview benefit with objects in motion usually requires feature-based inhibition of old items (Watson & Humphreys, 1998; see also Andrews et al., 2011; Watson, 2001). Moreover, Watson and Maylor (2002) found that these two inhibitory systems (location-based and feature-based) are differentially affected by ageing. Thus, location-based and feature-based inhibition may also have different maturational rates. The aim of Chapter 5 will be to determine the developmental trajectory of time-based visual selection with motion stimuli.

Chapter 5

Developmental Trajectories of Time-based Visual Selection of Objects in Motion

Synopsis

Although many studies have focused on the development of children's attention, few have examined the development of attentional mechanisms for moving stimuli. In the present chapter, 6- to 12-year-old children completed the preview search task for moving objects. The results indicate that: (a) 6-year-olds were able to inhibit a few moving items, (b) 8-year- olds were able to inhibit a large number moving distractors, but could not maintain the inhibitory template when the duration was extended, and (c) 12-year-olds and adults could inhibit moving items of all display sizes and durations, and this was coupled with individual differences in EF for adults. Humphreys et al. (2002) have previously suggested that the preview benefit is comprised of two components: initializing and consolidating a top down generated inhibitory representation via central resources, and maintaining this representation via visual resources. The results presented in the current chapter suggest that these two components have different developmental trajectories. Initializing and consolidating the top-down inhibitory representation of old moving items improves considerably between the ages of 6 to 8 years, whilst maintaining the inhibitory representation continues to develop between the ages of 8 and 12.

Introduction

One of the fundamental purposes of the attentional system is to focus on other living, moving beings around us. Attention sometimes needs to be focused on inanimate moving objects, such as a fruit falling from a tree or an object we must catch or avoid being hit by. Attention to moving objects is also vital for both drivers and pedestrians crossing busy roads. Essentially, attention to motion is crucial for safe and adaptive behaviour, and lapses can lead to increased danger and result in disastrous outcomes.

In an overview describing the types of features that are likely to guide search, Wolfe and Horowitz (2004) concluded that motion can strongly guide the deployment of attention (see also McLeod, Driver, & Crisp, 1988, for demonstrations of conjunctions of form and motion guiding search). Given the relevance of moving stimuli for action, the question of whether motion signals automatically capture attention has also been subject to extensive research. As discussed in Chapter 1, Hillstrom and Yantis (1994) concluded that moving objects do not capture attention, but perceptual objects do. More recently, Franconeri and Simons (2003, 2005) argued that some types of motion automatically captures attention (such as an increase in object size – simulated looming), due to its behavioral relevance, whereas a decrease in object size, does not capture attention. Abrams and Christ (2003, 2005) suggested a different interpretation of these results – that it is motion onset that captures attention, and not motion itself. However, they later supported Franconeri and Simons’ conclusions that in some situations, motion itself can capture attention (Abrams & Christ, 2006).

Surprisingly, few studies have examined how attention to motion develops in childhood. Are attentional mechanisms for moving stimuli fully functional or vulnerable in childhood, and which ages are critical in their development? Can children purposefully guide attention to objects that move, across time and space, and how efficient are they in doing so? This question is of utmost importance for understanding the developmental pathways involved in reaching the cognitive end-state of an adult, which provides a capability for independent and safe behaviour.

Visual Marking of Moving Objects

Watson and Humphreys (1998) showed that the preview benefit can be obtained when stimuli are in motion. As location information is changeable, ignoring moving items requires different strategies for the encoding and inhibition of old objects. One way to inhibit old moving items is by applying inhibition at the level of whole feature-maps (Treisman & Gelade, 1980), which requires a unique feature segregation (such as colour) between old and new items. Watson and Humphreys (1998) proposed that grouping and inhibiting old items by their features provides the cognitive system with an adaptive advantage of not having to track multiple moving objects individually, which is more complex, computationally expensive, and resource demanding. Watson and Humphreys (1998) concluded that the visual marking of moving items is feature based partly on the results of a repeat of the subset experiment from Watson and Humphreys (1997). This experiment was previously discussed in Chapter 1. In short, they found that if a small number of new stimuli sharing a feature (e.g., green colour) with the old items was added, the efficiency of the preview benefit with moving items was not affected. This was not the case if a greater number of new items was added – this created a large change in the feature map and reset inhibition. In contrast, if the items were stationary, small numbers of new items sharing features with old items slowed down performance (Watson & Humphreys, 1997). This suggested that old moving items could be inhibited on the basis of their features. Further evidence supporting a feature-based account came from Olivers et al. (1999), who showed that a feature difference between old and new moving stimuli is compulsory for a preview benefit to occur, when stimuli are in motion. Kunar et al. (2003b) showed that colour change, but not shape change, disrupted the preview benefit with moving stimuli, while the opposite was true for stationary items (see also Watson & Humphreys, 1997, 2002). Moreover, colour-carryover effects (Braithwaite et al., 2003, 2004), in which detection of a target sharing features with the inhibited distractors is slowed down, are much greater when stimuli were in motion in comparison to static (Andrews et al., 2011). It is worth noting that Watson (2001) showed that in some situations feature-based inhibition is not necessary. Specifically, if the spatial configuration between the moving items were held constant, old stimuli could still be excluded (Experiment 1). He proposed that this is because a constant spatial configuration allowed the items to be grouped into a single virtual moving object towards which inhibition could be applied. In contrast, the preview benefit was abolished if there was a non-fixed configuration of the rotating objects (Experiment 2). It seems that inhibiting moving items still requires more resources than inhibiting stationary items. Watson and Humphreys (1998) demonstrated that in young adults, despite there being a difference in slopes between the Preview and the FEB, overall RTs for preview and conjunction conditions did not differ (Experiment 3a). When more time was allowed for old objects to be encoded in preview by reducing the speed of the items, allowing for more practice, and making old and new items more discriminable in colour, a difference in overall RTs in Preview and FEB emerged (Experiment 3b). Watson and Humphreys (1998) argued that this was due to fewer resources needed to ignore old moving items in Experiment 3b in comparison to Experiment 3a. This finding also supported their claim that a commitment of resources is necessary for visual marking (Watson & Humphreys, 1997). Given that that preview search with moving items required practice, a greater difference between the old and new items, and slower speed, to produce a difference in baseline RTs between the preview and FEB, this suggested that moving objects might require more resources to be suppressed.

Age and the Development of Dynamic Attention

Developmental studies of visual marking have previously focused on investigating attentional selection of stationary objects (e.g., Mason et al., 2004, 2005). Nevertheless, the ageing literature suggests that visual marking of moving and stationary objects follow differential ageing trajectories (Watson & Maylor, 2002). Watson and Maylor (2002) tested older and younger adults with a preview search task with moving items (translational motion) and a preview search with rotating items (rotational motion). They showed that the preview benefit for objects in both translational motion, where objects move across points in space, and rotational motion, where the objects do not change their relative position but rotate around the screen center, is absent in older adults compared to young adults who demonstrated a preview benefit in both experiments. Yet, older adults showed a preserved preview benefit for stationary objects. These results suggest that time-based suppression of stationary distractors and time-based suppression of moving distractors have separate ageing trajectories.

Although no study so far has investigated the development of time-based selection for moving stimuli in childhood, recent research has shown that developmental changes exist in dynamic attention (Trick et al., 2005; Trick, Hollinsworth, & Brodeur, 2009). In a multiple-object tracking (MOT) task, participants are required to track a number of moving target objects, among a number of identical moving distractors (Pylyshyn & Storm, 1988). Trick et al. (2005, 2009) demonstrated that children have a reduced capacity to track multiple moving objects. Moreover, 6- to 7-year-old children were impaired in tracking even a single moving target when compared to the older age-groups who showed almost 100% accuracy (Trick et al., 2009). Trick et al. (2009) proposed that this result suggests that 6-7-year-old children's reduced tracking capacity may be due to difficulties in object-based inhibition of moving distractors, rather than difficulties in following multiple targets. Previously, Trick et al. (2005) have suggested that children's difficulty to ignore distractors (e.g., Hommel et al., 2004; Trick & Enns, 1998) may be more pronounced in dynamic displays, such as the MOT task, due to children having a less developed spatial resolution of attention – the minimum distance required between the target and distractors needed for efficient selection to occur (He, Cavanagh, & Intriligator, 1996). Thus, lower tracking capacity in the MOT task could be due to distractors having the opportunity to move closer to the target(s), and decreasing the attentional resolution children needed to select and track the target(s). These findings point to the possibility that a deficit in ignoring moving distractors in MOT tasks might extend to moving items visual search and/or preview search tasks. This, there is a need to understand how children deploy attention to objects in motion, and their ability to ignore moving distractors.

Whereas Chapter 4 examined the development of time-based visual selection with stationary stimuli, the present chapter will examine the developing ability to suppress moving distractors in time-based visual selection. Experiment 12 will examine the developmental changes in time-based attention with moving stimuli, and possible associations with individual differences in EF and STM. Experiment 13 will assess whether an extended duration of old distractors in the visual field can improve their encoding and filtering from future search.

