SELECTION HISTORY IN ATTENTIONAL CONTROL

SELECTION HISTORY IN ATTENTIONAL CONTROL:

EVIDENCE FROM CONTEXTUAL CUEING EFFECT AND

ITEM-SPECIFIC PROPORTION CONGRUENT EFFECT

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Lay Abstract

Where we attend in visual space can be affected involuntarily by memories of how we have attended to visual space in the past. In other words, automatically retrieved memories can control our visual attention independent of volition. This thesis examines two visual search phenomena that display this type of memory-based control over attention. The first phenomenon reveals that search performance improves with experience searching through the same set of visual distractors on multiple occasions. We demonstrate that this form of learning is remarkably flexible; it can occur for multiple targets associated with the same set of distractors. We also demonstrate that this form of learning probably involves long-term rather than short-term memory mechanisms. The second phenomenon reveals how memory-based processes can prevent attention from being captured by a salient distractor. Eye movement data reveal that this form of learning impacts search itself, rather the processes that precede or follow search.

Abstract

A long-held belief is that human attention can be deployed voluntarily according to observers' goals (top-down) or shifted automatically to the most salience object in the environment (bottom-up). Recent studies suggest a third category of attentional control: selection history. By this view, an observer's experience in performing a task that requires the control of attention could automatically affect subsequent attention deployment in the task. This thesis examined selection history mechanisms of attentional control in two visual search phenomena. The first phenomenon is known as the Contextual Cueing Effect (CCE), and refers to an increased search efficiency when a specific distractor configuration is repeatedly associated with a specific target location (Chun and Jiang, 1998). In one study, we found a CCE when one repeated configuration was associated with up to four different target locations, suggesting that the CCE may involve mechanisms other than attentional guidance by one-to-one context-target associations. In another study, we found that the CCE was not affected by concurrent working memory load, and that there was little correlation between the magnitude of the CCE and working memory task performance when measured separately in the same participants. These results suggest that working memory may not be involved in such contextual learning. The second phenomenon is known as the the Item-Specific Proportion Congruent (ISPC) Effect, and refers to item-specific learning that controls the extent to which salient distractors capture attention. Through manual response and eye movement measures, we demonstrate that the ISPC effect reflects the search process itself, rather than processes that precede or follow search. We propose does item-specific learning produces transient changes in the activation of goal-related processes that mediate attention capture.

Preface

This thesis is composed of five chapters. Chapter 1 overviews the background literature in bottom-up selection, top-down selection, and selection history, and introduces to the reader why selection history should be recognized as a third category of control over attention selection. Two empirical chapters (Chapters 2 and 4) have been submitted for publication and are currently under peer review. Chapter 3 is an empirical study exploring the relation between working memory and implicit spatial learning. Chapter 5 discusses the conceptual issues in this thesis, the findings of each empirical chapter, implications, and future study directions.

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Declaration of Academic Achievement

Chapter 2

The first empirical chapter (Chapter 2) has been submitted to *Attention, Perception, & Psychophysics*, Manuscript ID: PP-ORIG-19-208. I was involved in all aspects of this empirical research, including experimental design, programming, data collection, analyses, and writing. Dr. Hong-jin Sun made major contributions to the experimental design and manuscript revision. Dr. Guang Zhao contributed to the programming. An undergraduate thesis student, Elizabeth Ramirez, assisted in the data collection.

Chapter 3

I was involved in all aspects of the second empirical research project (Chapter 3), including experimental design, programming, data collection, analyses, and writing. Dr. Hong-jin Sun contributed to the experimental design and manuscript revision. Dr. Bruce Milliken contributed to manuscript revision. An undergraduate thesis student, Shree Venkateshan, assisted in the experiment design, data collection, analysis and manuscript revision. Undergraduate students Suganya Gnanakumarancontri, Jenefer Xu and Marco Morales assisted in the data collection.

Chapter 4

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List of Terminologies

Throughout the chapters in this thesis I use the following acronyms:

1C – 1T	One Context – One Target
2C – 2T	Two Contexts – Two Targets
4C – 4T	Four Contexts – Four Targets
12C – 12T	Twelve Contexts – Twelve Contexts
CCE	Contextual Cueing Effect
HPC	High Proportion Congruent
ISPC	Item-Specific Proportion Congruent
LPC	Low Proportion Congruent
RT	Reaction Time
SEM	Stander Error of Means
IL	Implicit Learning
SD	Standard Deviation
WM	Working Memory

Chapter 1: Introduction

Preface

Attention shapes human thought and behaviour. In our daily lives, we focus attention on important information and ignore unimportant information. Failure to accurately focus our attention makes our behaviour inefficient. For example, to solve a difficult math problem, we must focus on the content and the logic of the problem. At the same time, we must ignore the many potential distractions (e.g., birds singing outside, children playing in the nearby playground, and any other stimuli). Faced with potentially overwhelming input, we use attention to filter or attenuate unwanted inputs to prioritize the relevant information (Broadbent, 1958; Treisman, 1960). However, sometimes, we fail to filter effectively, and our attention can be pulled away from our current goal, to information that we had no intention to attend, such as the abrupt appearance of a bright colour, or the sudden onset of a loud sound. In other words, attention is sometimes controlled by our goals and intentions, and other times controlled by the world around us.

Indeed, the extent to which selection is controlled by voluntary, goal-directed, top-down processes or by automatic, stimulus-driven, bottom-up processing forms a central issue in the scientific study of attention (Corbetta & Shulman, 2002; Theeuwes & Belopolsky, 2010; Theeuwes, 2010). Top-down attentional control, also known as endogenous control, is driven by the current goals of the observer (Awh, Belopolsky, & Theeuwes, 2012; Foster & Awh, 2019; Theeuwes, 2019). For example, an observer can decide to attend to an object, a small region of space, or a particular colour. In contrast, bottom-up attentional control, sometimes known as exogenous control, is driven by physically salient stimuli regardless of the current goals or intentions of the observer (Schreij, Owens, & Theeuwes, 2008; Theeuwes, 1994; Theeuwes, 1991, 1992, 2004). For example, an observer may decide to attend to one object only to be distracted by the onset of another object. This dichotomy between top-down and bottom-up control of attention dominated theoretical considerations for decades (Posner & Snyder, 1975; Jonides, 1980).

However, this dichotomy fails to capture a critical aspect of attentional control: specifically, selection history needs to be considered (Foster & Awh, 2019; Awh, Belopolsky, & Theeuwes, 2012; Theeuwes, 2019). Selection history refers to a person's attentional processing during prior experiences. The effects of prior selection experience on current selection processes constitutes a unique source of attention control that is unrelated to stimulus salience and yet also unrelated to the goals of the observer (Awh et al., 2012). The present thesis focuses on selection history as a form of attentional control that does not fit the conventional distinction between top-down and bottom-up processing.

In the remainder of the Introduction, I will provide a brief review of literatures on top-down and bottom-up attentional control, respectively. I will then summarize evidence that supports selection history as a third source of attentional control. In the final part of the Introduction, I describe the empirical paradigms used in the thesis and how these paradigms are used to support the idea of selection history as a source of attentional control.

What is visual attention?

The environments in which we live contain more information than our brain can process simultaneously. Thus, interacting effectively with those environments requires selection of the most relevant information. Selecting information important to our goals and filtering out less important information is fundamental to human attention (see reviews, Carrasco, 2011; Katsuki & Constantinidis, 2014). Visual attention, in particular, has been likened to a spotlight that selects a small part of visual information around us (Posner, 1980). Attention can be allocated overtly by moving the eyes or covertly without moving the eyes. Both overt and covert attention allow humans to select information for further processing. According to the two-stage framework, visual processing consists of two functionally independent stages (Broadbent, 1958; Treisman & Gelade, 1980). An early visual stage, also known as the pre-attentive stage, processes information in parallel across the visual field, whereas a later visual stage, also known as the attentive stage, processes items serially. Only the information that passes through the initial stage of pre-attentive processing can be selected to be further processed in the later attentive stage (Broadbent, 1958; Treisman & Gelade, 1980). So what factors determine which object is going to be selected for further processing?

Bottom-up selection

Bottom-up selection is also known as stimulus-driven selection. This form of attentional control is premised on the idea that stimulus properties processed pre-attentively and in parallel across the visual field can determine what is selected for additional processing (Theeuwes, 1991, 1992). By this view, attention shifts automatically to the location in the visual field with the highest local feature salience. These automatic shifts of attention are often described as attention capture.

One method used to study attention capture uses a simple visual search task. Typically, visual search performance varies with set size—response time to detect the search target increases linearly with increasing number of distractors. However, if the target captures attention, then one would expect response time not to vary with the number of distractors (Yantis and Jonides, 1984). Indeed, when a target letter in a search display appears as an abrupt visual onset, reaction times are fast and not affected by the number of distractors. On the other hand, when a distractor appears as an abrupt onset, reaction times are slower and more affected by the number of distractors. The change in RT and the slope of the RT function across number of distractors highlights the attention capture produced by abrupt onsets (Yantis and Jonides, 1984) This finding of stimulus-driven attention capture appears to be robust and ubiquitous (e.g., Irwin, Colcombe, Kramer, & Hahn, 2000; Jonides & Yantis, 1988).

In addition to the abrupt onset of a new object, the presence of a singleton can also capture attention (Theeuwes, 1992, 1994). For example, consider search for a unique diamond target among circle distractors. The diamond is considered a singleton target in this context, as it differs from all other items in shape. Now consider the same search but with one of the distractors coloured red and all other items coloured green. The presence of the irrelevant colour singleton (i.e., the red circle) will interfere with search for the target. If its salience is higher than that of the relevant shape singleton target (i.e., the green diamond; Theeuwes, 1994). In other words, the initial shift of attention is directed automatically to the most salient singleton, and therefore whether an irrelevant singleton captures attention depends on the relative salience of that singleton (Theeuwes, 1991, 1992, 1994).

The distracting nature of the colour singleton occurs regardless of knowledge about its presence. In the original study on this issue (Theeuwes, 1992) the identity of the distractor and target remain the same across blocks of trials. Thus, participants knew that the red colour singleton would never be the target throughout the experiment. Regardless, the appearance of the colour singleton significantly slowed participants' response time. Even with extensive practice the interference produced by the colour singleton remained (Theeuwes, 1992). Critically, when the target and colour singleton distractor varied across trials the interference from the colour singleton was much larger (Theeuwes, 1991), implying that the consistent mapping aided participants, but did not eliminate the attention grabbing nature of the singleton.

The additional singleton task produces a robust effect which has been replicated and extended by other researchers. For example, identification of a letter is also slowed by the presence of a colour singleton distractor (Mounts, 2000). Search for a shape singleton target can result in interference from a colour singleton distractor, whereas no such interference occurs with the opposite task requirement of searching for a color singleton target with a shape singleton distractor (Schubö, 2009; Theeuwes, 1992). As noted above, this result also indicates that the attention capture effect is influenced by the relative target–distractor salience relation. Finally, knowing that the colour singleton is more likely to appear in one location than another can reduce, but not eliminate, the attention capture effect (Wang & Theeuwes, 2018).

Researchers have also studied attention capture with a cueing paradigm. The cueing paradigm examines whether top-down information about the target, presented before the search display, can facilitate search for the target. If the target is a singleton item, it would automatically capture attention, making a cue irrelevant (Theeuwes, Reimann, & Mortier, 2006). A verbal cue, which could be valid, invalid, or neutral, was presented before the search display. Observers had 1.5 seconds to process the cue prior to onset of the following search display. Response times were unaffected by the cue information, indicating that top-down information did not modulate search for the target singleton.

Several important assumptions regarding stimulus-driven capture need to be considered (Theeuwes, 2010). First, the calculation of feature differences occurs in a bottom-up fashion only when attention is spread throughout the visual display. Varying the size of attentional window can control the size of the attended area, thus controlling the extent to which pre-attentive analysis takes place. However, despite the admission that the attentional window size mediates attentional capture (Theeuwes, 2010), the initial pre-attentive analysis for feature differences, in the attended area, is basically stimulus-driven. Top-down processing then follows this pre-attentive analysis.

Top-down selection

Top-down selection refers to a voluntary process that internally guides attention to a particular location, feature, or object based on the observer's prior knowledge, plan, or current goal (see reviews, Carrasco, 2011; Katsuki & Constantinidis, 2014). The additional singleton search task and cueing paradigms provide evidence supporting top-down selection. By contrasting results from the same paradigms used to support bottom-up selection, researchers have been able to provide strong evidence for top-down selection operating in addition to bottom-up selection.

As noted above, the size of the attentional window appears to modulate the interference effect from a colour singleton (Belopolsky & Theeuwes, 2010; Belopolsky, Zwaan, Theeuwes, & Kramer, 2007). Belopolsky and Theeuwes (2010) used the additional singleton task and manipulated the attentional window by asking participants to detect either a global (large attentional window) or local (small attentional window) shape before searching for the target. They found an interference effect of the colour singleton with the large attentional window but the interference effect of the colour singleton disappeared when the attentional window was small. This result demonstrates that the size of the attentional window, which was under top-down control, can dictate whether or not attention was captured by the colour singleton distractor.

Top-down knowledge refers to certain states of an observer that can include an observer's knowledge or beliefs about the task. The contingent involuntary orienting hypothesis holds that whether a singleton captures attention is contingent on an observers' task-related attentional control settings (Folk, Remington, & Johnston, 1992). These attentional control settings are thought to be established by the goals held by the observer in relation to the particular task. For example, when an observer searches for a colour singleton, a top-down setting to search for colour singletons leads attention to shift preferentially to locations of colour singletons in the visual search field, while other potentially salient stimulus features, such as an abrupt onset, are completely ignored. Similarly, when an observer searches for an abrupt onset, an abrupt onset will capture attention whereas a colour singleton will be ignored. A real-world example may help to make this idea clear. When looking for your distinctively bright red car in a parking lot you may find that other brightly coloured cars in the parking lot tend to capture your attention, whereas even the abrupt appearance of a new car entering the parking lot fails to capture your attention. In this manner, endogenous, top-down control modulates attentional capture through specific task-related attentional sets held by observers.

Another form of top-down control over stimulus-driven capture is referred to as ‘search mode’. Bacon and Egeth (1994) pointed out that there are two different visual search modes that may be adopted in the additional singleton search task: feature search mode and singleton search mode. According to this view, feature search mode occurs when observers search for a specific feature, such as a red circle. In contrast, singleton search mode occurs when observers search for a singleton that is different from the other elements. The general idea is that observers will tend to be distracted by the presence of an irrelevant singleton when they adopt singleton search mode but not when they adopt feature search mode. Bacon and Egeth (1994) used the additional singleton search task to verify this idea. They created two different methods to dissociate the two different search modes. One method added more than one target to the search displays, making singleton mode ineffective for finding the target. The other method added additional non-target shape singletons (e.g., squares and triangles) to the search displays, making singleton mode ineffective because it would draw attention to distractors. Thus, both methods encouraged participants to adopt feature search mode. Indeed, both methods also eliminated the usual interference effect produced by colour singletons. This result suggests that interference by colour singletons presumably occurs when singleton search mode, rather than feature search mode, is adopted. All told, these results offer strong support for the view that attentional capture by irrelevant singleton depends on visual search mode.

Selection history — A third category of control over attention selection

In the previous sections, I provided a brief review of evidence that supports each of bottom-up and top-down control over attention selection and capture. These two distinct forms of control over attention selection are indeed supported by large bodies of empirical evidence. However, recent studies suggest that this dichotomy may be incomplete. In this section, I provide a brief review of the evidence that argues for a third form of control over attention selection.

The definition of bottom-up attention selection is very clear. Any shift of attention that is driven by physical stimulus features or properties can be classified as an example of bottom-up attention selection. However, the definition of top-down selection can be somewhat less clear. One definition of top-down control over selection includes all factors that do not belong to the above bottom-up category; that is, observers' knowledge, plans, goals, desires, as well as statistical regularities and prior selective attention behaviours would all fit within this definition of top-down control over selection. However, this particular definition conflates two influences on attention selection that may be quite different: the influence of current selection goals, and the influence of one's selection history (Awh et al., 2012). Note that the current goal of an observer and selection history may produce contradictory selection biases. Thus, Awh et al. (2012) first proposed that selection history should be recognized as a third category of attentional control that is separate from top-down processes related to one's current goal. In the following section, I review evidence that supports selection history as a third category of attention control over selection, one that affects attention selection in a fashion that cannot be explained by stimulus-driven physical salience or observers' current voluntary goals.

Reward-induced selection biases versus the observers' current goal.

One line of evidence for selection history influences on selection focuses on the influence of reward. In particular, monetary rewards could enhance the motivation to achieve more efficient goal-directed behaviour (Pessoa & Engelmann, 2010), and make it more likely that observers will orient attention to a location at which they stand to gain a reward. One example of this type of reward effect was reported by Hickey, Chelazzi, and Theeuwes (2010). They used the additional singleton task (Theeuwes ,1992), with participants required to make a response to the orientation of a line inside an odd shaped target object, while ignoring a singleton colour distractor. There were two important parameters of the search task: (1) the colours of the target and distractor changed randomly from trial to trial; and (2) participants randomly received either a high or low monetary reward if they responded correctly. The best way to maximize reward was to make a correct response on all trials. To do so, participants ought to have focused attention on the shape singleton and ignored the colour singleton equally on all trials. However, the results revealed that when the colour of the target and the colour of the distractor remained the same across trials (no colour swap condition), RT was faster following a high reward previous trial than following a low reward previous trial. In contrast, when the color of the target in the current trial was the same as the colour of the distractor from the previous trial, RT was slower following a high reward previous trial than following a low reward previous trial. In other words, participants were more likely to direct attention to the colour associated with a high reward from the previous trial, despite the high reward previous colour now being the colour of the distractor. The results of this study clearly show that reward automatically triggered a selection bias to the reward colour, despite that bias being entirely misaligned with the current task goal.

Anderson, Laurent, and Yantis (2011) found a similar result using a pre-training procedure. Participants were trained to associate a high reward and a low reward with two different colour targets, respectively. In the testing phase, the two target stimuli that had been associated with low and high reward were then used as distractor items. The results showed that RT for target detection was slower when the colour that was trained with high reward was used as a distractor than when the colour that was trained with low reward was used a distractor. Again, these results highlight a distinction between reward-induced selection biases and selection processes determined by the current goal of the observer.