Experiment 12: Time-Based Visual Selection of Moving Items

The main aim of Experiment 12 was to assess the development of time-based selection with moving items, and to investigate their relationship with measures of EF and STM. Based on evidence from the ageing literature, in which selective deficits emerged for visual marking of moving objects (Watson & Maylor, 2002), it is plausible that this ability has a later developmental onset. Past research has suggested that cognitive abilities that are first to decline in old age also develop slowly in childhood (Tamnes et al., 2013; Karama et al., 2014). Thus, younger children might show a poorer ability to suppress old moving items in comparison to older children and adults.

Method

Participants. Participants consisted of 24 *6-year-olds* (12 male, age 5-6, *M* = 5 years, 8 months, *SD* = 4.01 months), 24 *8-year-olds* (16 male, age 7-8, *M* = 7 years, 8 months, *SD* = 3.38 months)[2], 24 12-year-olds (12 male, age 11-12, M= 12 years, 4 months, SD = 4.36 months), and 24 adults (2 male, age 18-29, M= 19 years, 6 months, SD = 36.42 months). Children were recruited via an opt-out procedure granted with the Head Teacher’s agreement, from the three UK counties: West Midlands, Warwickshire, and Oxfordshire. Adult participants were recruited from the research participant pool at the University of Warwick, and did not participate in

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[2] One primary school declined to provide the children’s dates of birth. The mean age of 6-year-olds and 8-year-olds reported here is calculated based on the available information of 14 out of 24 6-year-olds, and 13 out of 24 8-year-olds.

any of the previous experiments. Adults signed informed consent forms, and children gave their assent to participate, and both were debriefed in an age-appropriate way. As rewards for participation, children received stickers, and adults received either course credit or small payment. All participants had normal or corrected-to-normal vision. Ethical approval was granted by the Psychology Research Ethics Board at the University of Warwick.

Search tasks. The methodology and equipment were essentially the same as that used in the experiments of Chapter 4 except that moving stimuli rather than stationary stimuli were presented. A custom computer program generated the displays and recorded responses on a Samsung 550P5 15-in. LCS (1366 × 768 pixels, 60 Hz) laptop. The target was a light blue [RGB values = 68, 164, 176] square and the distractors were pink [RGB values = 211, 103, 126] squares (8 mm × 8 mm) and light blue [RGB values = 68, 164, 176] circles (10 mm diameter), placed against the black monitor background. The stimuli were randomly distributed in an invisible 6 × 6 matrix with 28 mm center-to-center spacing, randomly jittered by ±5 mm. There was an equal number of pink and blue distractors to the right and left side of the screen, and the target always fell unambiguously into one of the two most leftward or rightward columns of the invisible matrix. In all conditions, stimuli moved downwards within a virtual window. Once they reached the bottom of the virtual window, they gradually disappeared bit by bit (1 pixel at every retrace of the screen) by sliding down behind the bottom of the window but then reappeared bit by bit in a continuous motion at the top of the window at the same horizontal location.. The gradual onset and offset of the moving items was necessary to ensure that rapid luminance changes would not interfere with the preview benefit (Watson & Humphreys, 1998). Continuous motion was created by moving stimuli one pixel downwards at every retrace of the screen (60 Hz), thus making the motion flicker-free and smooth. There were three experimental conditions, counterbalanced across participants: Half-element baseline (HEB), Full-element baseline (FEB), and a Preview search task. Each trial started with a presentation of a blank screen (500 ms), which was followed by a central white [RGB = 180,180,180] fixation dot (2 mm × 2 mm), before adding the stimuli. In the FEB and in the Preview condition, the displays consisted of 4, 8, or 16 items, and in the HEB the size was 2, 4, or 8 items. The FEB and preview consisted of blue and pink items, and the blue square target was always present. In the FEB, all the items were presented simultaneously, while the Preview condition consisted of a 2-stage distractor presentation: half of the pink items were presented for 1000 ms, after which the blue distractors and a blue target were added. In the preview condition, the participants' task was to ignore the preview items that were presented first, and indicate the location (left or right) of the target. The HEB was comprised of only the blue items from the FEB, and thus contained half the number of items compared with the FEB and preview displays. Participants pressed the left or right shoulder button on a gamepad device which was connected to the laptop, to indicate the location of the target. Visual feedback was given by presenting the word 'incorrect' at the center of the screen when errors were made.

Executive function tasks. As in the experiments described in Chapter 4, EFs (switching and inhibition) were assessed with the Shape-School task (Espy, 1997), in an extended version adapted for older children, adolescents, and adults (Ellefson et al., in preparation). To recap, the task was comprised of four conditions: (*Control, Inhibition, Switching, Both*), administered in a fixed order. All the conditions and stimuli were the same as in Chapter 4. Children completed a short practice example consisting of 6 figures for each condition. The dependent variables were RTs and number of errors, recorded by the researcher. They were computed as a final efficiency measure: Efficiency = [number of correct – number of errors]/total time

Working Memory Test-Battery for Children (WMTB-C). As in Chapter 4, two measures from the WMTB-C (Pickering & Gathercole, 2001) were administered: *digit recall*, measuring verbal STM, and *block recall*, measuring visuo-spatial STM. The tasks were the same as those in Chapter 4.

Design and procedure. Children were tested individually in a quiet room at their school, and adults were tested in a lab space at the University of Warwick. The search tasks were administered to children in one session, and the EF and STM tasks in another session, counterbalanced across participants. Adults completed all tasks in a single session, but counterbalanced as two separate parts. The session containing the search tasks consisted of a counterbalanced ABCABC design of the three search conditions (HEB, Preview, and FEB). There were two blocks of 36 experimental trials per condition, with a self-paced break between the blocks, resulting in a total of 6 blocks and 216 experimental trials. For each condition, there were 10 preceding practice trials. In the EF and STM session, the researcher recorded RTs and errors on a separate worksheet.

Results

Search tasks. Similarly to the previous chapters means with cutoffs were used (Ratcliff, 1993). Reaction times that were less than 200 ms or greater than 10s were removed as outliers. This resulted in 3.39%, 0.73%, 0.28%, and 0.12% of the data being removed, for 6-year-olds, 8-year-olds, 12-year-olds, and adults, respectively.

***Reaction times*:** Mean RTs as a function of display size, age, and condition are shown in Figure 26, and descriptive statistics are presented in Table 30. The existence of the preview benefit was assessed by comparing the search slopes in the preview condition with those of obtained from the two baselines, FEB and HEB (Watson & Humphreys, 1997, 1998). In addition, given the apparent difference between performance at large and small display sizes, similarly to Chapter 3, search performance was assessed at the smaller (4 to 8) and larger (8 to 16) display sizes individually.

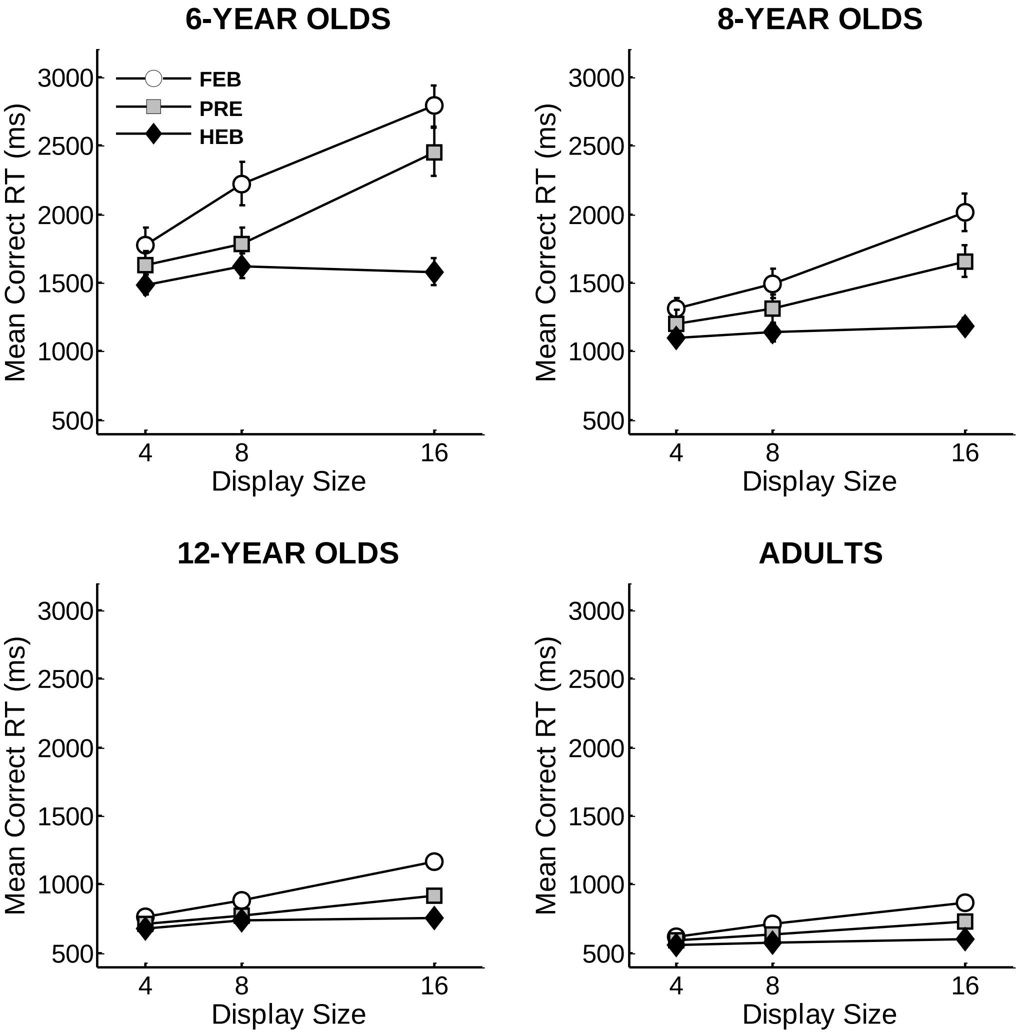

Figure 26. Mean correct reaction times (RTs) as a function of condition, display size and age for Experiment 12. Error bars indicate ±1SE.