A recent study suggests that selection history itself may be broken down into separable components (Kim & Anderson, 2019). In the training phase of the experiment, participants were asked to perform an antisaccade task in response to a coloured square presented left or right of fixation. The square could be one of two colours, and participants were rewarded for correct responses to one of the colours but not the other. Results from the training phase showed that participants learned in response to the reward; they were faster and more accurate for the rewarded colour. In a following test phase, a square and a circle were presented left and right of fixation, and participants were required to fixate on the circle (target) and ignore the square (distractor). The key finding involved performance in this task as a function of the target or distractor being presented in the rewarded colour from the training phase. Participants were particularly fast and more accurate when the target circle was rendered in the rewarded colour. This result highlights the idea that the reward did not strengthen the association between the colour and the task of 'looking away' to the opposite side of space (i.e, the antisaccade instruction from the training phase). Rather, the reward strengthened the association between the colour and a form of approach response that is precisely the opposite of the antisaccade requirement from the training task. In a following experiment, the reward in the training phase was eliminated. Participants were simply trained to look away from a square that was often presented in a particular colour, such as red. The testing phase was identical to the previous experiment. Here, participants were faster and more accurate when the distractor square was rendered in red, a result opposite that of the first experiment, but consistent with the idea that participants simply developed a habit of looking away from the red square in the training phase. These findings demonstrate separate components of selection history effects on performance, one related to reward and aligned with the law of effect (Thorndike, 1911) and another related to habit.

Together, these studies provide convergent evidence that reward–induced selection bias can produce an effect that is opposite to the current goal of the observer. As this reward-induced bias cannot be explained by stimulus salience, and it cannot be explained by the voluntary goals of the observer, it constitutes a good example of a third form of attentional control over selection, that is, a selection history effect.

Selection history and context specific learning

In addition to reward induced selection history effects, there are several other examples in the literature of selection history phenomena. In all cases, these empirical phenomena illustrate how an observer's past attentional experience shapes subsequent attentional selection in a manner that is unrelated to observers' voluntary selection goals. Here I describe two such phenomena, both of which involve context specific learning processes.

The item specific proportion congruency (ISPC) effect was first reported by Jacoby, Lindsay and Hessels (2003). Proportion congruent effects in Stroop (1935) and Stroop-like tasks had long been used to study the flexible control of attention (Logan & Zbrodoff, 1979; Lowe & Mitterer, 1982), but these effects had conventionally been attributed to top-down voluntary control mechanisms. Jacoby et al. manipulated proportion congruent at the level of items, with some colour words usually presented in a congruent colour and other colour words usually presented in an incongruent colour. All of these items were randomly intermixed in the experiment, so any difference in congruency effects for the two items types could not be attributed to top-down control implemented prior to onset of the item. Nonetheless, the Stroop congruency effect was larger for high proportion congruent items than for low proportion congruent items. This effect must be related to the item-specific histories of focusing attention on colour for low proportion congruent items and focusing attention on word for high proportion congruent items.

Crump, Gong, and Milliken (2006) extended this selection history effect from items to task-irrelevant contexts. Participants first saw a colour word prime (displayed in white) at fixation. Then, a colour patch probe appeared either above or below fixation. Proportion congruency between the prime and colour patch probe was varied as a function of probe location. Specifically, if probes appeared above fixation, the probes were highly likely to be congruent with the preceding prime word. If probes appeared below fixation, the probes were highly likely to be incongruent with the preceding prime word. The Stroop effect was larger for probes that appeared in the high proportion congruent location context than in the low proportion congruent context; the context-specific proportion congruent (CSPC) effect. Again, these results constitute a selection history effect because it is the item-specific history of particular items rather than voluntary top-down control mechanisms that produces the effect. Indeed, Crump, Vaquero and Milliken (2008) confirmed that this effect did not depend on the awareness of the context manipulation, indicating that selection history modulated the Stroop interference in an involuntary, automatic manner.

The logic underlying ISPC and CSPC effects has since been applied to the additional singleton paradigm (Crump, Milliken, Leboe-McGowan, Leboe-McGowan, & Gao, 2018; Thomson, Willoughby, & Milliken, 2014). Here, congruent trials were created by including items in which the colour singleton distractor coincided with the shape singleton target, whereas for incongruent trials the colour singleton distractor and shape singleton target were different objects. Again, proportion congruent was manipulated for two different item types, or for two different contexts, and the congruency effect reflecting capture by the colour singleton was larger for high proportion congruent than for low proportion congruent conditions. This result implies that participants learned a selection history that biased attention to the shape singleton more in the low proportion congruent condition than in the high proportion condition. Again, this selection history effect modulated attention in a fast, implicit and automatic manner.

Further evidence for selection history influences on the control of attention comes from studies of the contextual cueing effect (Chun & Jiang, 1998). When specific layouts of distractors are associated with specific target locations, implicit knowledge of this association can guide attention to the target location when participants encounter the same layout again. In a typical study of Chun and Jiang (1998), participants were required to search for a target letter ‘T’ among some ‘L’ distractors. Unknown to participants, half of the configurations in each block were repeated across learning blocks and the other half of configurations in each block appeared only once throughout the experiment. Participants were faster in searching for the target in repeated configurations than random configurations. This effect suggests that participants learned the association between repeated distractor configurations and particular target locations, and this learning biased shifts of attention toward target locations. In contrast, as the association between novel distractor configurations and target location could not be learned, biased shifts attention toward target locations would not have occurred in the novel distractor configuration condition. The contextual cueing effect indicates that observers can extract statistical regularities from their selection histories, and that this learning can bias attention as a consequence.

Summary

Conventionally, the sources governing attentional control of selection have been categorized into the dichotomy of bottom-up (stimulus-driven) and top-down. However, the definition of 'top-down' has been unclear. Generally, researchers hold the view that top-down factors are voluntary and goal-driven. To retain the above dichotomy, and the view that top-down factors are voluntary and goal-driven, then all attentional control mechanisms that are not stimulus-driven must be voluntary and goal-driven. This introduction highlights that this is not the case (Awh et al., 2012; Kim & Anderson, 2019; Theeuwes, 2019; Wolfe, 2019), that selection history should be recognized as a third category of attentional control over selection. Support for selection history as a third category of attentional control over selection stems from the following broad observations: (1) selection history biases attention in an involuntary manner and occurs without observers' awareness; (2) selection history is unrelated to stimulus salience of objects; and (3) selection history is unrelated to observers' current goals, being either aligned or misaligned with those goals. Yet, selection history is a relatively novel construct in the study of attention, and more research needs to be done to understand its properties. In this thesis, the contextual cueing and item-specific proportion congruency paradigms are used to examine selection history mechanisms.

Overview of the empirical chapters

As noted above, the contextual cueing effect refers to learning that speeds observers' search times for targets in repeated scenes relative to novel scenes (Chun & Jiang, 1998). It has been proposed that the effect reflects participants learning of the association between repeated configurations and target locations (Chun & Jiang, 1998). Prior research suggests that a repeated configuration may only be associated with one target location. In particular, the magnitude of contextual cueing effect was significantly reduced when one repeated configuration was associated with two different target locations, and no contextual cueing effect was found when one repeated configuration was associated with three different target locations (Zellin, Conci, von Mühlenen, & Müller, 2011). However, Zellin, Mühlenen, Müller, and Conci (2013) showed that a robust contextual cueing effect can be retained for two target locations associated with a single repeated distractor configuration if target locations are swapped between distractor configurations after a contextual cueing effect is established in a previous training phase. This result suggests that the association between repeated distractor configurations and target locations may be more flexible than assumed, as long as both the target location and distractor configuration have a 'predictive' history; that is, as long as both have been part of repeated configuration trials in the past. In the first empirical chapter, we examined whether this principle could be used to demonstrate a contextual cueing effect in which a single repeated distractor configuration is associated with multiple target locations. Five experiments were conducted, with the key manipulation being that repeated distractor configurations swapped their associated target locations across learning blocks. Experiment 1 adopted the classical contextual cueing paradigm and replicated the contextual cueing effect. In Experiments 2 to 4, the contextual cueing effect was demonstrated even when four different target locations were associated with a single repeated distractor configuration, indicating that the contextual cueing effect does not require associative learning between just one repeated distractor configuration and one target location.

The contextual cueing effect is thought to rely on associative learning between a repeated distractor configuration and target location. Once this contextual cueing association is learned, the effect on visual search can last up to one week (Chun & Jiang, 2003; Zellin, von Mühlenen, Müller, & Conci, 2014), suggesting that the learned associative information is stored in the form of a long-term memory. To the best of our knowledge, very few studies have examined the role of working memory in implicit contextual learning. In the second empirical chapter, we examined whether relational working memory is involved in contextual learning by requiring participants to perform a working memory task and a contextual visual search task concurrently or sequentially. In the first three experiments, we asked participants to perform a working memory task that either did or did not involve relational binding. One relational binding WM task involved colour–shape binding, and the other relational binding WM task involved shape–location binding. The non-relational WM task involved memory for three different colours. We found that contextual cueing occurred with both a relational binding WM task and with a non-relational WM task, suggesting that resources involved in relational binding in working memory are not involved in the learning that supports the contextual cueing effect. In the last experiment in this chapter, we examined the correlation between individuals' working memory performance and the magnitude of their contextual cueing effect in the visual search task. There was little correlation between working memory and the contextual cueing effect. Taken together, these results support the view that implicit contextual cueing is independent of working memory.

In the final empirical chapter, we examined another form of selection history effect—the item specific proportion congruency effect. Thomson Willoughby and Milliken (2014) revised the traditional additional singleton search task from Theeuwes (1992) by introducing the concept of congruency. The task was to search for a shape singleton target. In the incongruent condition, similar to Theeuwes (2012), the presence of a colour singleton distractor impaired search for a shape singleton target. In the congruent condition, the colour singleton distractor coincided with the shape singleton, allowing the colour singleton distractor to faciliate search for the shape singleton. Prior research had shown that capture by the colour singleton distractor could be modulated in a fast and flexible manner by item-specific and context-specific learning (Crump et al., 2018; Thomson, Willoughby, & Milliken, 2014). However, the specific mechanisms underlying this effect have not been studied further. By tracking eye movements, we found that item-specific influences on attention capture did not occur upon first glance of the display, but instead were driven by more and longer fixations on the colour singleton distractor for the high proportion congruent condition than for the low proportion congruent condition. We propose that this effect may be a product of transient item-specific learning influences on goal activation.

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Chapter 2: Learning of Association between a Context and Multiple Possible Target Locations in a Contextual Cueing Paradigm

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Preface

The influence of selection history on attentional control is manifest in the contextual cueing effect (CCE), which refers to improved visual search performance with experience searching through the same configurations on multiple occasions. The purpose of Chapter 2 was to examine the mechanisms underlying the contextual cueing effect. This memory-based control over attention has long been thought to occur as the result of attentional guidance from the repeated distractors to the target location. In a series of experiments, we manipulated the number of target locations associated with repeated configurations. In Experiment 1, the robust contextual cueing effect was observed for the one target–one distractor configuration condition, a replication of the typical CCE (Chun & Jiang, 1998). In Experiment 2, the CCE was also evident (although smaller in magnitude) when one context was associated with two possible target locations. In Experiment 3, we also found a CCE when each repeated context was associated with four possible target locations. We did not observe the CCE when each repeated context was associated with twelve target locations (Experiment 4). We further replicated the results of Experiment 3 by using a within-subject design, demonstrating that the pattern of effects found in Experiments 1 and 3 is robust. The CCE appears to occur when multiple possible target locations are associated with the same set of distractors, suggesting that learning of one-to-one context–target association does not necessarily drive the CCE, and that perhaps attentional guidance is not the only mechanism underlying CCE. Notably, the results reported here are the first to demonstrate this extent of flexibility in the implicit spatial learning that underlies the CCE.

Abstract

Searching for a target is faster in a repeated context compared to a new context, possibly because the learned contextual information guides visual attention to the target location (attentional guidance). Previous studies showed that switching the target location following learning, or having the target appear in one of multiple possible locations during learning, fails to produce search facilitation in repeated contexts. In this study, we reexamined whether the learning of an association between a distractor configuration context and a target is limited to one-to-one context–target associations. Visual search response times were facilitated even when a repeated context was associated with one of four possible target locations, provided the target locations were also shared by other repeated distractor contexts. These results suggest that contextual cueing may involve mechanisms other than attentional guidance by one-to-one context–target associations.

Key words: Contextual Cueing; Visual search; Implicit learning; Associative learning

Introduction

Although visual scenes are typically complex, there are often regularities embedded in scenes. The ability to extract such regularities is a key property of our cognitive system (Reber, 1967; Turk-Browne, Jungé, & Scholl, 2005). One such type of regularity is the spatial layout of objects in the environment. Extensive research has demonstrated that humans are able to learn to utilize repetitions in spatial layout (Goujon, Didierjean, & Thorpe, 2015; Reber, 1989). One example of this type of visual learning is the contextual cueing effect (CCE; Chun & Jiang, 1998). The contextual cueing effect occurs when visual search performance is improved by the repeated pairing across trials of a search target and a particular spatial configuration of distractors.

The Contextual Cueing Effect

In the seminal study of Chun and Jiang (1998), participants were required to search for a target letter T among rotated distractor letter Ls, and then to press one of two keys based on whether the target letter T was rotated 90 degrees clockwise or counter-clockwise from upright. Unknown to participants, for half of the trials the distractor contexts were repeated across blocks, and the target appeared consistently in the same location. For the other half of the trials, the distractor contexts were always novel, appearing only once in the experiment. The results showed that reaction time (RT) became faster across blocks for the trials with repeated distractor contexts relative to the trials with novel distractor contexts. Chun and Jiang (1998) proposed that observers learned an association between distractor contexts and target location, and that this learned association guided observers' search for the target, resulting in the CCE. Interestingly, in a follow-up recognition test, participants could not recognize repeated distractor configurations from novel distractor configurations, indicating that the CCE was actually based on implicit spatial learning.

Mechanisms Producing the CCE

It has been proposed that the CCE is driven by one or more of three stages of processing in the visual search task: initial perceptual processing, attentional guidance, and response selection (Chun & Jiang, 1998; Zhao et al., 2012). To study this issue, researchers have attempted to isolate the contribution of specific processes that contribute to visual search performance. For example, by varying the number of stimuli (set size) in the search display, and fitting a line to the RT data as a function of set size, one can obtain a slope and an intercept of the fitted line (Chun & Jiang, 1998; Kunar, Flusberg, Horowitz, & Wolfe, 2007; Sewell, Colagiuri, & Livesey, 2018; Zhao et al., 2012). Changes to the slope are thought to index search efficiency. If participants can learn the association between target location and distractor contexts, and if this learning supports attentional guidance toward the target, then the CCE might be captured in smaller slopes for the repeated contexts than for the novel contexts. In contrast, changes to the intercept are thought to reflect non-search factors such as initial perceptual processing and response selection. If learning associated with initial perceptual processes or response selection produces the CCE, then the intercept for repeated contexts should be lower than for novel contexts.

Many prior studies support the view that the mechanism underlying the CCE is attentional guidance (Chun, 2000; Chun & Jiang, 1998; Jiang, Song, & Rigas, 2005; Jiang & Wagner, 2004; Zellin, Conci, von Mühlenen, & Müller, 2011). For example, Chun and Jiang (1998) found smaller slopes for repeated distractor contexts than for novel distractor contexts. However, not all studies support the attendance guidance interpretation of the CCE. For example, Kunar et al. (2007) failed to find a significant slope difference for repeated and novel contexts. They also observed a CCE in an easy pop-out search task in which attentional guidance should play little role, and they found the CCE to be sensitive to the introduction of response selection demands. As a result, they argued against the attentional guidance view, and proposed instead that response selection mechanisms determine the CCE.

Yet other studies have suggested that both attentional guidance and response selection contribute to the CCE (Schankin, Hagemann, & Schubö, 2011; Schankin & Schubö, 2010; Sewell et al., 2018; Zhao et al., 2012). Zhao et al. (2012) used behavioural and eye movement measures to examine the three processing stages of the search task described above. Slope and intercept measures showed that both attentional guidance and response selection could play a role in the CCE. Eye movement measures were consistent with this interpretation. The search phase was shorter for repeated distractor contexts than for novel distractor contexts, indicating that attentional guidance contributed to the CCE, and the processing that followed search but preceded the response was also shorter for repeated than novel contexts, indicating that response selection could also contribute to the CCE. In line with these results, Schankin et al (2011; 2010) reported a CCE that was reflected in a late positive ERP component typically linked to response-related processes. Finally, Sewell et al. (2018) reported a diffusion model analysis of RTs that indicated both the speed of search and response level factors contribute to the CCE.

Multiple Target Locations in Contextual Learning

The CCE implies that participants can learn the association between a target location and a particular distractor configuration, but can participants learn the association between a distractor configuration and more than one target location? Chun and Jiang (1998, Experiment 6) first investigated contextual cueing with one repeated distractor context paired with two possible target locations; that is, although there was only one target on each trial, that target appeared in either of two possible target locations for a particular repeated distractor context across learning blocks. The results revealed a modest CCE. Zellin et al. (2011) confirmed that the CCE is reduced for two target locations relative to just one target location paired with a repeated distractor context, and no CCE was observed for three target locations paired with a single repeated distractor context. Furthermore, they found that when the CCE is observed for multiple targets, there is one “dominant” target location that is learned, and the overall CCE effect appears to be a blend of performance for trials in which a CCE occurs and trials in which a CCE does not occur. These findings suggest that a single distractor context may only cue one target well, which is consistent with the notion that attentional guidance contributes to the CCE.

Effect of Target Relocation on the CCE

In addition to varying the number of target locations associated with a given repeated context during learning, a target relocation paradigm has been used to examine the nature of the association between the target and distractor array. In this case, following learning of a constant association between a single target and a particular distractor configuration, the target is relocated to a different position. The question here is whether contextual learning of the distractor configuration can still benefit search following a relocation of the target. Clearly, if learning of an association between a particular target location and a consistent distractor configuration provides the attentional guidance responsible for the CCE, then the CCE should not occur with target relocation.