Table 30. *Search slope statistics for Experiment 12.*

Group and descriptive characteristic	HEB	FEB	Preview
6-year-olds			
Slope (ms/item)	6.14	82.49	70.69
Intercept	1506.20	1493.3	1297.6
R^2	0.28	0.99	0.98
8-year-olds			
Slope (ms/item)	6.93	59.25	38.64
Intercept	1076.7	1052.9	1030.1
R^2	0.98	0.99	0.99
12-year-olds			
Slope (ms/item)	5.79	34.42	18.14
Intercept	670.30	617.49	636.75
R^2	0.83	0.99	0.99
Adults			
Slope (ms/item)	3.82	20.99	11.70
Intercept	542.4	536.91	544.71
R^2	0.99	0.99	0.99

A 3(Condition: FEB, HEB, Preview) × 3 (4, 8, or 16 items) repeated measures ANOVA with age as the between-subject variable indicated significant main effect of condition, $F(2,184) = 107.97$, MSE = 98082.37, $p < .001$, $\eta_p^2 = .54$, display size, $F(2,184) = 170.39$, MSE = 56481.90, $p < .001$, $\eta_p^2 = .65$, and a between-subjects effect of age, $F(3,92) = 73.09$, MSE = 986420.22, $p < .001$, $\eta_p^2 = .70$. Pairwise comparisons with a Bonferroni adjustment suggested that performance differed across all age groups ($p < .001$), except for 12-year olds and adults. All interactions also proved significant, Condition × Display Size, $F(4,368) = 58.80$, MSE = 31004.34, $p < .001$, $\eta_p^2 = .39$, Condition × Age, $F(6,184) = 11.68$, MSE = 98082.37, $p < .001$, $\eta_p^2 = .28$, Age × Display Size, $F(6,184) = 15.92$, MSE = 56481.90, $p < .001$, $\eta_p^2 = .34$, Age × Condition × Display Size $F(12,368) = 7.66$, MSE = 31004.34, $p < .001$, $\eta_p^2 = .20$.

Similarly to the approach taken in Chapter 4 and by a previous age-based study of visual marking (Watson & Maylor, 2002), the preview benefit was assessed by comparing performance in the preview condition to that in HEB and FEB for each age group separately. Two separate 2 (Preview vs. HEB or Preview vs. FEB) × 3 (4, 8, or 16 items) within-subject ANOVAs were conducted for each age group. The results of these analyses are presented in Table 31. Although all age groups demonstrated shorter overall RTs in preview search than in FEB, the Condition × Display Size interaction proved significant in 8-year-olds, 12-year-olds, and adults, indicating that a preview benefit was obtained in these age groups. In contrast, there was little evidence of a preview benefit in 6-year-olds. There was a marginally significant Condition × Display Size interaction between FEB and preview search, $F(2,46) = 2.93$, MSE = 91314.96, $p = .063$, and as suggested from Figure 27, there may be a deviation from linearity at small display sizes in comparison to the large. Thus, for 6-year-olds, a further analysis compared preview slopes for small display sizes (4-8) and large (8-16) to the FEB.

Table 31. *F-values (top row), MSE values (middle row) and* η_p^2 *values (bottom row) for the analyses from Experiment 12. F-value significance levels are donated as follows*: *** = *p* < .001, ** = *p* < .005, * = *p* < .05

	Preview vs. HEB			Preview vs. FEB		
Age	Condition	Display Size	Condition × Display Size	Condition	Display Size	Condition × Display Size
6-year olds	20.03^{***} 278764.48 .47	25.87^{***} 114590.74 .53	33.42^{***} 61856.39 .59	19.22^{***} 175256.63 .46	60.33^{***} 256567.65 .72	2.93 91314.96 .11
8-year olds	16.08^{**} 139272.33 .41	55.79^{**} 16749.46 .71	19.59^{**} 23564.33 .46	23.89^{***} 69765.98 .51	57.02^{***} 122343.80 .71	4.40^{*} 43306.26 .16
12-year olds	28.87^{***} 7260.08 .58	49.51^{***} 4588.32 .68	12.95^{***} 4564.24 .36	122.98^{***} 5626.98 .84	133.12^{***} 13824.17 .85	43.01^{***} 4143.17 .65
Adults	80.66^{***} 2570.98 .78	40.95^{***} 2636.10 .64	20.57^{***} 1355.58 .47	49.16^{***} 4555.25 .68	123.12^{***} 3894.84 .84	22.39^{***} 2173.89 .49

This analysis showed that for small display sizes (4-8 items), there was a significant Condition × Display Size interaction, confirming a preview benefit, $F(1,23) = 8.42$, MSE = 61674.91, $p < .01$. A significant main effect of condition indicated that RTs were faster overall in the preview condition, $F(1,23) = 18.08$, MSE = 112620.73, $p < .001$, and a significant main effect of display size indicated that RTs were fastest at a display size of 4 items, $F(1,23) = 13.83$, MSE = 156593.43, $p < .001$. For large display sizes (8-16 items), the Condition × Display Size interaction did not reach significance, $F < 1$, providing no evidence for the existence of a preview benefit. The main effect of condition, $F(1,23) = 24.42$, MSE = 147022.66, $p < .001$, was significant, as well as display size, $F(1,23) = 133.70$, MSE

= 80494.05, $p < .001$. These results suggest that for 6-year-olds, with moving stimuli, a preview benefit occurs at small display sizes, but not at large display sizes.

Inspection of the preview indices revealed that 9 out of 24 6-year-olds had a PE of 0, suggesting that they did not show a preview benefit for moving stimuli. There were also five 8-year olds, one 12-year old, and four adults who did not show the preview benefit at all. It seems to be that, similarly to the results of Chapter 4, greater individual differences in the ability to ignore old moving stimuli are present in the youngest age group. However, it may be that the ability to inhibit moving stimuli elicits greater individual differences in the older age groups as well.

Error rates: Overall errors were low and decreased across age-groups: 7.81%, 4.24%, 1.74%, 1.00% for 6-year-olds, 8-year-olds, 12-year-olds, and adults, respectively. Error rates are presented in Table 32.

A 3(Condition: FEB, HEB, Preview) × 3 (4, 8, or 16 items) within-subjects ANOVA with age as the between-subject variable revealed a significant main effect of condition, $F(2,184) = 4.19$, MSE = 21.65, $p < .05$, $\eta_p^2 = .04$, and age, $F(3,92) = 13.78$, MSE = 148.03, $p < .001$, $\eta_p^2 = .31$. Bonferroni-corrected pairwise comparisons indicated that there were age differences in the error rate between 6-year-olds and 8-year-olds ($p < .05$) and 6-year-olds and 12-year olds and adults (both *p*s < .001), and 8-year-olds and adults ($p < .05$). There was no main effect of display size, $F(6,184) = 1.58$, MSE = 15.90, $p =.208$, $\eta_p^2 = .02$, and no Condition × Age interaction, $F(6,184) = 1.23$, MSE = 21.65, $p = .294$, $\eta_p^2 = .04$, Condition × Display Size, $F(4,368) = 1.65$, MSE = 11.08, $p = .16$, $\eta_p^2 = .02$, Age × Display Size, $F(6,184) = 1.69$, MSE = 15.90, $p =.125$, $\eta_p^2 = .05$. The Age × Condition × Display Size interaction also proved insignificant, $F < 1$.

A 3 (Condition: HEB, FEB, and Preview) × 3 (Display size: 4, 8, or 16 items) within-subject ANOVA was conducted for each age group. There was a significant effect of condition for 8-year-olds and 12-year-olds, revealing more errors in the FEB than in the Preview and HEB, $F(2,46) = 9.13$, MSE =14.11, $p < .001$, $F(2,46) = 3.59$, MSE = 11.46, $p < .05$, respectively. There were no significant Condition × Display Size interactions, indicating no speed-accuracy trade-offs, all remaining *F*s < 2.70, *ps* >.07.