Manginelli and Pollmann (2009) examined this issue with a conventional learning phase in which a single target was associated with a repeated distractor context, followed by a target relocation phase in which the target was relocated to a location that had been empty during the learning phase. The results showed that target relocation eliminated the CCE. Presumably, the implicitly learned association guided attention to the original target location, resulting in a slowing of RTs for the repeated distractor contexts with relocated targets. Makovski and

Jiang (2010) showed that the CCE decreases with increasing distance between the original target location and the relocated target. Moreover, the RT benefit for the repeated distractor contexts turned into an RT cost when the repeated context target switched with a distractor location. Zellin, Conci, Mühlenen, and Müller (2013) found that following CCE disappearance with target relocation, an adapted CCE effect to the relocated target did not emerge even after extensive training. Zellin et al. (2014) later confirmed that such effects upon target relocation involve learning that is slow and effortful, requiring three days of training and more than 80 distractor context repetitions.

Together, these results support the idea that attentional guidance causes the CCE. According to this view, attentional guidance is produced by a learned association between a target and a repeated distractor context, which facilitates performance for repeated distractor contexts relative to novel distractor contexts. Target relocation undermines the CCE effect because the learned association between target and distractor contexts guides visual attention to the originally learned target location, and perhaps also to the area spatially adjacent to this location. When targets are relocated far away from this original location, the learned association between target and distractor contexts becomes a misleading cue and can even reverse the effect of repeated contexts from a benefit to a cost.

At the same time, a recent study by Zellin, Mühlenen, Müller, and Conci (2013) reported a finding that is difficult to reconcile with a strict interpretation of the attentional guidance view. The key manipulation in their study was that target relocation was achieved by switching targets between different repeated contexts. The procedure had three phases: learning, exchange, and return. In the learning phase, participants learned an association between a target and distractor context as in a typical CCE paradigm. In the exchange phase, the target locations of two repeated contexts switched. In the return phase, the target locations reverted back to their original pairings with the distractor contexts from the learning phase. The results showed that the CCE in the exchange and return phases were largely equivalent to the CCE produced in the learning phase. This result demonstrates that target relocation does not always impact the CCE, in particular if the target is relocated to a location that previously served as a target location for another repeated distractor context.

Present Study

If attentional guidance from learned one-to-one target–distractor context associations is the only mechanism underlying the CCE, then the CCE ought to be smaller when a distractor context is paired with multiple possible target locations than when it is paired with one target location. The rationale for this prediction is that when a distractor context is possibly associated with more than one location during learning, attentional guidance does not unambiguously lead visual attention to the location of the target. Instead, on some trials a cost will be incurred when the distractor context cues attention to a wrong location. This search cost will increase with increases in the number of possible target location.

In the present study, we reexamined this issue using a modified multiple-targets contextual cueing paradigm. Our method was inspired by the study of Zellin, Mühlenen, Müller, and Conci (2013), in which the CCE was little affected with relocation of the target associated with one distractor context to the target location associated another distractor context. We used this method to examine the CCE in five experiments with different numbers of possible target locations associated with a given repeated distractor context.

Experiment 1 used the conventional CCE paradigm, with each repeated distractor context paired with only one possible target location (abbreviated as 1C–1T). Performance in this experiment served as a control against which the results from other experiments were compared. In Experiment 2, we examined the CCE using a procedure in which two particular repeated distractor contexts switched their targets randomly across blocks (abbreviated as 2C–2T). In Experiment 3, targets of four repeated distractor contexts switched randomly across blocks (abbreviated as 4C–4T). In Experiment 4, targets of twelve repeated distractor contexts switched across blocks (abbreviated as 12C–12T). Experiment 5 combined the methods of Experiments 1 (1C–1T) and 3 (4C–4T) in a within-subject design. In all experiments, there was only one target on each search trial, however, with the exception of Experiment 1, the target on repeated distractor trials was located in one of multiple possible locations. These trials are nonetheless labeled "repeated" because the same distractor configurations appeared once in every block.

Although our method was inspired by that of Zellin et al.(2013), it had several unique properties. First, no prior study had examined the CCE when one repeated distractor context is paired with 4 or 12 possible targets. Second, although Zellin et al. (2013) did examine the influence of switching targets between repeated distractor contexts, the learning phase itself in their study did not involve multiple target–context associations. Rather, the learning phase involved a one-to-one target–context association and then a following exchange phase introduced switched one-to-one target–context associations. In contrast, in our study participants encountered constantly changing target–context associations in the learning phase. Thus, in our study, the learning required to produce a CCE involved association of one invariant distractor context with two, four or twelve possible targets, with those targets switching constantly across blocks during the learning phase.

Experiment 1: One Context – One Target (1C–1T)

Experiment 1 was conducted to replicate the typical contextual cueing paradigm, and the results served as a baseline for comparison to following experiments. Critically, each repeated distractor context was associated with one specific target location. We hypothesized that a robust CCE should be observed in this experiment.

Method

Participants. Twenty university students (4 males) whose age ranged from 19 to 24 years (Mean = 20.1 year) took part in Experiment 1 for course credit. All participants had normal or corrected-to-normal vision, and none had previously participated in any similar laboratory visual search tasks.

Apparatus and Stimuli. The procedure and data collection were controlled by Experiment Builder, and carried out on an HP (Pavilion 23) computer. The stimuli were displayed on a 23-inch monitor, with a resolution of 1024 × 768 and a refresh rate of 60 Hz.

The search displays contained one T-shaped target that was rotated 90° from upright either clockwise or counter-clockwise, and 11 L-shaped distractors that were rotated a random 0°, 90°, 180°, 270° from upright. Each item was positioned within one cell of an invisible 6×8 grid that measured approximately 14°×18°. Each cell had a size of 2.25°×2.25°. The location of both targets and distractors within each cell was jittered randomly within a range of ±0.1°, horizontally or vertically, to avoid collinearities between stimuli. Both the horizontal and vertical size of each stimulus were about 0.7°. The 6×8 grid was divided into four invisible quadrants, and each quadrant contained three search items placed in three randomly selected cells within the quadrant. The viewing distance was about 57cm. The background color of the search display was grey, and all search items were displayed in black on the grey background.

Procedure. Each trial began with a fixation marker presented for a random duration between 400ms and 600ms. The search array was then displayed and remained on the screen until a response was made or 10 seconds had elapsed. Participants were required to search for the target letter T among 11 distractor letter Ls, and to identify whether the target T was rotated to the left or right from upright, as quickly and accurately as possible. If the target T was rotated to the left, participants were asked to press the F key on the keyboard, whereas if the target T was rotated to the right, participants were asked to press the J key. The search display was followed by a feedback display for 500ms. If participants made an incorrect response, an auditory beep occurred and the word "wrong" was presented. If participants made a correct response the word "correct" was presented. If no response was made within 10 s, the message "no response" was displayed. Following this feedback, the next trial proceeded automatically.

The experiment followed a 2 (Context: repeated, novel) × 32 (block: 1–32) within-subject repeated measures design. The repeated distractor contexts were repeated across blocks, while the novel distractor contexts appeared only once throughout the experiment. The learning session included 32 blocks. Each block contained 12 repeated distractor contexts and 12 novel distractor contexts. To rule out target location probability as the source of the CCE, 24 distinct target locations were selected, with 12 target locations assigned to repeated distractor contexts and the other 12 target locations assigned to novel distractor contexts. The eccentricities of the two sets of targets were comparable, with an average of 5.88° and 5.89° for repeated and novel contexts, respectively.

Before starting the experimental session, participants completed a practice block of 24 trials that were not repeated in the subsequent experimental session. Participants were given a 10 s break following each block in the experimental session. Overall, the experimental session consisted of 32 blocks of 24 trials each, for a total of 768 trials.

Recognition task. A recognition task followed the visual search task. In the recognition task, participants were required to judge whether they had seen each of the search displays in the prior search phase of the experiment. Participants pressed either the Y or N key on the keyboard to indicate ‘yes’ or ‘no’, respectively. Among the 24 search displays tested in the recognition phase, 12 were the repeated search displays and 12 were completely new displays that had not been presented previously in the search phase.

Results and Discussion

Data from the 32 blocks were collapsed into eight epochs, with four blocks in each epoch. Accuracy in the visual search task was high (98.6%), and repeated measures ANOVAs of error rates with factors Context (repeated, novel) and Epoch (1–8) revealed no significant main effects or interactions in any of the experiments (all *ps* > 0.1). As a result, analyses of error rates for this and subsequent experiments are not discussed further.

Mean RTs were computed for each condition, separately for each participant, after excluding trials in which the RT was less than 200 ms or exceeded the mean RT for that condition by two standard deviations. These two criteria were applied to all experiments in the present study, and resulted in exclusion from analysis of 5.75% of the trials in the present experiment. Mean RTs were submitted to a 2 × 8 repeated measures ANOVA with the factors

Context (novel, repeated) and Epoch (1–8). Means of the mean RTs, collapsed across participants, are displayed in Figure 1A.

The analysis revealed significant main effects of both Context, $F(1, 19) = 17.12$, $p < .01$, $\eta_p^2 = .47$, and Epoch, $F(7, 133) = 59.72$, $p < .01$, $\eta_p^2 = .76$. Responses were faster for repeated than novel contexts, and increased in speed across epochs. The interaction between Context and Epoch was also significant, $F(7, 133) = 2.93$, $p < .01$, $\eta_p^2 = .13$. As is clear in Figure 1A, the difference between repeated and novel contexts emerged across epochs, a hallmark of the CCE.

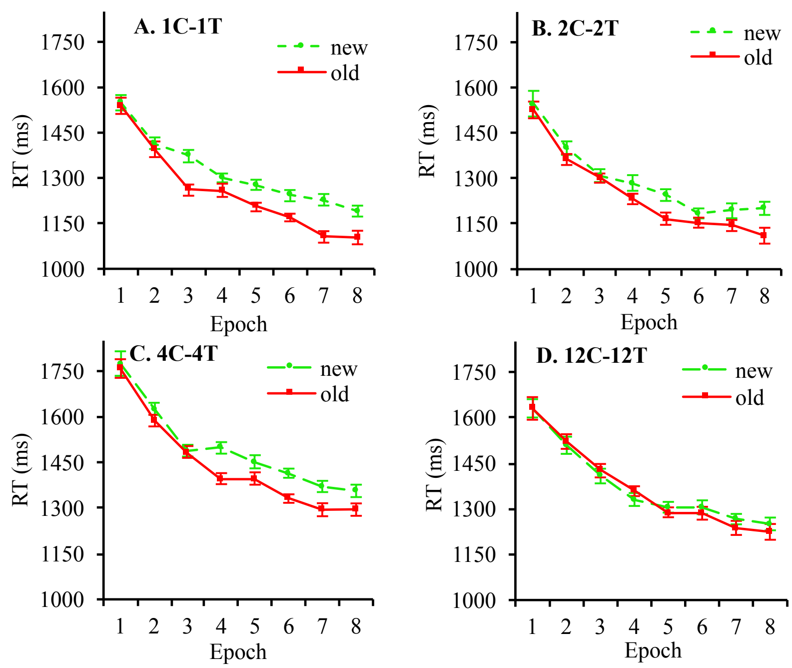

Figure 1. Mean RTs for repeated and novel contexts as a function of epoch in Experiments 1 (see panel A –1C–1T in repeated scenes), 2 (see panel B - 2C–2T), 3 (see panel C – 4C–4T) and 4 (see panel D – 12C–12T), respectively. Error bars represent standard errors corrected to remove between-subject variability in overall performance (Morey, 2008).

In the recognition task, the data from two participants were excluded from analysis as these participants pressed the same button throughout the task. Hit and false alarm rates from the remaining participants were submitted to a paired sample t-test. This analysis revealed a non-significant difference between the hit rate (55%) and the false alarm rate (56%), $t(17) = 0.069$, $p = .94$. This result indicates that participants could not explicitly discriminate repeated contexts from novel contexts. The recognition results of subsequent experiments were quite similar and in line with those of previous studies (Chun & Jiang, 1998), and as such are not discussed further in this article.

Taken together, Experiment 1 constitutes a successful replication of the CCE. When repeated distractor contexts were paired with a single target location, responses for repeated trials were faster than for novel trials, and this effect emerged across epochs. Moreover, the results of the recognition test indicate that implicit memory for the repeated contexts underlies this CCE.

Experiment 2: Two Contexts – Two Targets (2C–2T)

In Experiment 2, we examined whether the CCE can occur when one repeated distractor context is paired with either of two possible target locations. Importantly, the two targets were associated with a single repeated distractor context by switching the target locations of two repeated distractor contexts across blocks. In other words, the target location of one specific repeated distractor context served as the target location for another repeated distractor context in another block. In this manner, the two targets of the two repeated distractor contexts switched their respective target locations randomly across blocks. An implication of this method is that each repeated distractor context was paired with two possible target locations and yet no additional target locations were needed beyond the number used for the one-to-one mapping in Experiment 1.

Method

Participants. Twenty-six volunteers (5 males) ranging in age from 18 to 25 (Mean = 19.7 years) participated in this experiment.

Design. All details of the design were identical to Experiment 1, except that each repeated distractor context was paired with one of two possible target locations. Specifically, as shown in Table 1 and Figure 2, in contrast to the design in Experiment 1, the 12 repeated context were divided randomly into six context pairs, and then the two target locations of these pairs switched between blocks. The nature of the target location switch between repeated distractor contexts equally often involved a left-right, up-down, or diagonal switch in target location when considered with respect to the four quadrants of the search display.

<table>
<tr><th colspan="2">One context – one target (Exp 1)</th><th colspan="2">Two contexts - two targets (Exp 2)</th></tr>
<tr><td rowspan="4">32 blocks</td><td rowspan="2">Ca – Ta</td><td rowspan="2">16 blocks</td><td>Ca – Ta</td></tr>
<tr><td>Cb – Tb</td></tr>
<tr><td rowspan="2">Cb – Tb</td><td rowspan="2">16 blocks</td><td>Ca – Tb</td></tr>
<tr><td>Cb – Ta</td></tr>
</table>

Table 1. The design for Experiments 1 and 2. “C” in the table refers to Context and “T” refers to Target. Specifically, Ca means context “a “and Ta

means target location “a”. Ca-Ta means context “a” is associated with target location “a”.

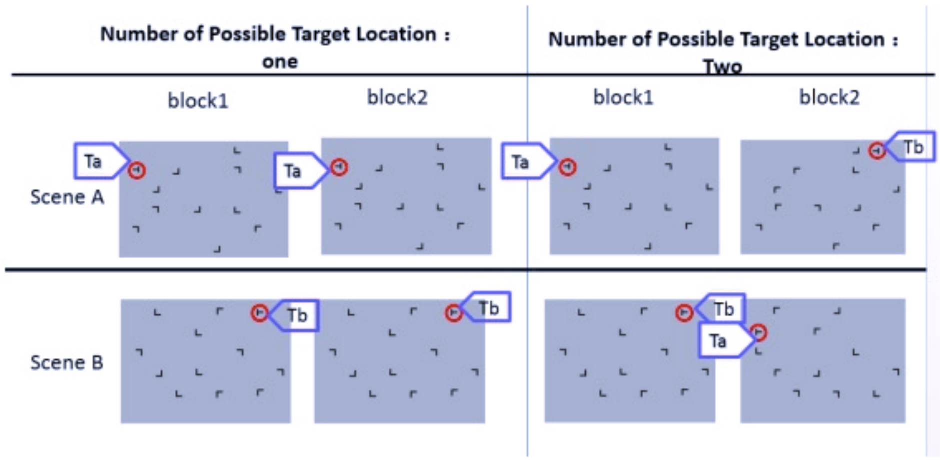

Figure 2. **Left:** Examples of two repeated contexts in Experiment 1. Context A paired with Target a in all blocks and Context B paired with Target b in all blocks. **Right:** Examples of two repeated contexts in Experiment 2. Context A paired with Ta and Context B paired with Tb in block 1, but Context A paired with Tb and Context B paired with Ta in another block. Thus the targets for Context A and Context B switched across blocks.

Results and Discussion

The same outlier procedure as in Experiment 1 was applied, resulting in the exclusion of 5.59% of RTs from further analysis. The resulting mean RTs were submitted to a 2 × 8 repeated-measures ANOVA with the factors Context (repeated, novel) and Epoch (1–8). Means of the mean RTs, collapsed across participants, are displayed in Figure 1B.

The main effect of Context was significant, $F(1, 25) = 10.68$, $p < .01$, $\eta_p^2 = .30$, as was the main effect of Epoch, $F(7, 175) = 41.49$, $p < .001$, $\eta_p^2 = .62$. As in Experiment 1, responses were faster for repeated than novel contexts, and increased in speed across the eight epochs (see Figure 1B). However, the interaction between Context and Epoch was not significant, $F(7, 175) = 1.39$, $p > .05$.

To provide a more sensitive analysis of the learning that occurred across the experimental session, we conducted an analysis that compared specifically Epoch 1 to Epoch 8 (see also Chun and Jiang, 1998; Chua & Chun, 2003). A repeated-measures ANOVA with the factors Context (repeated, novel) and Epoch (1, 8) revealed significant main effects of Context, $F(1, 25) = 49.66$, $p < .001$, $\eta_p^2 = .67$, and Epoch, $F(1, 25) = 38.79$, $p < .001$, $\eta_p^2 = .61$, and a significant interaction between Context and Epoch, $F(1, 25) = 29.64$, $p < .001$, $\eta_p^2 = .54$. As is clear in Figure 1B, the null effect of Context in epoch 1 contrasts sharply with the Context effect in epoch 8, which together demonstrate the presence of a robust CCE in this experiment.

Experiment 3: Four Contexts – Four Targets (4C–4T)

In Experiment 3, we examined whether a CCE would occur if four target locations associated with four repeated distractor contexts switched randomly across blocks.

Method

Participants. Twenty-six new volunteers (4 males) ranging in age from 18 to 27 (Mean = 21.3 year) participated in this experiment.

Design and procedure. The design of Experiment 3 was identical to Experiment 2 except the following. In Experiment 3, each repeated context was paired with four possible target locations in a manner similar to Experiment 2. Specifically, the 12 repeated contexts were divided into three groups of four, and within in each group the four target locations were assigned to each of the four repeated distractor contexts for an equal number of blocks. In other words, for each group of four repeated distractor contexts, the four target locations rotated among the four repeated distractor contexts across blocks.