Table 32. *Mean percentage error rates for Experiment 12*

	Display size		
Group and Condition	4	8	16
6-year-olds			
HEB	6.94	8.68	7.81
FEB	7.29	7.47	8.51
Preview	5.38	9.72	8.51
8-year-olds			
HEB	4.17	2.43	3.65
FEB	5.90	5.21	6.25
Preview	3.65	3.82	3.13
12-year-olds			
HEB	1.22	1.04	1.39
FEB	2.08	2.60	2.95
Preview	1.74	1.22	1.04
Adults			
HEB	0.69	1.39	0.17
FEB	0.69	1.22	1.91
Preview	0.69	1.04	1.22

EF and STM measures. Four 6-year-olds did not complete a full set of EF measures and their data was removed from the analysis in this section. Table 33 shows means and SDs of the EF and STM measures across the age groups. A MANOVA demonstrated a significant effect of age on all EF and STM measures, *F* = (18, 235) = 12.26, *p* < .001; Wilk's Λ = .15. This included control efficiency (*F*(3,88)= 84.69; *p* < .001); inhibition efficiency (*F*(3,88)= 66.06; *p* < .001), switch efficiency (*F*(3,88)= 55.63; *p* < .001), both efficiency (*F*(3,88)= 51.54; *p* < .001), digit recall (*F*(3,88)= 17.79; *p* < .001), and block recall, (*F*(3,88)= 27.69; *p* < .001).

Table 33. *Means and SDs (reported in parenthesis) for EF and STM tasks for 6-year-olds, 8-year-olds, 12-year-olds, and adults for Experiment 12.*

	Control	Inhibition	Switching	Both	Digit recall	Block recall
6-year-olds	.94 (.25)	.96 (.21)	.37 (.14)	.41 (.16)	25.75 (3.47)	19.92 (3.16)
8-year-olds	1.27 (.31)	1.19 (.31)	.54 (.16)	.56 (.19)	27.04 (4.95)	21.63 (2.63)
12-year-olds	1.81 (.31)	1.96 (.28)	.78 (.15)	.79 (.21)	32.08 (5.89)	26.79 (4.85)
Adults	2.43 (.43)	2.47 (.66)	.97 (.21)	1.12 (.25)	36.42 (6.52)	30.58 (5.36)

Similarly to the approach taken in Chapter 4, I examined whether individual differences in EF and STM underpin the preview efficiency, measured via the PE index (Blagrove & Watson, 2010). Given that 6-year-olds' search revealed a preview benefit at small but not large display sizes, separate PE indexes were computed for large and small display sizes for each age group. Preliminary rank order, bivariate, and partial correlations between measures of chronological age, PEs, EF efficiency, and STM measures (raw scores) are presented in Table 34. Of most interest, the two PE measures for small and large display sizes had different correlations with the EF measures. The PE index for small display sizes had no significant relationship with any EF or STM measure, while the PE index for large display sizes was correlated to the efficiency in the *Both* condition (switching and inhibition combined), $r(92) = .215$, $p < .05$. However, when age and baseline naming speed were taken into account, this relationship disappeared. To determine whether the reason for this was due to differing relationships amongst age groups, correlations between PE, EF, and STM measures were calculated while controlling for baseline naming speed for children and adults separately. In Chapter 4, a similar analysis was conducted by combining the data of the children's group together (ages 6-12) to obtain more power, as the adults' sample seemed to be driving the effects. In the same way, partial correlations (baseline naming speed controlled) for EF and STM, and PE measures, for the combined 6-12-year-olds' data, and the adult data are presented in Table 35. Interestingly, the PE for small display sizes was not correlated with the PE for large display sizes in any age group. Correlations for PE and EF were only observed in the adults' sample, between the PE for large display sizes and the *Both* condition (switching and inhibition combined), $r(21) = .446$, $p < .05$. A significant relationship between these measures is consistent with the findings from Chapter 4, in which the *Both* condition was correlated to the PE for ignoring stationary items in adults.

Table 34. *Relationships between chronological age, EF measures (Control, Inhibition, Switching, Both), STM measures (digit recall and block recall), and PE in Experiment 12.*

Values above the diagonal indicate bivariate correlations (Spearman's for age and Pearson's for the remaining variables) across measures, while values below the diagonal indicate partial correlations controlling for chronological age and baseline naming speed (the 'Control' condition in Shape School extended)

	Control	**Inhibition**	**Switching**	**Both**	**Digit recall**	**Block recall**	**PE small DS**	**PE large DS**
Age[a]	.877***	. 836***	.834***	.801***	.628***	.700***	.049	.117
Control		.877 ***	.826***	.746***	.569***	.743***	.063	.099
Inhibition			.804***	.835***	.599***	.706***	.078	.162
Switching		.220*		.803*	.433*	.664***	-.075	.084
Both		.516*	.411*		.506***	.667***	.007	.215*
Digit recall		.192	.-193	.035		.506***	.157	.057
Block recall		.142	.095	.221	.122		.049	.024
PE small DS		.052	-.236	-.061	.157	.004		-.061
PE large DS		.138	-.028	.196	-.024	-.087	-.067	

[a] Spearman's rank-order correlations are used between age and other measures

*	$p < .05$
**	$p < .005$
***	$p < .001$

Table 35. *Partial correlation coefficients (baseline naming speed controlled) for PE for large display sizes (8-16 items) and measures for EF, STM, and PE for small display sizes (4-8 items)*

	Children	**Adults**
Inhibition	.118	.246
Switching	-.003	.046
Inhibition & Switching	.142	.446*
Digit recall	-.046	.129
Block recall	.035	-.326
PE small DS	-.091	.026

Note. Childrens' *N* = 68
Adults' *N*= 24

* $p < .05$
** $p < .005$
*** $p < .001$

Discussion

In Experiment 12, I examined whether children can facilitate search for novel moving stimuli in time-based visual selection. The results revealed that the exclusion of old moving stimuli was present in 8-year-olds, 12-year-olds, and adults, but was insufficiently developed in 6-year-olds. This suggests that time-based selection has a longer developmental trajectory for moving objects than for stationary objects (see Chapter 4).

A subsequent analysis of the performance of 6-year-olds showed that facilitation occurred only at small display sizes, but not at large. This suggested that the youngest participants were able to ignore a few moving items, but were not able to do so when a larger number of moving items were present. The ability to ignore many moving items at large display sizes was correlated with individual differences in EF (switching and inhibition combined) in adults, but not children. This correlation is also consistent with the findings described in Chapter 4, in which switching and inhibition were found to be correlated with PE for stationary items in the adult sample only.

What cognitive mechanisms might underpin the suppression of small moving displays in young children? Three possibilities can be suggested to account for this result. Previous findings with adults have shown that time-based selection of a small number of items can supported by VWM (Al-Aidroos et al., 2012). Al-Aidroos et al. (2012) found that individual differences in the magnitude of the preview benefit are correlated with individual differences in the capacity of VWM. Given that the number of old items to be held in VWM at the smallest display sizes was 2, this corresponds approximately to children’s VWM capacity at the age of 6 years (Riggs, McTaggart, Simpson, & Freeman, 2006). A second possibility is that automatic capture by abrupt onsets (Donk & Theeuwes, 2001, 2003) underlies the prioritization of a small number of items in 6-year-olds. One of the difficulties of the onset account in explaining all aspects of the preview benefit is that its capacity it limited to prioritizing a total of approximately 4 new items (Yantis & Johnson, 1990; Yantis & Jones, 1991), since the number of items that can be prioritised in preview can be as large as 15 items, with no upper boundary yet determined (Theeuwes et al., 1998). It is nevertheless plausible that a preview benefit at small displays is achieved via this mechanism, which might explain the lack of correlation between small and large PEs in adults, and the lack of correlation between the EFs and the PE for small display sizes. A third possibility is that inhibitory processes might also play a role even in the suppression of a relatively small number of items. However, it is possible that the amount of time to inhibit (moving) items increases as a function of the number of items present, especially when attentional resources are limited as might be the case with younger children. It follows that younger children might require an extended preview duration in order to successfully encode and inhibit a larger number of moving objects (cf. Watson & Humphreys, 1998). In Experiment 13, this possibility will be tested.

Experiment 13: Time-Course of Time-Based Visual Selection with Moving Stimuli

The results of Experiment 12 showed that 6-year-olds were only able to prioritise a relatively small number of moving stimuli in time-based selection conditions. Given that moving stimuli require more cognitive resources to suppress (Watson & Humphreys, 1998; Watson & Maylor, 2002), it is possible that the 1000 ms temporal interval between the two sets of distractors was not sufficient for younger children to efficiently suppress the moving set of distractors. The aim of Experiment 13 was to assess whether extending the duration of the old stimuli (i.e., the preview duration) would facilitate preview search for moving displays in 6-year-olds. Given that 6-year-olds were not able to efficiently prioritise new moving objects in Experiment 12, we did not include a preview condition shorter than 1000 ms. Given that the main aim of this experiment was to test for the existence of a preview benefit relative to a FEB condition, a HEB was not included. This also provided the benefit of reducing the total number of trials required and thus reduced the likelihood of fatigue developing which might have further compromised the preview benefit. Therefore, the current set of conditions consisted of a FEB, and two preview conditions, one with a preview duration of 1000 ms and one with a preview duration of 2000 ms.

Method

Participants. Participants consisted of 24 *6-year-olds* (13 male, age 5-6, *M* = 5 years, 9 months, *SD* = 3.68 months), 24 *8-year-olds* (11 male; age 5-6, *M* = 7 years, 8 months, *SD* = 3.59 months), 24 *12-year-olds* (10 male; age *M* = 12 years, 3 months, *SD* = 3.4 months,), and 24 *adults* (10 male; 18 to 25 years, *M* = 20 years, 8 months, *SD* = 31.78 months). Children were recruited via an opt-out procedure granted with the Head Teacher's agreement. Adult participants were newly recruited for the purpose of this study and did not participate in any of the previous preview search experiments. Ethical approval was secured from the University of Warwick's Research Ethics Board. Children gave their assent and adult participants signed informed consent forms. One 6-year- old did not complete the full set of baselines, and an additional child was recruited instead. All participants were debriefed in an age-appropriate way.