Results and Discussion

The same outlier procedure as in previous experiments was applied, resulting in exclusion of 5.50 % of the RTs from further analysis. The resulting mean RTs were submitted to a repeated measures ANOVA with the factors Context (repeated, novel) and Epoch (1–8). Means of the mean RTs, collapsed across participants, are displayed in Figure 1C.

The analysis revealed significant main effects of Context, $F(1, 25) = 14.42$, $p < .01$, $\eta_p^2 = .37$, and Epoch, $F(7, 175) = 65.40$, $p < .001$, $\eta_p^2 = .72$, with faster responses for repeated than novel contexts, and increasing speed of responses across the eight epochs. Most important, the interaction between Context and Epoch also reached significance, $F(7, 175) = 2.39$, $p < .05$, $\eta_p^2 = .09$. As is clear in Figure 1C, the effect of Context emerged with increasing experience across the eight epochs, indicating the presence of a CCE.

Experiment 4: Twelve Contexts – Twelve Targets (12T–12C)

In Experiment 4, we examined whether the CCE would occur when all twelve repeated contexts switched target locations across blocks in the manner described in previous experiments. In particular, each of the twelve repeated distractor contexts was paired randomly with each of the twelve repeated target locations across blocks.

Method

Participants. Thirty-three new volunteers (7 males) ranging in age from 18 to 26 (mean = 20.2 years) participated in this experiment.

Design and procedure. All details were the same as in Experiment 3, except that target locations associated with all twelve repeated distractor contexts switched randomly among those repeated distractor contexts across blocks.

Results and Discussion

The same outlier procedure as in prior experiments resulted in exclusion of 5.49% of the RTs from further analysis. The resulting mean RTs were submitted to a repeated measures ANOVA with the factors Context (repeated, novel) and Epoch (1–8). Means of the mean RTs, collapsed across participants, are displayed in Figure 1D.

The analysis revealed a significant main effect of Epoch, $F(7, 224) = 85.52$, $p < .001$, $\eta_p^2 = .73$. As in prior experiments, the speed of responses increased steadily across the eight epochs (see Figure 1D). However, neither the main effect of Context, $F(1, 32) = .22$, $p = 0.64$, nor the interaction between Context and Epoch were significant, $F(7, 224) = 0.53$, $p = 0.81$. A repeated measures ANOVA that examined just the first and last epochs, and that treated Context (repeated, novel) and Epoch (1, 8) as repeated measures, also revealed that the interaction between Context and Epoch was not significant. These results indicate that there was no CCE when all 12 targets switched randomly among the repeated distractor contexts across blocks.

Experiment 5: Within-subject design comparing 1T–1C and 4T–4C

The results of Experiments 1 to 4 can be compared only informally, as participants belonged to different experimental groups, and the assignment to groups was not random. As such, although we were struck by the similarity of results between Experiments 1 and 3, with a robust CCE observed in both experiments, we were interested in directly comparing results across the 1C–1T and 4C–4T conditions in a better designed experiment. Here we manipulated this factor within-subjects. If the results observed in Experiments 1 and 3 are robust to this change in design, then we should observe a CCE effect in both the 1C–1T and 4C–4T conditions in Experiment 5.

Method

Participants. Twenty-one participants (6 males) ranging in age from 18 to 24 (Mean = 19.9 years) participated in this experiment.

Design and procedure. All details were identical to Experiment 1 with the exception of the following. We used a 3 (Contexts: 1C–1T, 4C–4T, novel) × 8 (Epochs: 1–8) within-subjects design. In each block, there were eight trials for each of three distractor context conditions: 1C–1T, 4C–4T, and novel. There were 32 learning blocks, and data for each of eight sets of four blocks were collapsed into epochs.

Results and Discussion

The same outlier procedure used in prior experiments resulted in exclusion of 5.79% of RTs from further analysis. The resulting mean RTs were submitted to a repeated measures ANOVA with Context (1C–1T, 4C–4T, novel) and Epoch (1–8) as factors. Means of the mean RTs, collapsed across participants, are displayed in Figure 3.

The results revealed a significant main effect of Context, $F(2, 40) = 11.52$, $p < .001$, $\eta_p^2 = .37$, and a significant main effect of Epoch, $F(7,140) = 32.61$, p $< .001$, $\eta_p^2 = .62$. The interaction between context and epoch was not significant, $F(14, 280) = 1.44$, $p > .05$. Post hoc tests showed that there was a significant difference between the 1C–1T condition and the novel condition, $t(20) = 3.87$, Cohen's d = 0.85, $p_{\text{bonf}} = .003$, and a significant difference between the 4C–4T condition and the novel condition, $t(20) = 3.84$, Cohen's d = 0.84, $p_{\text{bonf}} = .003$. However, there was no significant difference between the 1T–1C and 4T–4C conditions, $t(20) = -1.29$, Cohen's d = -0.28, $p_{\text{bonf}} = .64$.

A repeated measures ANOVA that focused on just the first and last epochs, and that treated Context and Epoch as within-participant factors, was also conducted. The interaction between Context and Epoch approached significance, $F(2, 40) = 2.88$, $p = .068$, generally supporting the view that a CCE occurred in this experiment. A follow up analysis that included only the 1T–1C and 4T–4C conditions revealed a non-significant interaction, F(7, 140) = 1.56, $p = .151$. In other words, there was again no evidence that the CCE differed for these two conditions.

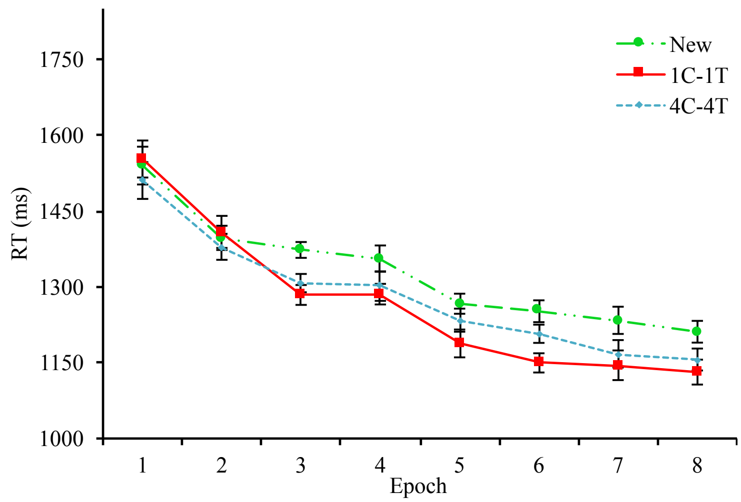

Figure 3. Mean RTs for repeated and novel contexts as a function of epochs in Experiment 5 (including 1C–1T and 4C–4T conditions in the repeated scenes through a within-subject design). Error bars represent standard errors corrected to remove between-subject variability in overall performance (Morey, 2008).

All told, the results generally replicated those of Experiments 1 and 3. Remarkably, there was no evidence that the CCE differed for the 1T–1C and 4T–4C repeated distractor contexts.

Magnitude of CCE across Experiments

We also compared the magnitude of the CCE at the end of learning across the five experiments described above. Following Chun and Jiang (1998), the CCE was defined as the mean RT for novel contexts minus the mean RT for repeated distractor contexts for the last two epochs (see Figure 4A). Results from the first four experiments indicated that the largest CCE (105ms) was in 1C–1T condition, whereas the CCE was comparable in the 2C–2T and 4C–4T conditions (69ms and 68ms, respectively). Similarly, results from the within-subject experiment (Experiment 5) indicated that the CCE (84 ms) was largest in the 1C–1T condition, and only slightly smaller in the 4C–4T condition (61 ms).

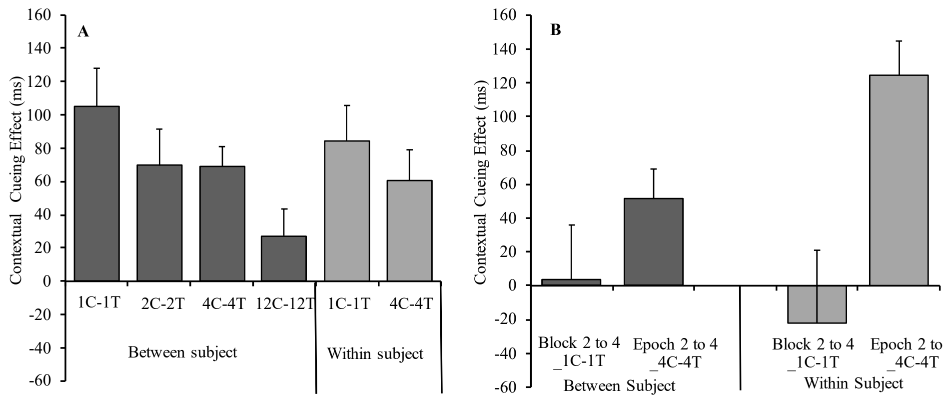

Figure 4. **A**: The contextual cueing effect (defined as the mean RT difference between novel and repeated distractor contexts for the last two epochs) in Experiments 1 (1C–1T in repeated scenes), 2 (2C–2T), 3 (4C–4T), 4 (12C–12T) and 5 (1C–1T and 4C–4T). **B**: Comparison of the average contextual cueing effect between Blocks 2 to 4 in the 1C–1T condition and Epochs 2 to 4 in the 4C–4T condition across experiments/conditions (both with the same accumulated amount of exposure for a particular context–target association). Error bars reflect the within-subjects SEM.

A one-way ANOVA was conducted to compare the CCE across the first four experiments. The results showed that there was a significant effect, $F(3, 101) = 2.82$, $p < .05$, $\eta_p^2 = .07$. Post hoc tests showed that there was a significant difference between Experiment 1 (1C–1T) and Experiment 4 (12C–12T), $p_{bnof} = 0.028$. There were no other significant differences between experiments. In addition, a paired t test comparing the two conditions in the within-subject experiment (Experiment 5) showed there was a significant difference between the CCE in the 1C–1T and 4C–4T conditions, $t(20) = -1.733$, $p < .05$, Cohen's $d = -0.38$.

Finally, when one context is paired with more than one possible target location across blocks, participants would have had many fewer exposures to a particular context–target association than in the 1C–1T condition. For example, participants would need four times of number of epochs to offer comparable opportunities to learn a specific one-to-one context–target association in the 4C–4T condition than in 1C–1T condition. Figure 4B shows the CCE during the earlier phases of learning for the same amount of accumulated exposure across Experiments 1 and 3 (left two bars) and in Experiment 5 (right two bars) if we assume participants learned an individual association between one context and one target. The CCE was generally larger for experiments/conditions with multiple possible targets compared to that for one target. Paired sample *t* tests showed that the CCE was significantly larger for the 4C–4T conditions (Epochs 2 to 4) than for the corresponding 1C–1T condition (Blocks 2 to 4) in within subject design in Experiment 5, $t(20) = -2.81$, $p = .005$, Cohen's $d = -0.61$, although the same difference did not reach significance for between subject design (Experiments 3 vs 1), $t(44) = -1.28$, $p = .10$, Cohen's $d = -0.38$.

General Discussion

In this study, we examined whether the CCE would occur when one repeated distractor context was associated with multiple possible target locations. Although the largest CCE was obtained in Experiment 1 in which each repeated context was associated with one specific target location, the CCE was also evident (although smaller in magnitude) when one context was associated with two possible target locations. Surprisingly, we also found a CCE when each repeated context was associated with four possible target locations. Importantly, the CCE found in the 4C–4T condition was comparable to that in the 2C–2T condition. Moreover, in addition to Experiments 1 to 4 in which the number of targets associated to repeated distractor contexts was manipulated between experiments, Experiment 5 used a within-subject design to compare 1T–1C and 4T–4C conditions. The results of Experiment 5 generally replicated those from the corresponding between-subject experiments, suggesting that the pattern of effects found across Experiments 1 and 3 is robust.

Interpretation of the CCE in Multiple Context–Target Association Tasks

Previous studies (Chun & Jiang, 1998; Zellin et al., 2011) had examined whether the CCE can occur when one context is paired with two possible targets. Chun and Jiang (1998) found a modest CCE in the last epoch (~40ms). Zellin et al.(2011) also found a small CCE (36ms), but mainly due to a learned association between each repeated distractor context and one particular target. However, in both of these studies, each repeated distractor context was associated with two unique target locations that were not shared with any other repeated context.

Thus, the total number of target locations across all repeated contexts was twice the number of repeated contexts overall.

In the present study, multiple associations between repeated distractor contexts and target locations were created without increasing the total number of target locations. This aim was achieved by dividing the 12 repeated distractor contexts into six groups of two (2C–2T), three groups of four (4C–4T) or one group of 12 (12C–12T), and then randomly switching target locations between the repeated distractor contexts within those groups. As a result, the total number of target locations for repeated distractor contexts in the 2T–2C, 4T–4C and 12C–12T conditions was 12, just as it was in the 1C–1T condition. This method of increasing the number of associations between repeated distractor contexts and targets without increasing the total number of target locations is a unique property of our designs, and very likely contributed to the significant CCEs found in the 2T–2C and 4T–4C conditions.

In addition to controlling the total number of targets across the entire set of repeated distractor contexts, the "reuse" of target locations between repeated distractor contexts may have played an important role in the results of the present study. As a fixed set of target locations was consistently paired with a fixed set of repeated distractor contexts, these repeated pairings did provide a basis for statistical learning that could, in principle, facilitate visual search; repeated distractor contexts did offer predictive information about likely target locations. Note that targets on novel context trials were not paired with repeated distractor contexts. Thus, our experimental design rules out target location probability alone as the cause of the multiple target CCEs that were observed. A target that is consistently paired with novel distractor contexts is missing the consistent pairing between context and target necessary for associative learning. Therefore, the CCEs observed here must in some way be related to multiple targets being associated with a consistent set of repeated distractor contexts, which in turn facilitated search relative to a comparable set of targets on novel context trials that lacked such an association. This type of contextual learning is somewhat different than that usually described in studies of contextual cueing, but could nonetheless contribute to the CCE (Zellin, Mühlenen, et al., 2013).

The results of Experiments 2–5 of the present study demonstrate that participants learned the association between multiple repeated distractor contexts and multiple target locations despite being exposed to the pairing of just one repeated context and one target on any given trial. We propose that this learning effect is unlikely to have occurred by learning that involved the specific relation between one repeated distractor context and a single target location. Such a relation would be difficult to learn, as it would be consistently subject to interference from exposure to the same context paired with other target locations, or the same target paired with other contexts. Learning of a one–to–one relation would also be of limited use as, for any particular trial, a repeated distractor context does not predict which of two or more targets will appear. For these reasons, we propose that our results are inconsistent with the notion that participants learned the association between one context and one specific target location. Indeed, for the same amount of accumulated exposure across experiments, the CCE was significantly larger for experiments/conditions with multiple possible targets compared to that for one target (see Figure 4B).

At the same time, we must acknowledge that the learning of multiple context–target associations likely requires more exposure than the one–to–one context–target associations typically measured in studies of the CCE. For example, in the 12C–12T condition of Experiment 4, each context–target pair was displayed fewer than three times on average across the whole experiment, and indeed there was no evidence of a CCE. In the 4C–4T condition of Experiment 3, each context–target pair was displayed eight times in total, and although it is remarkable that a CCE effect was observed, this effect did appear to be somewhat smaller than that observed in the 1C–1T condition of Experiment 1. In summary, we cannot be certain whether insufficient exposure to particular context–target associations, or difficulty in learning a complex mapping that involves multiple contexts and multiple targets, lies at the root of the effects reported here. Future research that examines whether a CCE could be obtained if the number of blocks for the 12C–12T condition were increased substantially would usefully address this issue.

Implications of Our Results for the Mechanisms of CC

Our proposed statistical learning of multiple target locations as a result of exposure to pairing of those target locations with multiple repeated distractor contexts differs substantially from the conventional notion of attentional guidance, the most widely accepted mechanism to explain the CCE. Attentional guidance requires a one–to–one association between a context and a target location, and the learning of this association then guides attention definitively towards the target. Many studies in the literature support the notion that implicitly learned associations between repeated distractor context and target location guides visual attention, and that this type of attentional guidance is the mechanism underlying contextual cueing (Chun & Jiang, 1998; Jiang & Wagner, 2004; Makovski & Jiang, 2010; Tseng & Li, 2004).

In our study, we found a CCE for repeated contexts that were associated with two targets (Experiment 2: 2C–2T) and with four targets (Experiment 3: 4C–4T). Importantly, the CCE effects found in these two experiments were comparable. For any given trial in both of these experiments, the target location that would be paired with a repeated distractor context was not predictable. Consequently, a one–to–one attentional guidance process would have a 50% of chance of misguiding attention in the 2C–2T condition, and a 75% chance of misguiding attention in the 4C–4T condition. If attentional guidance were the only mechanism underlying the CCE, then the CCE ought to be smaller in the 4C–4T condition than in the 2C–2T condition, which was not the case. Therefore, attentional guidance cannot possibly be the only mechanism underlying the CCE in our study.

Although attentional guidance in the conventional sense (one–to–one context–target associations) may not be the mechanism underlying the CCE in our study, it may be that repeated distractor contexts can facilitate search by guiding attention to a small number of "hot" spots. Although the exact target location was not predictable, it would still have been beneficial to predict a small number of possible target locations implicitly. One can think of this type of contextually based prediction as an extension of the "attentional guidance" mechanism discussed in the contextual cueing literature.

Alternatively, search times for repeated context items in the present study may have been facilitated by decision or response selection processes that occur after the eyes move to a target location. In our earlier work on the CCE that focused on RT x set size functions and eye movement indicators, we found that the intercept of the set size function was lower for repeated compared to novel contexts, suggesting that response selection processes contribute to the CCE (Zhao et al., 2012). Other studies have also pointed out the contribution of response selection to the CCE (Kunar et al., 2007; Schankin et al., 2011; Schankin & Schubö, 2010). In the current study, it is conceivable that response selection processes could be responsible for the CCE in the 2T–2C and 4T–4C experiments.

Beesley et al. (2015) suggested that participants can learn the associations *among* distractors as well as associations between distractor configuration and target location. According to this view, repeated presentation of the distractor contexts irrespective of target location may be responsible for the CCE. In our study, repeated distractor contexts appeared in consecutive blocks, whereas target locations associated with these repeated distractor contexts often did not repeat in consecutive blocks (in the 2C–2T, 4C–4T, 12C–12T conditions). As a result, the targets might have stood out as "unusual" items thus attracting attention. However, the results from the 12C–12T condition (Experiment 4) suggest that the contribution of repeated distractor contexts to the CCE in the present study was minimal, as the same repeated distractor contexts that produced a reliable CCE in Experiments 1, 2, and 3, produced no CCE at all in Experiment 4.

Interestingly, to isolate the effect of repeated distractor contexts, in the Experiment 1 of Beesley et al (2015), they implemented a pre-exposure phase where the distractor contexts were repeated but target locations were only occasionally repeated. Their pre-exposure phase happened to involve essentially the same design as that in our Experiment 3 (4C–4T). In their study, each repeated context was also paired with one of 4 possible target locations. However, their design differed from ours in two respects. They only implemented 4 repeated contexts (and equal number of novel contexts) while we implemented 12. In total their pre–exposure phase contained 20 exposures for each repeated context (5 blocks of 32 trials) while ours contained 32 exposures (32 blocks of 24 trials) for each repeated distractor context. They concluded that no CCE were found in their pre–exposure phase, although there were some small trends of learning in 4 out of 5 blocks. The difference in results between our two studies could be caused by the different amount of exposure for the repeated contexts. In our 4C–4T condition, the learning became more evident starting in Epoch 4 (16 exposures for each repeated context).

It is also important to point out that mechanisms of contextual learning may not be fixed and instead may vary as a function of task context. We have concluded that attentional guidance (in the sense of one–to–one repeated context–target associations) may not be the only mechanism responsible for the CCE. At the same time, there may be task contexts in which attentional guidance is indeed the predominant mechanism underlying the CCE. For example, when one repeated context is constantly paired with one fixed target location, attentional guidance might play the main role in the CCE. However, when repeated contexts are paired with multiple possible target locations in the manner of the present study, the contribution of one–to–one context–target attentional guidance to the CCE could decrease. Future studies would benefit from further study of this multiple process view of the CCE.

Conclusion

Although the CCE is typically measured by pairing each of a set of repeated distractor contexts with one particular target, we found that the CCE can also be obtained when repeated distractor contexts are associated with as many as four possible target locations, provided the target locations are also shared by other repeated contexts. The current study suggests that contextual cueing could involve mechanisms other than the conventional “one–to–one” context–target attentional guidance implicated in many prior studies of the CCE.

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Declaration of conflicting interests

The authors declare that there is no conflict of interest.

Open practice statement

The study was not pre-registered. Data and material will be made available upon request.

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Chapter 3: Relation between Working Memory and Implicit Learning in the Contextual Cueing Paradigm

Preface

The experiments in the previous chapter demonstrate that implicit spatial learning is remarkably flexible. Yet, an important question in the literature revolves around the role of working memory in implicit spatial learning. Visual search performance is facilitated by implicitly learned spatial associations in the CCE (Chun & Jiang, 1998). However, it is unknown whether relational WM is involved in this form of contextual learning. The experiments reported in Chapter 3 were designed to examine whether implicit contextual learning involves working memory. We addressed this research question with two different approaches. In Experiment 1, we found that the CCE remained relatively intact when a relational/non-relational WM task and contextual cueing task were performed concurrently. In Experiment 2, we did not find a significant correlation between the magnitude of the CCE and performance accuracy in a location change detection WM task when these two tasks were performed separately. This result also suggests that implicit spatial learning as measured in the contextual cueing task does not rely heavily on WM. Together, the results are consistent with theoretical frameworks in which implicit contextual learning is robust to dual task WM interference.

Abstract

We examined whether implicit learning (IL) in visual search involves working memory (WM). Implicit learning was examined in a contextual cueing paradigm in which visual search performance is facilitated by implicitly learned spatial associations (the contextual cueing effect; Chun & Jiang, 1998). In Experiment 1, the IL and WM tasks were performed concurrently. Participants were tested in one of three types of WM tasks testing memory of (1) object color, (2) relation between object shape and color, and (3) relation between object location and identity. Results showed that the CCE remained relatively intact regardless of the type of WM task. In Experiment 2, IL task and spatial WM task were performed in succession. We found little correlation between the magnitude of the CCE and the accuracy of WM task. These results fail to support the idea that implicit learning and working memory are related.

Keywords: contextual cueing, visual search, relational working memory, implicit learning

Introduction

Learning and working memory.

Generally, there are two different types of learning: (1) explicit learning, which occurs with awareness that learning has taken place and what is being learned; and (2) implicit learning, which occurs incidentally and without awareness that learning has taken place, and without the learning outcome being accessible for conscious report. During explicit learning, information is first stored in working memory (WM) which acts as a portal to long-term memory where the information is stored for later retrieval (Baddeley, 2003; Baddeley & Hitch, 1994). Although WM is a construct most often related to explicit (intentional, conscious) information processing (Baars & Franklin, 2003), it is reasonable to argue that representations derived from implicit learning should in theory also require a process like WM. After all, even through incidental learning, humans have the ability and flexibility to represent the regularities embedded in the environment and build up the knowledge that guides future tasks. Whereas the role of WM in explicit learning is well studied, relatively little is known about the role of WM in implicit learning (Reber, 2013).

Implicit learning and the contextual cueing effect (CCE).

One of the well-known methods to measure implicit learning is contextual cueing paradigm (Chun & Jiang, 1998). In this paradigm, participants perform a visual search task, searching for a target letter T amongst a random array of distractors (rotated letter Ls). Unknown to participants, half of the scenes are repeated across blocks and the other half are novel, appearing only once during the experiment. Participants are required to make their response as quickly as possible without sacrificing accuracy. Chun and Jiang (1998) found that reaction time (RT) in such a task became faster for the repeated distractor configurations compared to novel distractor configurations across blocks. Interestingly, during a subsequent recognition task, participants could not recognize the repeated configurations presented among novel configurations, suggesting that the CCE is actually based on implicit spatial learning. Chun and Jiang (1998) suggest that observers learned the spatial relation between distractor configuration and target location, thus leading to the contextual cueing effect. Once the contextual learning underlying the CCE is acquired, it appears to persist up to one week (Chun & Jiang, 2003), indicating the CCE is stored in the form of long-term memory.

As mentioned above, an interesting question is whether WM is involved in such contextual learning. Chun and Jiang (1998) proposed a hypothesis of where and how these memories of the spatial associations are stored. They put forth the idea that there is a unitary memory store, which contains explicit memories and implicit memories. Furthermore, they proposed that this unitary memory store could be used by multiple processes including those involved in storing and retrieving implicit memories, and possibly those involving in WM (Chun & Jiang, 1998).

In the present study, we wish to examine the relation between WM and implicit learning in two ways. In Experiment 1, an implicit learning (IL) task and a WM task were performed concurrently, and we examined the possible effect of interference from WM on the learning that supports the CCE. In Experiment 2, the IL task and the spatial WM task were performed in succession, and we examined the correlation between the performance of the two tasks across individuals.

Experiment 1

Linking contextual learning and working memory through dual task methods.

If WM and IL share the same resources, it is reasonable to expect that tasks involving WM would interfere with those used to measure implicit learning. This approach has been adopted in studies investigating whether WM contributes to the CCE (Annac et al., 2013; Annac, Zang, Müller, & Geyer, 2019; Manginelli, Geringswald, & Pollmann, 2012; Manginelli, Langer, Klose, & Pollmann, 2013; Pollmann, 2019; Travis, Mattingley, & Dux, 2013; Vickery, Sussman, & Jiang, 2010). All of these studies used a similar experiment design that combined a visual search task with a concurrent WM task. Specifically, in a given trial, participants were first exposed to a WM stimulus, then they performed a visual search task, and finally they were to respond to the WM task.

The first study of this type was reported by Vickery et al. (2010). They varied the WM load and WM type. In their Experiment 1, the WM task required participants to remember the colors of a set of colored squares (0, 2, 4, items). In their Experiment 2, participants had to compare the location of a number of dots presented in learning with those presented in the test stimulus. In Experiment 3, the same number of dots was tested, however, the dots in the WM study stimulus were presented sequentially while dots in the WM test stimulus were presented simultaneously. The sequential presentation during learning was adopted to ensure that participants could not extract any static patterns from the spatial layout of the stimuli which might have occurred in Experiments 1 and 2, forcing participants to engage in other types of spatial processing to accomplish the task (Vickery et al., 2010). Across all three experiments, Vickery et al. found that adding a concurrent visuospatial WM load had no effect on search facilitation. They concluded that the CCE is robust to any changes in WM load, stimulus type or presentation style (Vickery et al., 2010).

Manginelli et al.(2013) examined how non-spatial and spatial WM tasks might affect implicit learning. In a non-spatial WM task, participants memorized the identity of letters or colors, whereas in the spatial WM task, participants memorized the location of a number of squares. The WM task could be imposed during the initial learning phase or later testing phase while participants performed the visual search task in both learning and testing phases. Manginelli et al. (2013) reported that a concurrent spatial WM task reduced the CCE only when it was performed concurrently with visual search during the test phase. A non-spatial WM task did not affect the CCE. Manginelli et al. (2013) concluded that

WM disrupted the expression of learning during the testing phase (not the establishment of learning during the learning phase) and only for spatial WM tasks.

Using a similar paradigm to Manginelli et al. (2013), Manginelli et al. (2012) also compared how non-spatial and spatial WM tasks affect implicit learning. In this study, they found that although the CCE remained intact with a concurrent non-spatial WM task involving memorization of the identity of letters or colors, the CCE was eliminated with a concurrent spatial WM tasks that involving memorization of the location of stimulus items. Annac et al. (2013) also found a reduction of the CCE when a spatial WM task was performed concurrently with a visual search task.

Travis et al. (2013) also demonstrated that adding a concurrent spatial WM load affected the magnitude of the CCE. Travis et al. (2013) examined how differences in presentation style affected the link between the CCE and WM. Contrary to Vickery et al. (2010), who presented the WM study items sequentially and WM test items simultaneously, Travis et al. presented both the study and test items sequentially. This method required participants to compare the temporal pattern of the learned stimuli and the test stimuli, creating an additional memory load. Travis et al. argued that this sequential presentation method is one of the reasons why, unlike Vickery et al. (2010), they were able to demonstrate an interference effect of concurrent WM on the CCE.

Given the limited number of studies on this issue, it remains unclear what particular aspects of WM tasks are also involved in implicit learning as measured by the CCE. So far, studies have examined the number of items in WM, the type of WM task (non-spatial or spatial), and the presentation style (simultaneous or sequential presentation of WM items). In the present study, we address this question from yet another perspective.

Present study.

Although the evidence is limited and inconsistent, some studies (Annac et al., 2013; Manginelli et al., 2012; Travis et al., 2013) have shown that, during the establishment of contextual learning, a concurrent spatial WM task (but not a non-spatial WM task) can disrupt or reduce the CCE. This finding is understandable given that the implicit learning in the classical contextual cueing paradigm (finding a target letter T among distractor letters Ls) is basically a spatial learning task. In such a task, participants would be expected to place high weight on spatial rather than verbal representations when conceptualizing and performing the task, and thus visuo-spatial WM capacity should be more highly related than verbal WM capacity to this form of learning.

When considering only the match between task representations held in WM and representations involved in implicit learning, an important aspect of implicit learning in the contextual cueing paradigm may have been overlooked. In particular, the contextual cueing paradigm involves learning of spatial relations between items in the search array. As such, it seems possible that WM tasks requiring relational learning may be the key to producing interference with the contextual learning underlying the CCE, regardless of the visual attribute (e.g., location or color). Therefore, in this study, rather than varying the nature of the visual feature (spatial or non-spatial) that was the focus on remembering in the WM task, we focused the nature of the learning, in particular focusing on associative learning.

Associative learning involves learning the relation between two stimulus attributes such as a color and a shape (Bower, 1981). In the contextual cueing paradigm, it has been shown that observers engage in two forms of associative learning (Jiang & Wagner, 2004). At a local level they learn the relation between the target location and its adjacent distractor locations, while at a global level they learn the relation between the target location and the spatial pattern formed by all of the distractors (Jiang & Wagner, 2004). If a WM task that requires learning of relational information is conducted concurrently with the contextual cueing task, it may be that this type of relational WM task would would reduce the CCE.

In the present study, two types of WM tasks were implemented: one WM task involved no relational binding and two WM tasks involved relational binding. For the WM task involving no relational binding we used the WM task of Luck and Vogel (1997). In this task, participants are required to learn the colors of four squares, and during the WM test they are asked to indicate whether a probe square is identical in color to any one of the squares they studied. For the WM task that involved relational binding, we used two variants of WM task. The first task was a non-spatial colour–shape binding WM task. Participants were required to remember the color and shape of three items (e.g., green circle, blue square, and yellow triangle) while completing the visual search task. Afterward, they had to indicate whether a colored shape probe presented during the WM test was identical to any of the colored shapes presented at study. The second task was a spatial relational binding WM task. Participants were required to remember the location of four shapes presented simultaneously, and during the WM test they had to indicate whether the probe was identical in both shape and location to any of the objects seen at study. Note that in this task, participants must learn the pairing of shape and location for each item, but may also learn the relative spatial relations (together with the identities) between items.

We hypothesized that concurrently performing the contextual cueing task and a WM task that involved relational processing (both colour-shape binding and shape-location binding) would interfere with implicit learning. In contrast, we hypothesized that there would be no effect on contextual learning produced by a concurrent WM task that does not involve relational binding (the colour only WM task).

In our experiment, following the concurrent implicit learning and WM tasks, we also implemented a test phase in which there was no WM task. The test phase was intended to explore the possible dependence of the expression of contextual learning on the presence of concurrent WM task. If we observed no CCE during the learning phase, we would then want to know whether the WM task interfered with learning, or the expression of learning, by examining whether the CCE would occur in the test phase when the visual search task was performed on its own.

Methods

Participants. A group of 25 participants (20 females, 5 males; mean age = 19 years) took part in Experiment 1A, a different group of 24 participants (19 females, 5 males; mean age = 18 years) took part in Experiment 1B, and another different group of 23 participants (17 females, 6 males; mean age = 18 years) took part in Experiment 1C. All participants had normal or corrected- to-normal visual acuity and normal color vision. Participants gave informed consent at the outset, they were naïve as to the specific purpose of the experiment, and they were compensated with course credit. This and all subsequent experiments reported here were approved by the McMaster Research Ethics Board.

Apparatus. Stimuli were presented on a 21-inch color monitor with a display resolution of 1024 x 768 at a viewing distance of 57 cm. The experiment was generated and controlled by Experiment Builder 2.0 (Psychology Software Tools, Pittsburgh, PA).

WM stimuli[1]. In all three experiments, each WM stimulus subtended 0.6^{o} x 0.6^{o} visual angle. In Experiment 1A (Color WM task), the WM memory stimuli for each trial were four colored squares. The four squares were located directly above, below, to the left, and to the right of the fixation point, with a distance of 1^{o} of visual angle from the center of the fixation point. The color of each square was randomly generated from a total of seven possible colors including red, blue, violet, green, yellow, black and white for each trial (Luck & Vogel, 1997), whereas the four locations of the squares were consistent across the experiment. During test, participants were required to report whether a probe color square presented in the test display was the same color as one of the squares presented at study.

In Experiment 1B (Color/Shape WM task), the coloured shape stimuli were constructed by randomly selecting three colour–shape combinations. The three coloured shape stimuli were located directly above, to the left, and to the right of the fixation point, with a distance of 1° of visual angle from the center of the fixation point. The colours used were the same as Experiment 1A, and the shapes were a cross, square, circle and triangle. The color–shape combinations were randomly generated for each trial. At test, participants responded by indicating if the test probe matched the color and shape of one of the previous memory stimuli.

In Experiment 1C (Shape/Location WM task), the locations of four shapes (presented in black) were randomly selected from an imaginary 4 x 4 grid positioned in the center of the monitor. Each object had a unique identity with respect to both location and shape. At test, participants indicated whether the test probe matched one of the objects previously presented. For 50% of the trials, for test probe did not match any of the items presented at study.

Stimuli for contextual cueing paradigm. The stimuli consisted of one target letter T (rotated 90 or 270 degrees from upright), and 16 distractor letter Ls (rotated 0, 90, 180, 270 degrees from upright). The size of the letters was 0.7 x 0.7 degrees. All of the search display items were placed randomly in a cell within an invisible 6 x 8 (14 degrees x 18 degrees) matrix. There were 12 repeated or “old” and 12 novel or “new” configurations within each block. In the repeated configurations, the location, orientation, and color of the distractor Ls and the color and location of the target were repeated across blocks. The only thing that varied across blocks was the orientation of the target (90 or 270 degrees). For the new configurations, the distractor configurations varied across trials whereas the target locations were repeated across blocks. To control for location probability learning, 24 distinct target locations were selected; 12 target locations were assigned to novel configurations and the other 12 target locations were assigned to repeated configurations. The eccentricities of the two sets of targets were equivalent. The average eccentricity of targets was 5.88° for repeated configurations and 5.89° for novel configurations.

Design. In the dual task learning phase (CCE task + WM task), the experiment implemented a 2 (Context: repeated, novel) × 5 (Epoch:1–5) repeated measures design. Both factors were within-subject variables. The repeated distractor configurations were repeated once in each block, while the novel distractor configurations appeared only once in the entire experimental session.

The learning session was divided into 15 blocks, with each set of 3 blocks collapsed into an epoch, resulting in 5 epochs in the learning phase.

Following the dual task phase, there was one epoch of the search task alone (the test phase). In the test phase, to rule out the possibility of new learning, both the new scenes and old scenes were repeated across blocks. Thus, any CCE found in the test phase must constitute transfer from the learning phase. Also, by having the single CCE test phase following the dual task learning phase, we can examine whether the WM dual task procedure affected the implicit learning itself or just the expression of learning during the test phase.

The design of the three experiments was the same with the exception of the WM task used in each experiment. WM task was treated as a between-subject variable, with the color WM task used in Experiment 1A, the color–shape binding WM task used in Experiment 1B, and the shape–location binding WM task used in Experiment 1C.