Apparatus, stimuli, and procedure. The apparatus and stimuli were the same as in Experiment 12, except that the HEB condition was replaced by a preview condition with a duration of 2000 ms. All three conditions were counterbalanced across participants. The design and procedure were similar to those of Experiment 12, except that no individual difference measures were taken, thus all participants were tested in a single session.

Results

All outlier RTs faster than 200 ms or slower than 10s were omitted from the analysis. This resulted in 3.78%, 1.19%, 0.28%, and 0% of data being removed for 6-year-olds, 8-year- olds, 12-year-olds, and adults, respectively. In addition, one 12-year-old completed one rather than two blocks of trials for each of the search tasks, and so their results were based on average RTs and error rates from a single block for each condition. The rationale for the cutoffs and RT means was the same as in the previous chapters. Figure 27 shows the mean correct RTs as a function of display size, condition, and age. Search slope statistics are presented in Table 36.

As revealed by a 3(Condition: FEB, PRE_{1000}, PRE_{2000}) × 3 (4, 8, or 16 items) repeated measures ANOVA with age as the between-subject variable, there was a significant main effect of condition, $F(2,184) = 40.62$, MSE = 45876.53, $p < .001$, $\eta_p^2 = .31$, display size, $F(2,184) = 251.24$, MSE = 56213.75, $p < .001$, $\eta_p^2 = .73$, and a between-subjects effect of age, $F(3,92) = 43.48$, MSE = 2134187.15, $p < .001$, $\eta_p^2 = .59$. Pairwise comparisons with a Bonferroni correction again showed that all age groups differed in their performance ($p < .001$), with the exception of 12-year-olds and adults. There was a significant interaction of Condition × Display Size, $F(4,368) = 4.58$, MSE = 26219.09, $p < .005$, $\eta_p^2 = .05$ and Age × Display Size, $F(6,184) = 25.01$, MSE = 56213.75, $p < .001$, $\eta_p^2 = .45$. The Condition × Age interaction proved insignificant, $F < 1$, as did the Age × Condition × Display Size $F(12,368) = 1.53$, MSE = 26219.09, $p = .110$, $\eta_p^2 = .05$.

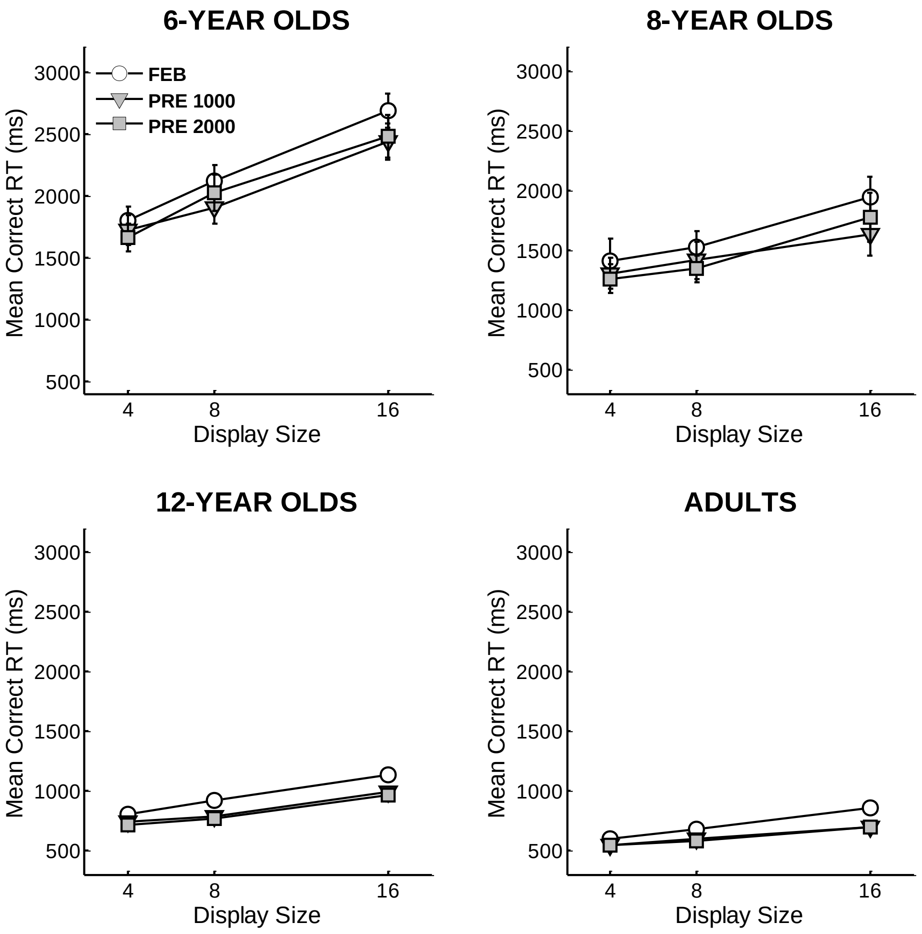

Figure 27. Mean correct reaction times (RTs) as a function of condition, display size and age for Experiment 13. Error bars indicate ±1SE.

Influence of preview duration. A 2(Preview Duration,$_{1000,2000}$) × 3 (Display Size: 4,8,16 items) within-subjects ANOVA was used to analyze the RTs for each age group, and the outcomes are presented in Table 37. RTs increased with display size for all age groups, but there was no significant main effect of condition for any age group. There was a Condition × Display Size interaction for 8-year-olds, indicating steeper slopes for PRE$_{2000}$. No interaction reached significance for any of the other age groups, suggesting that search performance in the two preview conditions did not differ.

Table 36. *Search slope statistics for Experiment 13*

Group and descriptive characteristic	FEB	PRE 1000 ms	PRE 2000 ms
6-year-olds			
Slope (ms/item)	73.83	60.22	66.59
Intercept	1513.1	1458.8	1434
R^2	0.99	0.99	0.99
8-year-olds			
Slope (ms/item)	45.72	27.37	44.69
Intercept	1199.1	1196.9	1044.2
R^2	0.98	1	0.97
12-year-olds			
Slope (ms/item)	27.95	21.45	20.96
Intercept	692.11	639.6	619.28
R^2	0.99	0.97	0.98
Adults			
Slope(ms/item)	21.39	12.16	12.92
Intercept	509.57	499.32	486.43
R^2	0.99	0.99	0.99

Table 37. *F-values (top row), MSE values (middle row) and ηp2 values (bottom row) for the analyses from Experiment 13. F-value significance levels are donated as follows:* $*** = p < .001$, $** = p < .005$, $* = p < .001$

Age group	PRE_{1000} vs PRE_{2000}			$\text{PRE}_{1000,2000}$ vs FEB		
	Condition	Display Size	Condition × Display Size	Condition	Display Size	Condition × Display Size
6-year-olds	.35 124200.19 .02	69.31^{***} 130598.17 .75	1.46 94073.57 .06	$5.77^{*(*)}$ 115506.12 .20	91.53^{***} 186756.94 .79	1.42 57535.15 .06
8-year–olds	.12 24556.84 .01	27.04^{***} 151322.79 .54	4.70^{*} 52263.95 .17	13.15^{***} 69104.73 .36	58.16^{***} 119412.19 .72	2.76^{*} 87208.75 .11
12-year-olds	1.65 13005.46 .07	54.19^{***} 24279.33 .70	.05 14482.28 .00	28.93^{***} 13581.38 .56	87.93^{***} 27372.78 .79	2.87^{*} 12329.32 .11
Adults	.36 3427.23 .02	104.65^{***} 3981.34 .82	.29 2249.19 .01	54.14^{***} 4388.67 .70	141.60^{***} 7782.97 .86	9.59^{***} 3491.02 .29

Existence of the preview benefit. In order to determine whether a preview benefit occurred, a 3 (Condition: FEB, $\text{PRE}_{1000, 2000}$) × 3 (Display size: 4,8,16 items) within-subjects ANOVA was conducted for the individual age-groups. The outcomes of this analysis are shown in Table 37. RTs increased with display size and overall RTs were greater in FEB than preview search. For 6-year-olds, the Condition × Display Size interaction did not reach significance, indicating no overall statistical difference in search slopes between both preview conditions and the FEB. An interaction emerged in 8-year-olds, and the older age groups. However, a difference between the two preview conditions in 8-year-olds suggested that only search in the PRE_{1000} was more efficient than that in the FEB, while a lack of difference between the PRE_{2000} and FEB conditions suggested a lack of preview benefit at longer durations. Indeed, a 2 (Condition: FEB, $\text{PRE}_{1000)}$ × 3 (Display size: 4,8,16) within-subjects ANOVA, showed a main effect of condition, *F*(1,23) = 14.37, MSE = 75366.75, *p* < .005, display size, *F*(2,46) = 79.89, MSE = 30153.37, *p* < .001, and a Condition × Display Size interaction, *F*(2,46) = 4.27, MSE = 39224.00, *p* < .05. This indicated 8-year-olds could prioritise new items, when the duration of the old items was 1000ms. In contrast, the 2 (Condition: FEB, PRE_{2000}) × 3 (Display size: 4,8,16) within-subjects ANOVA showed main effects of condition *F*(1,23) = 17.16, MSE = 56799.79, *p* < .001, and display size, *F*(2,46) = 55.27, MSE = 67903.47, *p* < .001, but no Condition × Display Size interaction, *F* < 1, suggesting no preview benefit when the duration of old items was extended to 2000 ms. This was not the case for 12-year-olds and adults, who showed a preview benefit at both durations.