Procedure. Each experimental session had three phases: a learning phase with 5 epochs of visual search trials performed under dual task conditions, a test phase with 1 epoch of visual search performed alone, and an explicit recognition phase that examined participants' ability to remember the spatial layout of visual search displays. Twelve practice trials were performed at the beginning of the experiment prior to the learning phase.

As in the study of Manginelli et al. (2013), articulatory suppression was used to rule out verbal coding of the WM stimuli. At the beginning of each trial in the learning phase, each participant was required to remember two single digit numbers and rehearse these numbers aloud until the end of the trial. The numbers were chosen randomly on each trial and no combination of two numbers repeated in any one condition.

During the learning phase, a fixation cross was presented for 1600 ms and it appeared simultaneously with onset of auditory presentation of the two numbers to be used for articulatory suppression. The WM stimuli were then presented for 800 ms. All WM stimuli were presented concurrently. Next, the visual search display appeared and remained either until the participant responded or until 10,000 ms had passed. Following auditory feedback for the visual search task, the search display disappeared. The fixation cross then appeared again for 500 ms, followed by the test probe for the WM task. The test probe remained present for 10,000 ms or until the participant made a response. Participants were instructed to respond quickly and accurately as possible, and were given visual feedback for incorrect answers on the WM task. The general stimulus sequences are illustrated in Figure 1.

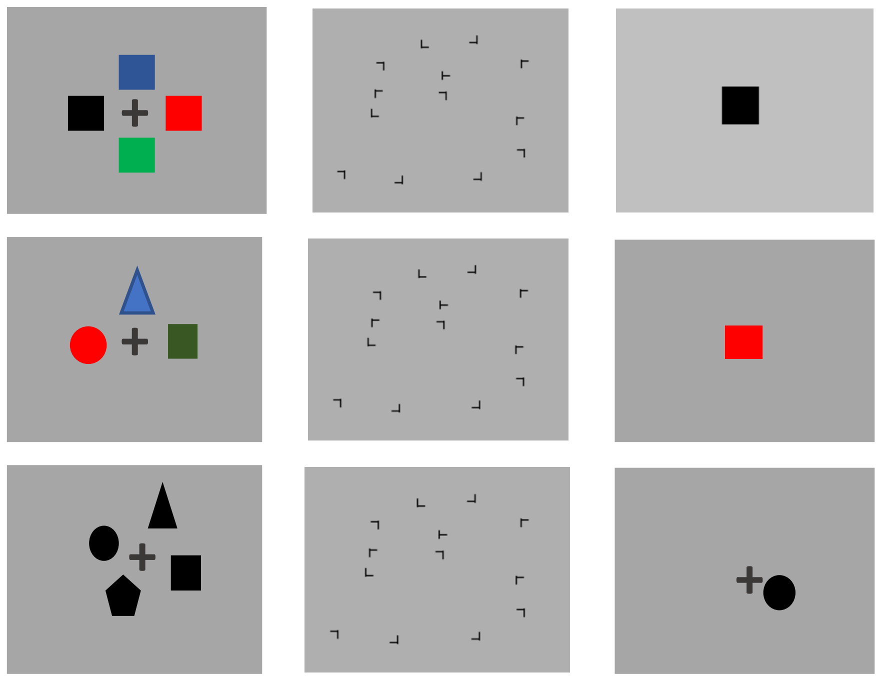

Figure 1. WM stimuli are presented in the left panel, an example of a visual search trial is presented in the middle panel, and a WM test probe is presented in the right panel. The top row depicts Experiment 1A (color WM task), the middle row depicts Experiment 1B (color/shape WM task), and the bottom row depicts Experiment 1C (shape/location WM task). Participants were required to memorize the WM stimuli, then perform the visual search task (search for the rotated target letter T and indicate whether it is tilted left or right), and then make a yes/no response for the WM test probe to indicate whether or not it was presented among the WM stimuli earlier in the trial. In the three example trials here, participants should yes, no, and no responses to the WM test probes for the top, middle, and bottom row trials.

Recognition task. Following the IL and WM tasks, all participants completed a recognition test to examine the implicit nature of the learning underlying the contextual cueing effect. Participants saw exactly the same 12 old visual search configurations and 12 brand new visual search configurations generated in the test phase. Participants responded "yes" if they thought they had seen the configuration before, and "no" if they thought they hadn't seen the configuration before. This recognition task was untimed; participants could take as long as they needed to respond.

Results

In each experiment, we excluded visual search trials in which RTs were greater than 2 standard deviations from the mean RT for each epoch of each condition separately each participant. This procedure excluded an average of 2.47% of the trials for the three experiments.

Accuracy in the WM task. The mean accuracy was 84% (SD = 0.08) for the color only task (Experiment 1A), 69% (SD = 0.10) for color/shape task (Experiment 1B), and 62% (SD = 0.08) for location/shape task (Experiment 1C).

Accuracy in the Search task. Participants were highly accurate in performing the search task. In Experiment 1A, the mean accuracy across the dual task learning and single task test phases was 99%, ranging from 96% to 100% across participants. In Experiment 1B, the mean accuracy was 98%, ranging from 96% to 100%. In Experiment 1C, the mean accuracy was 98%, ranging from 91% to 100%.

RT analysis in the search task.

Each set of three blocks was collapsed into an epoch, yielding five epochs for the learning phase and one epoch for the test phase. The mean RTs in the three experiments for both learning and testing phase are plotted in Figures 2, 3 and 4, respectively.

For Experiment 1A (see Figure 2), a repeated measures ANOVA was conducted on mean RTs from the dual task learning phase, with Configuration (old, new) and Epoch (1,5) as within-subject factors. The analysis yielded a significant main effect of configuration, $F(1, 24) = 7.81$, $p = .01$, $\eta^2 = 0.25$, indicating that RTs for old scenes were significantly faster than for new scenes. The main effect of epoch was also significant, $F(4, 96) = 6.45$, $p < .001$, $\eta^2 = 0.21$, indicating a general improvement in search time across epochs. Finally, the interaction between configuration and epoch was significant, $F(4, 96) = 2.48$, $p = .04$, $\eta^2 = 0.09$, indicating that the RT difference between new and old configurations became larger as the experiment progressed.

For the single task test phase (Epoch 6), we conducted a paired sample t-test to compare the means of old and new configurations. Indeed, there was a significant difference between old and new configurations, $t(24) = 2.670$, $p = .014$, $t(24) = 2.77$, $p = .005$, Cohen's d = 0.55. The magnitude of the CCE was 95.5 ms, indicating that the contextual cueing remained in the single task test phase.

In order to compare the dual task learning phase to the single task test phase, we conducted a repeated measures ANOVA with Configuration (old, new) and Phase (last epoch of learning phase, test phase) treated as within-subject factors. This analysis yielded a significant main effect of configuration, $F(1, 24) = 14.15$, $p < .001$, $\eta^2 = 0.37$. This result indicates that RTs for old configurations was significantly faster than for new configurations. The main effect of epoch was also significant, $F(1, 24) = 5.92$, $p = .023$, $\eta^2 = 0.20$, indicating faster search times for the single task test phase than for the dual task learning phase. The interaction between configuration and epoch was not significant, $F(1, 24) = 0.59$, $p = .45$, suggesting that the CCE was comparable for the last epoch of the learning phase and the test phase.

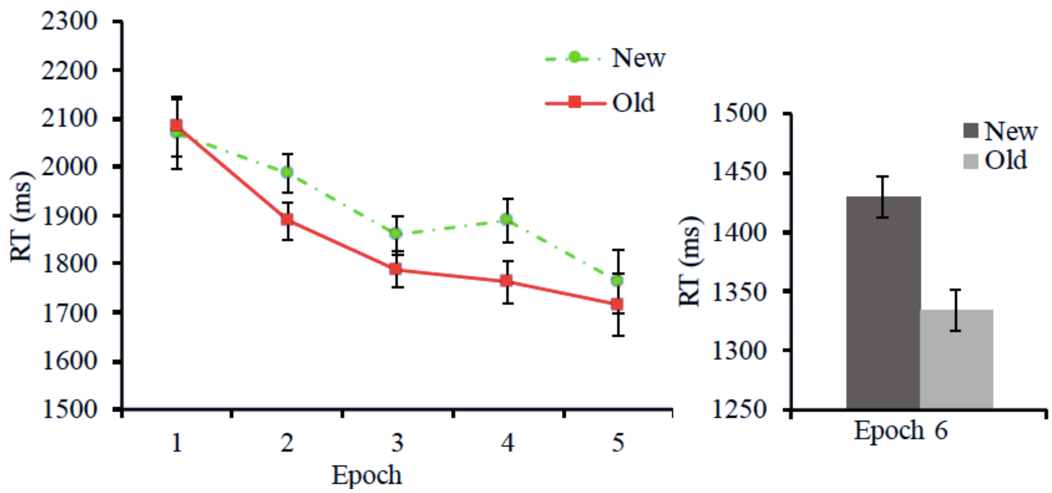

Figure 2. Mean RTs for the dual task learning phase (left panel) and single task test phase (right panel) of Experiment 1A (Colour WM task). Error bars represent standard errors corrected to remove overall between-participant variation (Morey, 2008)

For Experiment 1B (see Figure 3), a repeated measures ANOVA was conducted on mean RTs from the learning phase, with Configuration (old, new) and Epoch (1,5) treated as within-subject factors. This analysis yielded a significant main effect of configuration, $F(1, 23) = 11.11$, $p = .003$, $\eta^2 = 0.33$, indicating that RT for old configurations was significantly faster than for new configurations. The main effect of epoch was significant $F(4, 92) = 30.40$, p

< .001, $\eta^2 = 0.57$, indicating a general improvement in search speed over time. The interaction between configuration and epoch was not significant $F(4, 92) = 0.81$, $p = .51$, $\eta^2 = 0.03$. The CCE was 19 ms in epoch 1, 34 ms in epoch 2, 84 ms in epoch3, 82 ms in epoch 4 and 54 ms in epoch 5. Separate comparison between old and new configurations revealed that RTs were significantly faster for old than new configurations in epoch 3, $F(1, 23) = 8.32$, $p = .008$, and epoch 4, $F(1, 23) = 6.31$, $p = .01$, but there were no differences between old and new configurations in the other epochs, *Fs* < 2.23, *ps* > 0.1.

For the single task test phase, the paired sample t-test was significant, $t(23) = 2.67$, $p = .007$, Cohen's d = 0.55. The magnitude of the CCE was 74 ms. This significant CCE in the single task test phase indicates that the colour–shape relational binding WM task did not disrupt the contextual learning underlying the CCE.

In order to compare the dual task learning phase to the single task test phase, we conducted a repeated measures ANOVA with Configuration (old, new) and Phase (last epoch of learning phase, test phase) treated as within-subject factors. This analysis yielded a significant main effect of configuration, $F(1, 23) = 14.69$, $p < .001$, $\eta^2 = 0.39$, indicating that RTs for old configurations were significantly faster than for new configurations. The main effect of epoch was significant, $F(1, 23) = 9.54$, $p = .005$, $\eta^2 = 0.29$, indicating faster search times for the single task test phase than for the dual task learning phase. The interaction between configuration and epoch was not significant, $F(1, 23) = 0.16$, $p = .69$, suggesting that the CCE was comparable for the last epoch of the dual task learning phase and the single task test phase.

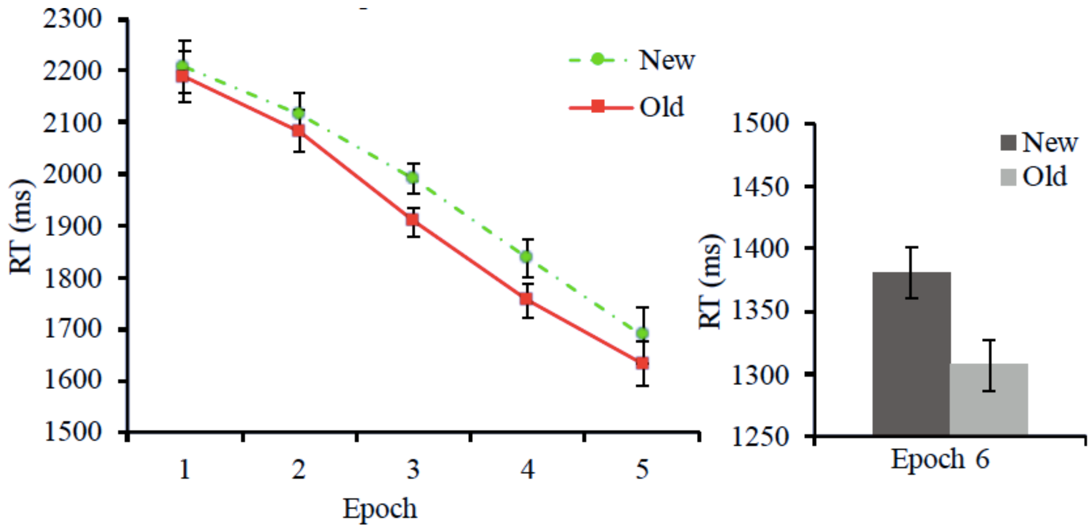

Figure 3. Mean RTs for the dual task learning phase (left panel) and the single task test phase (right panel) in Experiment 1B (colour–shape WM task). Error bars represent standard errors corrected to remove overall between-participant variation (Morey, 2008).

For Experiment 1C (see Figure 4), a repeated measure ANOVA was conducted on mean RTs from the learning phase, with Configuration (old, new) and Epoch (1,5) treated as within-subject factors. This analysis yielded a significant main effect of configuration, $F(1, 22) = 14.30$, $p = .001$, $\eta^2 = 0.39$, indicating that RTs for old configurations were significantly faster than for new configurations. The main effect of epoch was also significant $F(4, 88) = 40.58$, $p < .001$, $\eta^2 = 0.65$, indicating a general improvement in search speed over time. In addition, the interaction between epoch and configuration was significant, $F(4, 88) = 2.91$, $p = .02$, $\eta^2 = 0.12$, indicating that there was a significant CCE when the shape–location relational binding WM task was performed concurrently with the search task.

For the single task test phase, the paired sample t-test was significant, $t(22) = 3.89$, $p < .001$, Cohen's d = 0.81. The magnitude of the CCE was 84 ms. This significant CCE in the single task test phase indicates that the shape–location relational binding WM task did not disrupt the contextual learning underlying the CCE.

In order to compare the dual task learning phase to the single task test phase, we conducted a repeated measures ANOVA with Configuration (old, new) and Phase (last epoch of learning phase, test phase) treated as within-subject factors. This analysis yielded a significant main effect of configuration, $F(1, 22) = 5.83$, $p = .025$, $\eta^2 = 0.21$, indicating that RTs for old configurations was significantly faster than for new configurations. The main effect of epoch was significant, $F(1, 22) = 22.51$, $p < .001$, $\eta^2 = 0.51$, indicating faster search times for the single task test phase than for dual task learning phase. The interaction between configuration and epoch was not significant, $F(1, 22) = 0.036$, $p = .99$, suggesting that the CCE was comparable for the last epoch of the dual task learning phase and single task test phase.

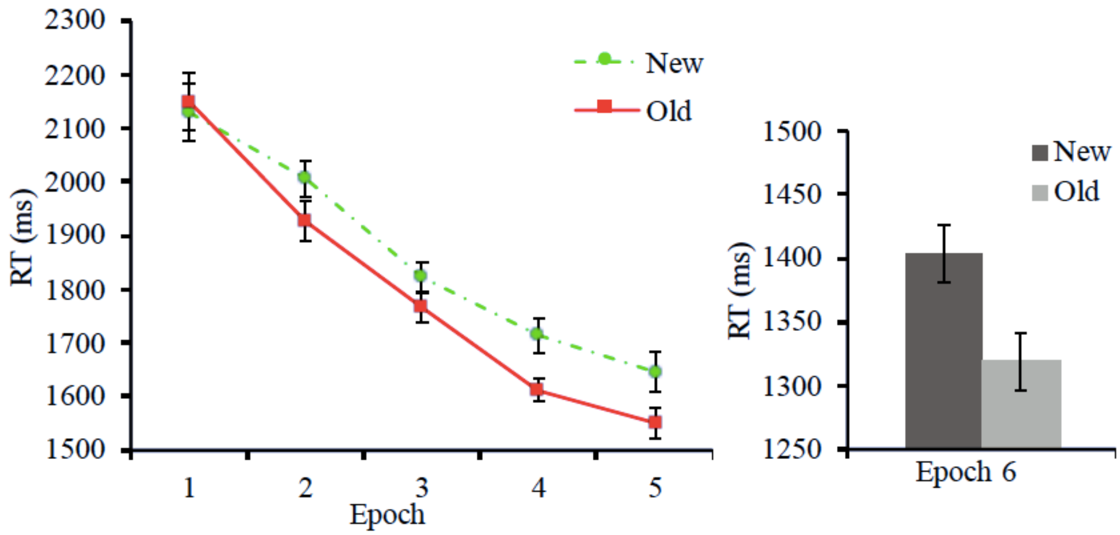

Figure 4. Mean RTs for the dual task learning phase (left panel) and the single task test phase (right panel) in Experiment 1C (location–shape WM task). Error bars represent standard errors corrected to remove overall between-participant variation (Morey, 2008).

A one-way ANOVA was then conducted to compare the CCE collapsed across the final two epochs of the dual task learning phase across the three experiments (see Figure 5). The results showed that there was no significant difference across the experiments, $F(2, 69) = 0.27$, $p = .76$, indicating that the magnitude of the CCE for the different WM tasks in the dual task learning phase was comparable across Experiment 1A (colour WM task), Experiment 1B (colour/shape WM task), and Experiment 1C (shape/location WM task).

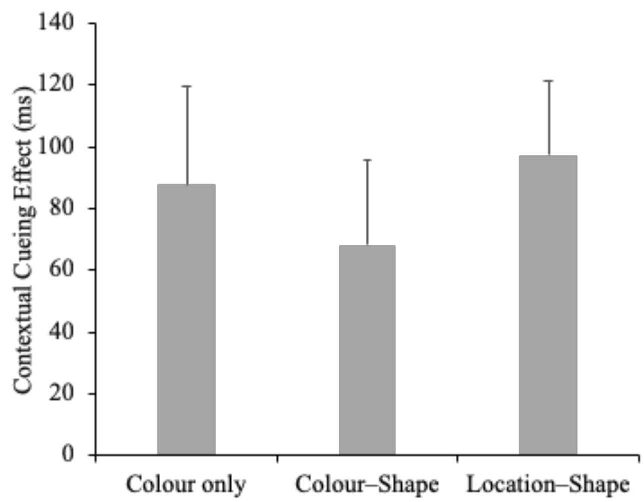

Figure 5. The contextual cueing effect (defined as the mean RT difference between novel and repeated distractor contexts for the last two epochs of the dual task phase) in Experiments 1A (Colour WM), 1B (Colour–shape WM), and 1C (shape–location WM).