To confirm the finding from Experiment 12 that 6-year-olds were able to prioritise only a few moving items, and because here, similarly to Experiment 12, Figure 27 suggested a lack of linearity, a similar analysis for small and large display sizes was conducted for 6-year-olds only. For small display sizes (4-8 items), there were significant main effects of condition, *F*(1,23) = 6.24, MSE = 80664.34, *p* < .05, and display size, *F*(1,23) = 46.54, MSE = 32841, *p* < .001. Search RTs were faster overall at PRE_{1000} than FEB, and increased at large display sizes. More importantly, there was a significant Condition × Display Size interaction, confirming a preview benefit at small display sizes, *F*(1,23) = 4.41, MSE = 28267, *p* < .05. For large display sizes (8-16 items), there were also significant main effects of condition, *F*(1,23) = 17.84, MSE = 74619.24, *p* < .001 and display size, *F*(1,23) = 41.19, MSE = 175490.73, *p* < .001. However, crucially, the Condition × Display Size interaction did not approach significance, *F* < 1, indicating that on the basis of search slopes, there was no preview benefit at larger display sizes. This replicates the results of

Experiment 12 that a preview benefit in 6-year-olds is obtained at small display sizes only.

Error rates. Overall errors were low, and decreased as a function of age. There were 8.08%, 3.34%, 1.17%, and 3.05% of errors in the data for 6-year-olds, 8-year-olds, 12-year-olds, and adults, respectively.

A 3(Condition: FEB, PRE_{1000}, PRE_{2000}) × 3 (4, 8, or 16 items) within-subjects ANOVA with age as the between-subject variable revealed a significant main effect of condition, $F(2,184) = 3.82$, MSE = 27.87, $p < .05$, $\eta_p^2 = .04$, and a Condition × Age interaction, $F(6,184) = 4.72$, MSE = 27.87, $p < .001$, $\eta_p^2 = .13$. There was no effect of display size, $F(2,184) = 2.52$, MSE = 13.55, $p = .083$, $\eta_p^2 = .03$, Condition × Display Size, $F(4,368) = 1.65$, MSE = 12.27, $p = .16$, $\eta_p^2 = .02$, nor age, $F(3,92) = 2.59$, MSE = 326.03, $p = .057$, $\eta_p^2 = .08$. The Age × Display Size, and Age × Condition × Display Size interactions did not prove significant, *Fs* < 1.

Mean percentage error rates as a function of condition and display size for each age group are presented in Table 38. The results were analysed with a 3(Condition: FEB, $PRE_{1000,}$ PRE_{1000}) ×3 (Display size: 4,8, or 16 items) within-subject ANOVA for each age group. More errors were made by 6-year-olds at large display sizes, $F(2,46) = 3.40$, MSE = 26.96, $p < .05$. However, none of the other main effects or their interaction approached significance, all *F*s < 1.9, *p*s > .11.

Table 38. *Mean percentage error rates for Experiment 13*

	Display size		
Group and Condition	4	8	16
6-year-olds			
FEB	8.33	7.99	9.90
PRE 1000 ms	6.94	5.38	7.99
PRE 2000 ms	7.47	8.51	10.24
8-year-olds			
FEB	2.95	4.34	3.65
PRE 1000 ms	3.47	1.91	3.47
PRE 2000 ms	3.41	3.21	2.95
12-year-olds			
FEB	1.74	1.74	2.60
PRE 1000 ms	1.39	0.87	1.74
PRE 2000 ms	1.91	1.04	2.26
Adults			
FEB	3.30	3.13	3.13
PRE 1000 ms	2.78	2.43	2.78
PRE 2000 ms	3.26	3.26	3.62

Discussion

Experiment 13 fully replicated the results of Experiment 12, showing that children of 8 years and older can ignore moving items at 1000 ms duration, whereas 6-year-olds can prioritise only a small number of moving items. However, a surprising finding of Experiment 13 is that contrary to expectations, extending the duration of old items in the visual field hindered, rather than improved, the preview benefit in young children. This was the case for both 6-year-olds, who did not benefit from an extended duration, but also for 8-year-olds, in which an extended duration completely abolished the preview benefit that was nonetheless present when the preview duration was 1000 ms. It seems that children have difficulties in maintaining a recently matured feature-based inhibitory mechanism, and that the maturation of the underlying mechanism continues well after its first developmental onset. On the contrary, 12-year-olds and young adults obtained a strong preview benefit at both durations.

The results of Experiment 13 confirm the findings from Experiment 12, that 6-year-old children were able to ignore only a few moving items. However, this did not occur at durations of 2000 ms in either 6-year-olds or 8-year-olds, which is inconsistent with the prediction that children are recruiting a different, smaller capacity mechanism such as onset capture or VWM. Previously, Humphreys et al. (2002) have proposed that visual marking consists of two components: initializing the attentional set (i.e., establishing the inhibitory goal state and consolidating the representation of the preview), and maintaining a representation of the old items. The findings suggests that within a preview benefit, these components mature at different rates, and that maintaining the benefit by visual resources has a later developmental onset than initializing and consolidating it.

General Discussion

The primary aim of the work presented in this chapter was to examine the developmental trajectories of attentional mechanisms for suppressing irrelevant old moving distractors. Previous studies have seldom provided insights into the development of attention to moving stimuli, or described the mechanisms that may drive age-related changes in this domain, such as a smaller MOT capacity (Trick et al., 2005, 2009).

Experiment 12 compared 6- to 12-year-olds' and adults' performance in a preview search task which required inhibition of old, irrelevant moving distractors, to enhance the selection of new, goal-relevant moving stimuli. In addition, the different age groups' preview efficiency was examined with respect to individual differences in EF and STM. The experiment yielded two novel findings: (a) 6-year-olds were able to inhibit only a few old moving items, but failed to inhibit a larger number of distractors. However, the ability to ignore a larger number of moving distractors does seem to be in place from the age of 8 years onwards, and (b) Visual marking of large moving displays is associated with individual differences in EF (switching and inhibition combined) only in adults.

Experiment 13 replicated the findings from Experiment 12, confirming that with preview durations of 1000 ms, 6-year-olds could ignore a few moving items only, whilst older age groups were able to ignore a larger number of moving distractors. To address the question of whether ignoring a few moving distractors in youngest children might still be a result of visual marking, the preview duration was extended to 2000 ms in Experiment 13, to allow more time for encoding and suppression. First, the findings showed that exposing the distractors for a longer time did not aid search facilitation in 6-year-olds. Second, the preview benefit was completely abolished in 8-year-olds. This suggests that the apparently recently matured inhibitory mechanism in 8-year-olds is not fully developed, and inhibition cannot be sustained over extended durations. In addition, the elimination of the preview benefit in 8-year-olds and a similar numerical trend in 6-year-olds for 2000 ms durations, suggests that the preview benefit is a result of differential developmental change occurring in the two preview components: initialization and consolidation of old items via central resources, and maintenance of a representation of old items via visual resources (Humphreys et al., 2002). The ability to consolidate a feature-based representation of old items might be due to an increase in the capacity of central resources between 6 and 8 years, while the ability to maintain visual representations for longer periods develops between the ages of 8 and 12 years. Finally, 12-year-olds and adults exhibited a preview benefit at both longer and shorter durations (2000 ms and 1000 ms, respectively).

Mechanisms of the Preview Benefit for Small and Large Display Sizes

One aspect of the current findings relates to the lack of correlation between individual differences for small and large display sizes, as well as a correlation for performance between large display sizes and EF measures for adults only. This is potentially suggestive of a different mechanism being employed for dealing with small display sizes, such as onset capture (Donk & Theeuwes, 2001, 2003) or VWM (Al-Aidroos et al., 2012), as both have similar capacities to the number of items in the small display sizes in the present study. Nevertheless, the elimination of the preview benefit at small display sizes in 6-8 year olds when the preview duration was extended (Experiment 13), goes against the VWM account (Al-Aidroos et al., 2012), since longer encoding time should not reduce the capacity of VWM (e.g., Luck & Vogel, 1997). With regards to onset capture, however, there is some evidence that attentional focus at a certain spatial location (Yantis & Jonides, 1990; but see Folk, Leber, & Egeth, 2002), or attentional engagement (Folk, Ester, & Troemel, 2009) can prevent attentional capture. In the context of the present study, a longer duration of old items may have resulted in increased focus or engagement onto them, thus abolishing the effect for small display sizes. Establishing the exact mechanism(s) that might be mediating preview effects at small display sizes, and determining whether it differs across age groups, remains a question for future research.