Recognition test. For Experiment 1A, the probability that old displays were correctly recognized (i.e., the hit rate) was .51, and the probability that new displays were misidentified as old (i.e., the false alarm) was .46. A paired t-test indicated that this difference was not significant $t(25) = 0.29$, $p = 0.77$, suggesting that participants could not explicitly discriminate old scenes from new scenes. For Experiment 1B, the hit rate was .54, and the false alarm was .50. A paired t-test indicated that this difference was not significant $t(23) = 0.64$, $p = .52$, suggesting that participants could not explicitly discriminate old scenes from new scenes. For Experiment 1C, the hit rate was .55, and the false alarm was .45. A paired t-test indicated that this difference was not significant $t(22) = 0.19$, $p = .85$, suggesting that participants could not explicitly discriminate old scenes from new scenes.

These results indicate that the contextual cueing effect was driven by implicit memory. Similar results were found in the other two experiments.

Conclusion and Discussion

Three experiments were conducted to investigate whether performing a relational WM task concurrently with a visual search task would obstruct the contextual learning underlying the CCE. Experiment 1A was set as a control condition, in that no relational binding was involved in the colour only WM task. The results from this experiment showed that a significant CCE can indeed be observed with colour only WM task. Colour–shape binding and location–shape binding WM tasks were adopted in Experiments 1B and 1C, respectively. Again, and despite these WM tasks involving relational binding, the dual task demands did not block the occurrence of the CCE; the CCE remained significant and there was little difference in the magnitude of the CCE across the three experiments.

In the single task test phase, a significant main effect of configuration was observed in all three experiments. This result indicates that the contextual learning benefit associated with old configurations remained during the test phase. As both new and repeated configurations were repeated in the test phase, new learning from the test phase alone could not explain this result. Instead, the difference between old and new configurations must be attributed to transfer of learning from the dual task learning phase to the single task test phase.

Experiment 2

In Experiment 1 we examined whether WM is involved in the implicit learning that underlies the CCE by introducing various types of WM load during the visual search task. In Experiment 2, we took an alternative approach to examine the relation between WM and the CCE. Specifically, we examined whether individual differences in WM performance are related to the degree of contextual learning as measured by the CCE. We addressed this issue by measuring the correlation between the CCE and WM performance across participants when the CCE and WM performance were delivered sequentially rather than concurrently as in Experiment 1.

The link between WM and IL has been extensively studied in the implicit learning literature using tasks such as the serial reaction time (SRT) task (e.g., Nissen & Bullemer, 1987). The SRT task is a continuous reaction time task in which participants make responses to the location of a target item on each of a long series of trials. Unknown to the participants, the sequence of targets from one trial to the next can follow a predictable rule or can occur randomly. Decreases in RTs with practice for trials that follow a sequential rule relative to the random sequence provides evidence that learning has occurred. However, participants are typically unable to report any knowledge of the predictable sequence. The relation between implicit sequence learning and WM motivated a series of studies because it is seemed plausible that higher WM capacity would open a larger window within which a sequence might fall, thereby allowing sequence learning to be more robust.

Some studies found no relation between implicit sequence learning and WM capacity; high and low WM capacity individuals did not differ in performance on implicit sequence learning (Unsworth & Engle, 2005). Kaufman et al. (2010) also found that individual performance on a probabilistic implicit sequence learning task was not related to WM capacity as measured by Operation Span.

However, there is also evidence that WM capacity is reliably correlated with implicit sequence learning performance. For example, Bo, Jennett and Seidler (2011) found that performance on a change detection working memory task explained a significant portion of the variance in the rate of improvement in an implicit serial reaction time task. This result suggests that visual spatial WM may play a role in implicit sequence learning.

Although correlation studies that point to a possible link between implicit sequence learning and WM suggest that WM plays a role in the implicit learning of temporal order information, it remains unknown whether there is a correlation between implicit spatial learning and WM. It seems plausible that a higher level of WM capacity would open a larger spatial window, allowing spatial learning to be more robust. To the best of our knowledge, there have been no studies examining the correlation between WM performance and implicit spatial learning. Thus, Experiment 2 examined the correlation between individual differences in WM performance measured using a location change detection task and implicit spatial learning using the contextual cueing paradigm. To make the stimulus in

WM and IL tasks as comparable as possible, we used the same type of display simulating a three-dimensional space with a set of objects with different identifies positioned on the ground. Participants could take advantage of location, identity or binding of location and identify to perform the task.

We expected to find a correlation between accuracy in the location change detection WM task and the magnitude of the CCE. To measure WM performance, a change-detection paradigm involving learning of spatial layout was used. To measure the CCE, a visual search task that involved a real world scene with a random array of chairs of different identities was used. If implicit learning in visual search relies on WM capacity, then there should be a positive correlation between the magnitude of CCE (defined as RT for new scenes – RT for old scenes in the last two epochs of the visual search task) and accuracy in the WM task.

Method

Participants.

Ninety-six participants (57 females, mean age = 19.2 years) enrolled in undergraduate courses at McMaster University were recruited for this experiment. All participants had normal or corrected- to-normal vision. Participants gave informed consent at the outset, they were naïve to the specific purpose of the experiment, and they were compensated with course credit.

Apparatus and stimuli.

The stimuli were presented on a 24-inch flat screen color monitor with a resolution of 1280 x 800 and a refresh rate of 60 HZ. The viewing distance was approximately 60 cm. The experiment was programmed using Vizard 4.0 (Wordviz, 2016) software.

WM task. Using the location change detection paradigm, we presented a layout of six chairs, each subtending 1.6° x 1.6° of visual angle, on a gray background (see Figure 6). The chairs were randomly placed in an imaginary 8 x 6 grid covering approximately 32° x 26° of visual angle and centered on the black fixation point in the middle of the screen. For a typical WM trial, the fixation point was presented in the center of the display for 500 ms. Then six different chairs were presented for 800ms. Participants were required to memorize each chair's location. Then, after a six second delay, a test display was presented. Participants were required to point out which chair's location was changed and to press the corresponding number key on the keyboard.

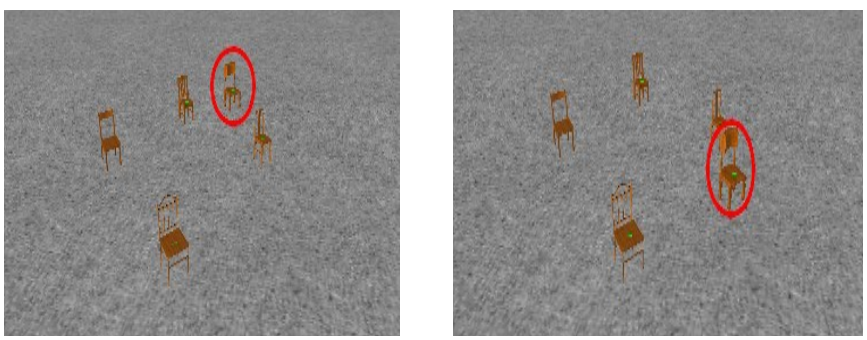

Figure 6. WM Stimuli. Example of the stimuli in the WM task. Participants were required to remember each chair's location in the left image. After a retention period of six seconds, participants were required to point out which chair's location was changed in the test display. The circle in the figure was not displayed during the actual experiment, and is presented here simply to highlight the change detection target.

Contextual cueing task. The experimental design for the implicit learning phase was adapted from the contextual cueing paradigm (Chun & Jiang, 1998). Each display contained 10 chairs. One of the chairs was deemed the target as indicated by the presence of the letter “i” (a 90 degree or 270 degree rotated “i”) on the seat of the chair, while the other 9 chairs were distractors indicated by the presence of the letter “l” on the seat of the chair (see Figure 7). The orientation of the target “i” was randomly chosen in each trial, so that the dot of the “i” pointed either to the right or to the left. The colour of all chairs was brown while the letters “i” or “l” were green. The background was always grey (RGB=128, 138, 135). Each chair subtended 1.6° x 1.6° in visual angle. The displays were generated by randomly placing chairs on an imaginary 8° x 6° grid that subtended approximately 32° x 26° of visual angle.

Figure 7. An example of visual search task stimuli.

Procedure.

The experiment consisted of two tasks that lasted a total of approximately 50 minutes. The first task was contextual cueing task, and consisted of three phases: 12 practice trials of visual search, 30 blocks of experimental trials of visual search. The second task was the WM task, and consisted of 5 practice trials and 60 test trials.

For the contextual cueing task, each block contained 8 repeated configurations and 8 novel configurations. The repeated configurations (repeated location of both target and distractor) appeared once in each block, while the novel configurations appeared only once in the whole experiment. The contextual cueing task implemented a 2 (Context: old, new) × 30 (Block:1-30) repeated measures design. Both factors (context and block) were within-subject variables. The 30 blocks were divided into 6 epochs with each epoch containing 5 blocks in length.

Results

Accuracy. Two participants were excluded from analysis because they did not complete the WM task. All participants were highly accurate in performing the visual search task, with a mean accuracy of 99%, ranging from 96% to 100%. For the WM task, the mean accuracy was 72%, ranging from 40% to 92%. Incorrect response in the visual search task as well as trials with response times shorter than 200 ms or longer than 4000 ms were discarded from the analysis. This outlier procedure led to an exclusion of an average of 1.47% of trials for each participant.

RT analysis. A two-way repeated measures ANOVA was conducted with the factors Configuration (old, new) and Epoch (1-6) as the within-subject factors. The results yielded a significant main effect of configuration, $\underline{F}(1, 93) = 107.42$.

$p < .001$, $\eta^2 = 0.54$, indicating overall faster search times for the old displays than the new displays (see Figure. 8). The main effect of epoch was also significant, $F(5, 465) = 37.08$, $p < .001$, $\eta^2 = 0.29$, indicating a general reduction of search times throughout the course of the experiment. The interaction between epoch and configuration was significant $F(5, 465) = 3.15$, $p = .008$, $\eta^2 = 0.03$, indicating that the difference between old and new displays increased across the experiment; that is, a robust CCE was observed.

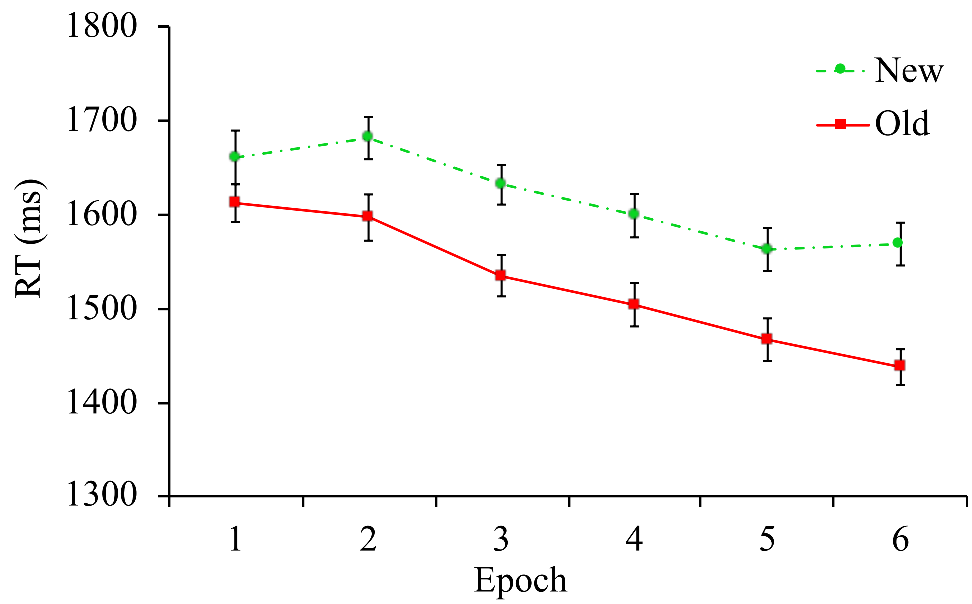

Figure 8. Mean RTs for the contextual cueing task. The search times are displayed for old and new configurations as a function of epoch. Error bars represent standard errors corrected to remove overall between-subject variation (Morey, 2008).

Correlation. The correlation between IL (i.e., the magnitude of the CCE) and WM (WM accuracy) was examined next[2]. The CCE was calculated for each participant by subtracting the old configuration mean RT from the new configuration mean RT for the last two epochs. WM performance was measured simply is accuracy in the WM task for each participant. A Pearson correlation coefficient was computed to assess the relation between the CCE and WM accuracy. The correlation between the two variables was not significant, $r = -0.14$, n = 94, $p = .17$. A scatterplot summarizes this result below (see Figure 9).

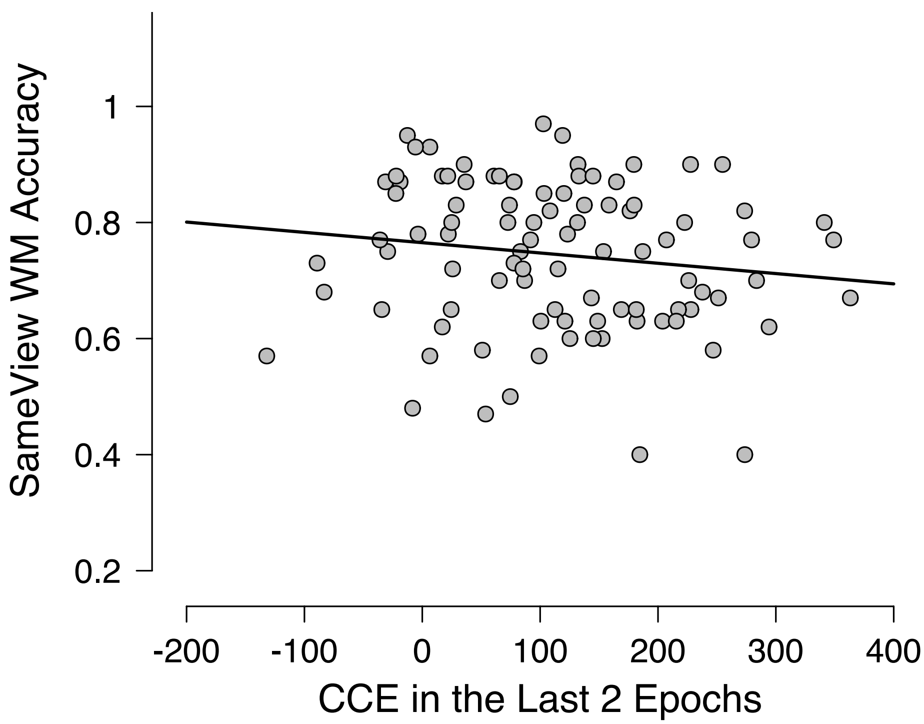

Figure 9. Correlation between the CCE and WM accuracy. The X-axis indicates the magnitude of the CCE measured in the visual search task. The Y-axis indicates accuracy in the change-detection WM task. The r value for the correlation was -0.014, $p = 0.17$.

Conclusion and Discussion

In Experiment 2, each participant performed the contextual cueing task and WM task sequentially. The correlation between the CCE and WM task accuracy was not significant. These results are in line with those observed in Experiment 1, indicating that WM may not be involved in the implicit contextual learning that drives the CCE.

General discussion

In this study, we examined the relation between IL and WM in two ways: (1) by examining whether WM would interfere with IL if a WM task and an IL task were performed concurrently; and (2) whether performance in WM task and IL tasks would be correlated across participants if the two tasks were performed separately. IL was examined in a contextual cueing paradigm in which participants gradually improve the efficiency of visual search for repeated scenes compared to novel scenes, possibly due to learning of spatial relation between target and distractor layout.

The results of the concurrent tasks showed that the CCE remained intact regardless the type of WM task; that is, whether or not the WM task involved relational binding. We also did not find a significant correlation between the magnitude of the CCE and WM task accuracy when these two tasks were performed separately. Taken together, these results suggest a lack of a relation between implicit learning and WM.

In Experiment 1, we were mainly interested in whether relational WM was involved in implicit contextual learning. Experiment 1A was regarded as a control condition because the WM task did not tap into the relational binding processes. In Experiment 1B and 1C, the WM tasks were designed to require relational processing. Participants were required to bind the color and shape for each object in Experiment 1B, and to bind the shape and location for each object in Experiment 1C. Our logic was that if implicit contextual learning involves the same resources required for relational binding in WM, then the CCE ought to be reduced when a relational binding WM task and a contextual learning task are performed concurrently.

The results from Experiment 1A involving the non-relational colour WM task paralleled the results found by Manginelli et al. (2013). We found that a robust CCE was observed. However, we also found a robust CCE when contextual cueing visual search task was performed concurrently with both of the relational WM tasks in Experiments 1B and 1C.

The reason for the absence of interference between a spatial WM task and a measure implicit contextual learning in our study is puzzling. One reason for the absence of interference is that the WM load in our study may not have been large enough produce interference. Note that we presented the WM items at study simultaneously. In contrast, Travis et al (2013) demonstrated an interference effect when presenting both the study and test WM items sequentially. They suggested that stimulus items presented simultaneously might lead to perception of an overall shape due to perceptual grouping of the items, which could in turn reduce the WM load. Indeed, the results of Travis et al (2013) also contrast to those of Verkery et al. (2010), who used a similar design but presented the study items sequentially and the test items simultaneously, and yet failed to demonstrate interference.

At the same time, sequential presentation of items in the WM task does not appear to be a necessary condition for measuring WM interference on the CCE. In three studies by Manginelli and colleagues (Annac et al, 2013; Manginelli et al 2012; Manginelli et al, 2013), simultaneous presentation of items was adopted. The three studies used essentially the same spatial WM task and stimulus parameters, and an interference effect (either a reduction or elimination of the CCE) was observed in two of the three studies. Again, however, given that three similar studies from the same lab produced inconsistent results, these studies also highlight that interference from a concurrent WM task on contextual implicit learning is not a very robust phenomenon.