There appears to be a clear developmental trajectory in the increasing ability to reduce interference from old moving distractors, and its association with individual differences in EFs. This demonstrates that visual marking is the result of a maturing top-down inhibitory mechanism, at least when it comes to filtering a large number of moving distractors. The differences in the development of inhibition of stationary and moving stimuli (Chapters 4 and 5), further support the proposed differential inhibitory systems underlying them, location-based inhibition for stationary stimuli (Watson & Humphreys, 1997), and feature-based inhibition for motion stimuli (Watson & Humphreys, 1998). Clearly, there exists a dissociation in the developmental trajectory for the temporal suppression of location-based stationary distractors and the temporal suppression of feature-based motion distractors.

Age and Visual Marking

Developmental frameworks have proven to be powerful tools in understanding the mechanistic composition of different cognitive functions in adults (Astle & Scerif, 2009), and in helping to resolve theoretical debates regarding possible processes that can account for different effects. For example, although visual marking for stationary and moving stimuli seems to operate in a similar fashion in adults, examining time-based visual selection across the life-span has revealed that attentional inhibition for moving and stationary stimuli follow an asynchronous trajectory, both in the case of cognitive development (Chapters 4 and 5), as well as in ageing (Watson & Maylor, 2002). Taken together, these findings are also supportive of an inverted U-relationship between development and ageing, which suggest the last brain functions to develop in childhood are the most vulnerable to atrophy in old age (Tamnes et al., 2013; Karama et al., 2014).

Limitations

The limitations of the experiments in Chapter 5 are similar to those in Chapter 4. A number of factors that were discussed in Chapter 4 may have contributed to differences between children and adults in their performance in Experiments 12 and 13. These factors are most notably developing motor abilities, experience with video-gaming, and engagement with the task. For instance, experience with video-gaming enhances the capacity of multiple-object tracking (Trick et al., 2005). It is also possible that a longer duration of the preview items in Experiment 13 and consequent longer trial duration, resulted in younger children being less engaged or with the task or becoming fatigued. Thus, a reduced performance in 6- and 8-year olds on the preview task for a larger number of moving items may not solely be a result of developing cognitive abilities, but of developing motivational, learning, and motor abilities in younger children.

Implications

Important theoretical and practical implications emerge from the presented findings. First, the findings call for dual investigations of attention for stationary and moving stimuli across development. The developmental principles of attention to stationary stimuli and their relationship to other domains of cognition may not be generalizable to principles of developing attention to moving stimuli. Second, this point might prove to be especially relevant to understanding behavioural disorders that are specified by attentional difficulties such as ADD or ADHD. For these children, moving stimuli may pose increased constraints in processing information in a way that can be crucial for safe, adaptive, and appropriate behaviour in many everyday situations. Finally, distinct developmental patterns for stationary and moving stimuli can be critical for effective child road safety policies. These implications will be discussed further in Chapter 6.

Conclusions

The research in Chapter 5 examined the development of the ability to suppress moving distractors from middle to late childhood. The findings lend support for a slower development of top-down attentional inhibition for objects in motion, than it is the case for stationary objects (Chapter 4). In particular, 6-year-olds were limited in the number of old moving stimuli they were able to ignore. Children aged 6-8 years also showed difficulties in ignoring old distractors when their duration in the visual field was increased prior to the presentation of the second set of items. This suggested that developmental change occurs separately in two preview-related components: initialization and consolidation of old items via central resources, and maintenance of a representation of old items via visual resources (Humphreys et al., 2002). In addition, and similar to the findings from Chapter 4, Chapter 5 revealed that the efficiency of the preview benefit in adults was associated with individual differences in EF performance, and that this association was not present in children. The findings from Chapter 5, which suggest a decreased ability of younger children to ignore moving objects in time, may have important implications for everyday behavioural outcomes in childhood, road safety policies, and set the stage for further investigations in atypical populations.

Chapter 6

General Discussion

The aim of this final chapter is to provide an integrated discussion of the findings presented in Chapters 2 to 5. Three themes of research around the topic of time-based visual selection were generated and presented throughout these chapters. The first line produced insights for internal (subject-driven) and external (stimulus-driven) factors that determine the effectiveness of time-based visual selection. The second revealed the multi-mechanistic side of the preview benefit. The third line showed the importance for distinguishing attentional principles for stationary and moving stimuli when plotting their developmental trajectory.

First, this chapter will provide an overview of these three lines of evidence. Second, I will discuss the applications of these lines of evidence to various domains of public interest: education, clinical practice, and public policy.

Endogenous and Exogenous Characteristics of the Preview Benefit

Chapter 2 investigated how top-down inhibition in the preview benefit is controlled endogenously, and under what conditions might or might not occur. This chapter showed that endogenous control of attentional inhibition in humans is not omnipotent; most of the time, people still applied inhibition when it did not provide any benefit, and even when they were explicitly instructed of its disadvantages (Experiments 1-4). However, the modest modulation found in Experiment 5 indicated that it is possible for the mechanism to be under the observers’ control in certain conditions.

These results challenge the notion that top-down processes are always controlled consciously, as it is often postulated (Umiltà, 1988, Dehaene & Naccache, 2001; Jack & Shallice, 2001). Given that past research has shown that inhibition can be fully withheld when it is at odds with the observers' goals (Watson & Humphreys, 2002), Chapter 2 suggested that goal-directedness, and not necessarily control, consciousness, or the level of automaticity, might be pertinent in distinguishing top-down in comparison to bottom-up mechanisms. Albeit top-down processes can be controlled, it does not necessarily mean that they always are. Indeed, much recent research shows that top-down processes can operate outside of conscious awareness, in order to free limited mental resources (e.g., Hassin, 2013). Moreover, Chapter 2 also highlighted the importance of how different visual environments can change the way in which selection is (or is not) controlled.

Chapter 3 showed how the characteristics of the to-be-ignored stimuli can limit the efficiency of top-down inhibition in preview search. Although past studies have suggested that up to 15 old items can be excluded (Theeuwes et al., 1998), Chapter 3 showed that this is not the case for complex stimuli that require perceptual grouping, and that this does not depend on whether the stimuli are grouped as a cluster, or whether they are bound to construct a meaningful shape (cf. Trick & Enns, 1997).

In sum, both the endogenous and exogenous limits described in Chapters 2 and 3 illuminates some of the boundary conditions under which top-down inhibition in time-based visual selection fails to operate optimally. A lack of strategic modulation of top-down inhibition and a large number of complex stimuli can both lead to reduced attentional efficiency.

The Mechanisms behind the Preview Benefit

Chapters 3 and 5 question whether the preview benefit may be driven by multiple mechanisms at large and small display sizes. This possibility was first suggested by Al-Aidroos et al. (2012), who examined the role of VWM in preview search at small display sizes. By using very different methodologies (perceptual groups as stimuli and developmental trajectories of preview search for moving stimuli) the results of Chapters 3 and 5 provide converging evidence that there might indeed be a role for a different mechanism at small display sizes. They extend the findings of Al-Aidroos et al. (2012) by showing that an alternative mechanism may operate in conjunction to inhibition when cognitive resources are limited (by the properties of the environment or by cognitive development). Chapter 3 showed that complex, perceptually grouped stimuli constrain inhibition at large display sizes, but that a preview benefit is preserved at small display sizes. Chapter 5 showed that for 6-year-old children, a preview benefit for moving items is only observed at small display sizes. In Chapter 3, it was argued unlikely that a reduced preview benefit was due to a mechanism other than a depleted inhibitory resource. However, the results from Chapter 5 are more in favour of children using onset capture to prioritise a small number of novel moving items. Moreover, this might even be the case for adults when prioritizing a small number of moving items, as there was no correlation between the PE for small and large display sizes in any age group, and EFs were only correlated to PEs for large display sizes. Taken together, these results suggest that a preview benefit for moving displays might be mediated by a mechanism other than inhibition at small display sizes. Future research is needed to unambiguously determine what mechanism underlies the preview benefit for a small number of moving distractors. In addition, determining the maximum capacity to prioritise complex objects and moving objects also remains a question for future research, and answering this may also help in elucidating the different mechanisms. Chapters 3 and 5 provide a step towards defining the multi-mechanistic nature of the preview benefit, which was earlier hypothesised (e.g., Olivers et al., 2006), but never completely understood.

All chapters provided further evidence for the role of inhibition in time-based visual selection. Chapter 2 demonstrated that there is a reduced preview benefit in easy search contexts, suggesting that the process is a result of top-down control. Chapter 3 demonstrated limits in the ability to prioritise new items in certain contexts, again suggesting a limited-capacity, top-down mechanism. Finally, Chapters 4 and 5 showed that there is both a quantitative as well as a qualitative development of the ability to exclude old distractors from future search from the ages of 6-12. Furthermore, both Chapters 4 and 5 showed that adults' efficiency when ignoring distractors is related to individual differences in EF, thus showing converging support for the role of inhibition. Moreover, Chapter 5 showed that the EF involvement is only present for inhibition of a large number of moving displays. This is consistent with some past research that demonstrated colour-carryover inhibitory effects in preview search only with large display sizes (cf. Braithwaite et al., 2003, 2004), as well as that other mechanisms may be involved in small display sizes (Al-Aidroos et al., 2012).

In sum, the preview benefit is unambiguously driven by top-down inhibition when there is a large number of distractors. Although this does not preclude the additional role of other mechanisms (e.g., Olivers et al., 2006), inhibition most likely plays a larger role at larger display sizes. This confirms and extends a past study suggesting that small display sizes may be supported by other mechanisms (Al-

Aidroos et al., 2012). Moreover, this may particularly apply to preview search when the stimuli are in motion (Chapter 5).

Development of Time-Based Visual Selection

Chapters 4 and 5 addressed how time-based visual selection develops in childhood. Chapter 4 showed that children young as 6 years can enhance attentional selection, by ignoring distractors that have previously been present in the visual field. Nevertheless, the preview benefit in 6-year-olds was smaller in comparison to older age groups. In contrast, a preview benefit was almost abolished in 6-year-olds when the very same distractors were in motion (Chapter 5). This indicated that motion hampered children's attentional control for distractors. Although 8-year-olds were able to effectively ignore moving objects, they could not sustain top-down inhibition if the duration of the distractors was extended by 1s. This elimination of the preview effect in 8-year-olds and a similar numerical trend in 6-year-olds suggests that the preview benefit is a result of asynchronous maturation of two preview components: initialization and consolidation of old items via central resources, and maintenance of a representation of old items via visual resources (Humphreys et al., 2002). Consolidation of a feature-based representation of old items in 8-year olds is likely to be a result of an increase in the capacity of central resources, while maintaining feature-based visual representations seems to have a later developmental onset, between 8 and 12 years. Top-down inhibition stabilized by the age of 12 years, and both 12-year-olds and adults could effectively ignore moving and stationary objects. Moreover, the efficiency of the preview benefit for both stationary and moving stimuli was coupled with individual differences in EFs for adults only, showing that this functional connectivity is established during the course of development.

Chapters 4 and 5 were ground breaking for understanding children's attentional development. Conventional models of developmental attention are based on examining attention for stationary objects in space. For the first time, it has been demonstrated that there exists a dissociation in the maturation of attentional mechanisms for stationary and moving stimuli. The finding that children can use time-based information to allocate attention in space, shows that children are endowed with an important ability that can improve their attentional selection. A further contribution of the work in Chapters 4 in 5 is the elucidation of the role of EF in attentional development, as top-down processes may not necessarily rely on EFs in order to be functional, but optimal performance may benefit from this connection acquired during cognitive development.

Impact

Education

Chapters 4 and 5 showed that information presented in time can boost children's selective attention. They also clarified which age-groups may benefit the most from a time-based procedure and for which types of stimuli (e.g., 6-year-olds for stationary stimuli, and 8 years and above for moving stimuli). Today, technology is pervasively introduced in classroom settings, including tablet and mobile-based learning, as well as e-learning. Given that a pre-digital world is already overwhelming with information that we are able to process, digital environments may add increased stimulation. Thus, employing time-based visual selection procedures can enhance how efficiently visual information is selected, and lead to more effective digital classroom instruction. For instance, presenting and introducing visual information successively in a step-by-step manner will enhance attention in comparison to presenting information simultaneously. Furthermore, presenting stationary visual information to younger age groups would be more beneficial than presenting moving material. Such an approach would improve children's learning and cognitive performance in digital environments.

Clinical Practice

Although the findings from Chapters 4 and 5 were based on the performance of typically developing children, they can be extended to applications for research and practice in atypically developing groups. They can be used as an age-based standard in healthy development in order to trace early cognitive vulnerabilities. The observed developmental patterns highlight the importance of an age-based approach when examining cognitive mechanisms in children. Such practice clearly reveals qualitative and quantitative differences in how different age groups perform, and could lead to more accurate diagnostic criteria for ADHD and related disorders. Three further recommendations can be made for research and clinical practice. First, these findings call for examining whether attention to moving and stationary stimuli need to be separately assessed in children with ADHD and ADD. It may be that deficits with moving stimuli are even greater for these children, and might therefore account for many real-world problems they face. Second, time-based information can be used to improve attention in children that have attentional difficulties. For example, Mason et al., (2003, 2004) have previously shown that children diagnosed with ADHD are able to ignore old distractors and prioritise novel information. Crucially, using a procedure of successively presenting distractors in time would aid attentional selection in these children, and encourage their use of top-down processes in attentional control. Third, research and clinical practice for children with genetic disorders such as William's Syndrome (WS), may also benefit from investigations of the development of attention to moving stimuli. It has been previously identified that children with William’s syndrome have a dysfunctional dorsal stream leading to atypical processing of low-level perception to motion (Atkinson et al., 1997). Chapter 5 opens an interesting and novel question of how attention (as opposed to perception) to motion may be deployed, as inattention is at the crux of behavioural difficulties that characterize WS. In terms of real-world implications, the development of attention to motion is also a pertinent issue for those who are less able: many everyday activities rely on allocating attention to moving objects, such as crossing the street or following a group of children who are walking or running. Such an approach would elucidate the mechanisms that cause atypical processing of stimuli, and inform interventions that aim to improve poor attentional skills.

Policy Implications

The work presented in this thesis is of interest to policy makers in at least two domains. First, one of the UK Government’s 2010-2015 priorities was to improve road safety, including the development of evidence-based road safety policies (Department of Transport et al., 2015). The AXA RoadSafe report (2013) has shown that the number of deaths and injury rates in the U.K. is the highest in the past 10 years, for children under the age of 8. Despite there being different statistics on the frequency of accidents per age group, policies and campaigns are poorly supported by evidence-based research on risk factors that may be crucial for certain developmental stages. There seems to be a need for far more extensive and stronger evidence-based guidelines of age-based safety recommendations to avoid child causalities. In particular, top-down attentional mechanisms are easily impaired if resources are allocated to a secondary task (e.g., Pashler, 1994; Tombu & Jolicoeur, 2003; Humphreys et al., 2002), and this might be even more true for children who demonstrate a smaller resource capacity for tracking motion stimuli (e.g., Trick et al., 2005) or to reduce interference from old moving distractors (Chapter 5). The detrimental effects of distractions on safety, is evidenced by the nature of child causalities in road accidents. Namely, the time of the day (typically end of school day) when child pedestrian accidents happen, correlates with the usage of mobile devices (AXARoadSafety, 2012), suggesting that such accidents are due to lapses in attention. The findings in this thesis (Chapter 5) suggest that there are substantial developmental differences in how children are able to efficiently allocate attention to objects in motion. Thus, it is crucial to translate research of this kind into practice, in order to identify which age-groups are more likely to become victims of road accidents due to insufficiently developed cognitive and neural mechanisms. Chapter 5 provided scientific evidence that can be used and extended to design child road safety policies targeting specific age groups.

A second application of the findings in this thesis relates to the field of behavioural science. The discovery that top-down inhibition in attention can operate unconsciously (Chapter 2) is relevant for research aimed at developing nudges (e.g., Thaler & Sunstein, 2008) to steer behaviour towards favourable outcomes (e.g., improving population health). Recently, it has been proposed that unconscious processes are likely to mediate people's behaviour more frequently than has previously been thought (e.g., Marteau, Hollands, & Fletcher, 2012; Hassin, 2013) and are vital for instantiating behavioural change. Previous work on unconscious cognition (e.g., space-based and object based attention, EF) has largely based evidence on subliminal perception (e.g., Van Gaal et al., 2008; Zhou & Davis, 2012; Norman et al., 2013) rather than unconscious cognition. Whereas subliminal perception shows how non-conscious stimuli are processed, unconscious cognition demonstrates that the subject is not aware of the cognitive process or its outcomes

(Hassin, 2013; Bargh & Morsella, 2008). Uniquely, Chapter 2 demonstrated that, even when stimuli are consciously perceived and people explicitly informed of the disadvantages of ignoring them, top-down inhibition of distractors can occur by default if aligned with the current goals. As such, goal-directed behaviour can recruit accompanying attentional mechanisms that are insufficiently controlled. This can be detrimental in contexts in which ignored information may become relevant over time, or in contexts in which there is one or more resource-demanding secondary task(s) which needs to be performed. Chapter 2 demonstrated that different visual environments can alter the manner in which attentional mechanisms operate, thus highlighting the necessity of understanding the nature of cognitive and attentional mechanisms in different contexts, in order to effectively implement behavioural change.

Concluding Comments

The first aim of this thesis was to document various endogenous and exogenous constraints of time-based visual selection. The results derived from these experiments can be used to inspire advancement of theoretical accounts of time-based visual selection, perception, consciousness, and extended to research and policy making in behavioural science. The second aim of this thesis was to determine the development of time-based visual selection in children. The findings suggested qualitative and quantitative developmental changes in attention, and an asynchronous development of inhibition for moving and stationary distractors. Besides advancing theoretical accounts of the preview benefit by uncovering the nature of its mechanisms and elucidating when children come to effectively prioritise new information, these results set valuable insights that are relevant for child road safety policies, as well as educational and clinical practice. The application of the developmental trends observed should be useful in tailoring more safe and optimal learning environments for the youngest minds.

The findings in this thesis elucidate when time can or cannot be used to boost attentional performance in adults and in children. Besides offering many implications for theoretical accounts in cognitive and developmental science, such understanding refines and clarifies how attention can be efficiently deployed in real-world settings.

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