Note also that in the studies of Manginelli and colleagues, participants had to identify whether the location of a test item matched the location of any item in the learning array of four objects. All of the learning array objects had the same shape and color, therefore the only dimension that could be used for WM task was location. In our study, participants had to memorize both the location and shape of four learning array objects, as participants had to identify whether a test item completely matched any of the four learning array objects. The mismatch on ‘different’ trials occurred randomly and with equal probability for the location, identity or both. Therefore, our task appears to be more challenging than that of Manginelli and colleagues, and yet we did not find an interference effect. Once again, these results suggest that interference from a concurrent WM task on contextual implicit learning is not a robust phenomenon.

It is also possible that participants in our study found an alternative way of encoding the WM stimuli that did not rely on relational processing, allowing for less interference between relational WM and implicit learning. Luria and Vogel (2011) suggested that shape and colour conjunction stimuli are represented as bound objects in visual working memory. Therefore, it is possible that participants integrated the colour and shape of each object in our colour–shape binding WM task. If this were the case, then our colour–shape binding WM task may not have provided an ideal measure of relational binding. The same explanation applies to the shape and location binding WM task in Experiment 1C. Location might be bound with shape relatively automatically, forming a temporary episodic representation that was called as object file (Kahneman, Treisman, & Gibbs, 1992). If this were the case, then location and shape may have been represented in an integrated object with little demand on relational binding resources.

The lack of interference from the WM task on the CCE could also be caused by the limited sensitivity of contextual cueing paradigm. The CCE effect can be established after only a few exposures of the repeated scenes, which may make the rate of learning hard to measure. The concurrent WM demands could influence the rate of learning rather than the final learning benefit, but this type of effect would be difficult to measure. The noise inherent in the measure of a relatively small RT effect may well overshadow any effect of WM on learning rate.

Finally, dual task interference can influence performance in either of the two tasks. Although the present study and other similar studies were primarily concerned with interference of the WM task on implicit contextual learning in visual search task, participants could have chosen to sacrifice performance in the WM task instead. In our study, to control for the factor of differential influence from different WM task on the IL task, we conducted a pilot study[1] using a different set of participants in which we created three WM tasks that were matched for difficulty. However, after introducing a concurrent visual search task in the formal experiment, we found that the concurrent visual search task had different effects on the three WM tasks. The largest reduction (15%) of WM accuracy was seen in the location–shape binding WM task while minimal reduction was seen in the other two WM tasks. Thus the same visual search task that led to implicit learning imposed different influences on the three different WM tasks. Given that none of the three concurrent WM tasks affected implicit learning performance, interference as the results of dual task was reflected on the WM task accuracies rather than the contextual cueing task. This pattern of results suggest that spatial WM resources could be involved in contextual learning. A future study could more carefully examine the interaction between the implicit contextual learning task and WM task by comparing the WM performance before and during the visual search task in the same set of participants.

In any case, given that we failed to observe interference from the WM task on the CCE, the effect is likely very small if it exists. Overall, the results of Experiment 1 suggest that a concurrent WM task does not affect the CCE. Our findings support Reber's framework which suggests that, unlike explicit learning, implicit learning is less affected by interference from tasks that draw on attention and memory (Reber, 2013). Moreover, in Experiment 2, we examined the relation between contextual learning in the CCE and WM by asking participants to perform the contextual learning task and WM task sequentially instead of concurrently. If WM contributes to implicit contextual learning, then WM performance should be highly correlated with our measure of contextual learning, the CCE. Consistent with the results of Experiment 1, the results of Experiment 2 showed that there was a very weak correlation between CCE and WM performance. Together, the results of Experiments 1 and 2 provide no evidence that WM contributes to implicit contextual learning underlying the CCE.

Conclusion

Using a concurrent WM load in Experiments 1A, 1B, and 1C, we found that WM tasks did not interfere with implicit learning as measured in the contextual cueing paradigm. We also did not find any evidence for a correlation between the CCE and WM performance. Together, our results suggest that implicit spatial learning as measured in the contextual cueing task does not rely heavily on WM, and are consistent with theoretical frameworks that predict implicit contextual learning is robust to dual task WM interference.

Footnote

1. A pilot study was conducted to test the response accuracy for three different types of WM tasks with number of remembered item varied systematically. The ultimate goal was to find a set of three types of WM task with comparable accuracy. Six participants were recruited for this pilot study. We eventually identified the three different WM tasks with accuracy 91% for the colour only (four items) WM task, 73% for the colour + shape binding (three items) WM task, 87% for the shape + location binding (four items).

2. Only if the measures of CCE and WM performance are reliable can we expect the correlation between these two measures to correlate significantly. To evaluate the reliability of the CCE across adjacent epochs, we focused on the CCE in the last and second last epochs. The correlation between these two measures was significant, $r(91) = 0.31$, $p < .01$, 95% CI = [0.16, 0.69], but modest. To evaluate the reliability of WM performance, the WM trials were split into two halves randomly for each participant, with an equal number of trials for each half. WM performance was calculated for both halves for each participant. The correlation between these two measures was significant, $r(91) = 0.59$, $p < .001$, 95% CI = [0.47, 0.84]. Together, these results demonstrate modest reliability for the CCE measure, and better reliability for the WM measure.

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Chapter 4: Using eye movements to study a selection history effect in visual search: The item-specific proportion congruent attention capture effect

Wang, C., Lapointe, M., Zhao, G., Sun H., & Milliken, B. (in review)

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Preface

The previous two chapters examined selection history in attentional control of selection using contextual cueing effect. Here, in Chapter 4, we examined another phenomenon of selection history: the Item-Specific Proportion Congruent (ISPC) attention capture effect. This ISPC effect refers to item-specific learning that controls the extent to which salient distractors capture attention. The ISPC effect is defined by a larger congruency effect for high proportion congruent (HPC) items than for low proportion congruent (LPC) items. In the context of attention capture of eye movements, the ISPC effect would be defined by the eyes moving toward a distractor with a greater likelihood in the HPC condition than in the LPC condition. Prior studies using RT measures were limited in their ability to discriminate why the ISPC effect occurs. The experiment reported in Chapter 4 examined the mechanisms that contribute to the

ISPC effect by monitoring participants' eye movements. The results are consistent with the view that item-specific learning modulates the association between task goal-related representations and perceptual representations.

Abstract

Attentional sets can be formed and bound to specific stimuli and contexts. Upon new instantiations of the stimulus or context, retrieval of the attentional set can then guide attention (Crump, Gong & Milliken, 2006). In the current study, we examined this conceptual issue by tracking eye movements that accompany the item-specific proportion congruency (ISPC) effect on attentional capture(Crump, Milliken, Leboe-McGowan, Leboe-McGowan, & Gao, 2018; Theeuwes, 1991). On congruent trials, a singleton shape target was presented amidst distractors that differed from the target in shape, but also colour. On incongruent trials, a singleton shape target again differed from all distractors in shape, but matched the colour of all distractors except one, the colour singleton distractor. We manipulated the relative proportions of congruent and incongruent trials separately for two distinct item types that were randomly intermixed, and observed a larger congruency effect for the high proportion congruent (HPC) item type. The accompanying eye movement data suggest that this ISPC effect did not occur as a result of early perceptual processes prior to the capture of overt attention by distractors, and cannot be explained entirely by increased time spent fixating distractors after the capture of attention. The results are discussed within a framework in which item-specific learning and memory can impact the activation of goal-related processes that mediate attention capture.

Introduction

It is well known that attention is attracted to perceptually salient objects. For example, imagine looking for a friend in a crowd. As you actively scan the scene, and despite knowing that your friend is short with blond hair, your attention might be captured by a person wearing a bright orange jacket. This is an example of attention being captured exogenously by a salient visual property of the scene (Posner, 1980; Theeuwes, 1991; Yantis & Jonides, 1990). The present study describes an experiment in which we measured attention capture influences on eye movements, and in particular how those ocular capture effects are influenced by item-specific learning processes. Brief descriptions of the attention capture method, and our item-specific learning and eye movement research strategies, are provided below.

Measuring Attention Capture

Theeuwes (1991) introduced a now commonly used task to measure attention capture in the laboratory. The stimulus displays contained an array of objects that varied on two dimensions, shape and colour. On critical trials, there were two singletons in the array, an odd-shape singleton and an odd-colour singleton (e.g., a red square, a green circle, and several red circles). Participants were required to search for the shape singleton (i.e., the square). Performance was slower in this condition than a control condition in which there was a shape singleton but no colour singleton. This result implies that despite searching for the odd shape participants' attention was captured by the odd colour. Subsequent studies showed that neither extensive training nor advanced cueing of the target dimension eliminated this effect (Theeuwes, 1992; Theeuwes, Reimann, & Mortier, 2006; Theeuwes & Van der Burg, 2011). Such results are consistent with the view that this attention capture effect is insensitive to top-down influences.

However, other studies suggest that such attention capture effects are indeed subject to top-down influences. Bacon and Egeth (1994) modified the method used by Theeuwes (1991) by including either multiple identical targets (Experiment 2) or multiple singleton distractors (Experiment 3). These changes were intended to make search for a singleton less useful, and to encourage participants to search instead for a target defining feature. With these changes to the search displays, attention capture by irrelevant colour singletons was eliminated. Bacon and Egeth proposed that attention capture by singleton items depends on the top-down search mode used by participants. If participants are in 'singleton search mode' (e.g., find the odd shape), they become sensitive to capture by irrelevant singletons. However, if participants are in 'feature search mode' (e.g., find the square), they are much less sensitive to capture by irrelevant singletons. In other words, the attention capture effect was modulated by the top-down search strategy of the observer (see also Folk, Remington, & Johnston, 1992).

Several additional studies have now demonstrated that an observer's search mode can influence attention capture. Leber and Egeth (2006) trained participants to use a feature search mode in a task identical to that used by Theeuwes (1991, 1992), and found that capture by the irrelevant colour singleton was eliminated. Turatto and Galfano (2001) demonstrated that prior knowledge, such as knowing that the location of an irrelevant colour singleton is negatively correlated with the target location, can override attention capture. Zehetleitner, Goschy, and Müller (2012) demonstrated that participants can learn to suppress attentional capture by an irrelevant colour singleton through extended practice. And finally, Geyer, Müller, and Krummenacher (2008) demonstrated that attention capture depends on the relative proportions of distractor and no-distractor trials within a block, with larger attention capture effects associated with a low proportion of distractor trials. Together, these findings support the idea that attention capture by singletons can be modulated by top-down factors.

Measuring Selection History Effects on Attention Capture

In addition to bottom-up perceptual salience, and top-down cognitive control, researchers have recently identified a third class of processes that can influence attention capture. Imagine searching for a friend in a crowded environment in which you customarily search for an available passing taxi. Despite the top-down goal of searching for your friend, you may find that your attention is susceptible to capture by each passing taxi. In this case, the capture of attention by passing taxis is neither strictly top-down (it is not your current goal), nor strictly bottom-up (there are many moving objects in the scene as salient as the moving taxis). Rather, the capture of attention by the taxis is a product of your having a history of selectively attending to taxis in this context in the past. Such an effect is sometimes referred to as a *selection history* effect (Awh, Belopolsky, & Theeuwes, 2012). A well known example of a selection history effect in visual search is the contextual cuing phenomenon (Chun & Jiang, 1998), and there is now a wide array of selection history effects in studies of attention (e.g., Hickey, Chelazzi, & Theeuwes, 2010; Jacoby, Lindsay, & Hessels, 2003; Maljkovic & Nakayama, 1994; Umemoto, Scolari, Vogel, & Awh, 2010; Wolfe, 2019; Wolfe, Butcher, Lee, & Hyle, 2003).

Of particular relevance here, several selection history effects on attention capture have recently been reported. For example, Cosman and Vecera (2013a, 2013b) trained participants to associate two different attentional sets with two different task-irrelevant contexts (forest vs. city). Specifically, participants were trained to use feature search mode with forest background scenes and to use singleton search mode with city background scenes. Learning of these two contexts influenced the magnitude of attention capture in a following phase, suggesting that distinct attentional sets that impact attention capture had become associated with the two background scenes.

Another selection history effect on attention capture draws on the logic of proportion congruent effects in interference tasks (Crump et al., 2018; Thomson, Willoughby, & Milliken, 2014). Crump et al. studied this issue using a modified version of Theeuwes's (1991, 1992) attention capture procedure. The critical modification was the inclusion of a congruent condition, in which the irrelevant colour singleton and the relevant shape singleton were one and the same object (e.g., a red circle displayed amidst green squares). Incongruent trials were the standard distractor trials from the procedure of Theeuwes (1991; e.g., a singleton target red circle displayed amidst red squares and a singleton distractor green square). As expected, responses were faster for congruent trials than incongruent trials. Moreover, the congruency effect was larger for a group tested with 80% congruent trials than for a group tested with 20% congruent trials. This finding is in line with the results of prior studies of both attention capture (Geyer et al., 2008), and other attention filtering effects (Logan & Zbrodoff, 1979; Lowe & Mitterer, 1982).

However, when proportion congruent is manipulated between groups, the proportion congruent effect can be attributed to top-down control over selective attention (for a review, see Bugg & Crump, 2012). Numerous recent studies have now shown that proportion congruent can also be manipulated at the level of items (Jacoby et al., 2003) or task-irrelevant contexts (Crump, Gong, & Milliken, 2006; Lehle & Hübner, 2008) that are randomly intermixed within a block of trials. These item-specific proportion congruency (ISPC) and context-specific proportion congruency (CSPC) effects cannot be attributed to top-down control of selective attention, and instead must be related to the history of association of particular items or contexts with proportion congruent. As such, ISPC and CSPC methods fit within the broader family of methods that can be used to study selection history effects on attention allocation.

To measure an ISPC effect on attention capture, high proportion congruent (HPC) trials were assigned to one item type and low proportion congruent (LPC) trials were assigned to another item type (Crump et al., 2018). For example, trials in which a singleton target square was presented among distractor circles were 80% congruent and 20% incongruent. In contrast, trials in which a singleton target circle was presented among distractor squares were 20% congruent and 80% incongruent. These two trial types were randomly intermixed, meaning that participants could not predict which of the two trial types would occur prior to stimulus onset. Consequently, participants could not engage in any top-down preparation that was different for the two trial types. Nonetheless, the congruency effect was larger for the HPC item type than for the LPC item type. This result suggests that participants learned somehow to attend differently for the two item types, and this learning resulted in more efficient filtering of the irrelevant colour singleton for the LPC item type (see also Thomson et al., 2014).

The Present Study

More efficient filtering in the attention capture ISPC effect (Crump et al., 2018; Thomson et al., 2014) has several possible interpretations. One possibility is that item-specific learning modulates the attention capture process itself.

According to this view, the singleton colour distractor draws attention with a higher likelihood for HPC items than for LPC items. This greater likelihood of misdirecting attention to the singleton colour distractor would slow performance on incongruent trials more for HPC than LPC items. Another possibility is that item-specific learning modulates processing that occurs after attention is captured by a colour singleton distractor. For example, the colour singleton distractor may be no more likely to draw attention for HPC items than for LPC items, but once captured, attention may remain longer on the colour singleton distractor for HPC than for LPC items. This longer dwell time of attention on colour singleton distractors would also slow performance on incongruent trials more for HPC than LPC items. Yet another possibility is that item-specific learning affects processes that occur prior to participants even beginning to search for the target. For example, search might well be initiated more quickly for HPC than LPC items, due to the redundant shape and color singleton signals that occur on most trials. Rapid initiation of search might well carry a cost on incongruent trials that does not occur for more deliberate initiation of search.

To date, prior studies have used only response time (RT) to measure ISPC effects on attention capture, and mean RTs for HPC and LPC conditions cannot discriminate between the accounts of the ISPC effect described above. In the present study, we used eye tracking methods to address this issue. In line with the first of the three accounts described above (see also Geyer et al., 2008), we examined whether the eyes would move toward the colour singleton distractor with a greater likelihood in the HPC condition than in the LPC condition. We refer to this as the *ocular capture* hypothesis. In line with the second of the three accounts described above (see also Geyer et al., 2008), we also examined whether the eyes would remain fixated on the colour singleton distractor longer in the HPC condition than in the LPC condition. We refer to this as the *distractor dwell time* hypothesis. As noted above, both the ocular capture and distractor dwell time hypotheses offer plausible accounts of how search processes might be affected by item-specific learning to produce the ISPC effect. The third of the three accounts described above points to processes that precede search as a potential source of the ISPC effect. In line with this idea, we examined whether there were differences in the speed with search processes were initiated for HPC and LPC items. Such a difference might occur if the speed of initiating search depends on rapid categorization of items as belong to either HPC or LPC item type. As such, we call this the *rapid categorization* hypothesis. If an item is rapidly categorized as belonging to the LPC item type, a cautious orienting strategy could follow in which overt attention shifts to an item only after substantial perceptual analysis. This cautious orienting strategy might reasonably lower the likelihood of misdirecting attention to the singleton colour distractor on LPC trials relative to HPC trials, but would also be accompanied by a slower initial shift of the eyes to an item in the periphery for LPC than for HPC trials.

Methods

Participants

Sixteen undergraduate students (7 males) at McMaster University, ranging in age from 18 to 32 years (M = 23.8, SD = 4.4), participated in the experiment in exchange for partial course credit or $15 CAD. All participants had normal colour vision and normal or corrected-to-normal visual acuity.

Apparatus and Stimuli

The experiment was conducted using a Corsair computer, which was controlled by PsychoPy2 open source experimental software (v1.85.1, Peirce, 2007, 2009). Stimuli were presented on a 24-inch BenQ LED monitor with a resolution of 1920 x 1080 pixels and a refresh rate of 60-Hz. Participants sat 57 cm from the computer monitor using a chinrest to control head movement. Manual responses were recorded using a standard keyboard. Eye movements were recorded using EyeLink II (SR Research, Canada, Version 2.31) with a 250-HZ temporal resolution and a 0.2˚ spatial resolution.

Each stimulus display consisted of six shapes spaced evenly around the border of a centrally positioned imaginary circle with a radius of 10.2˚. The same six locations were used for the shapes across trials. The shapes were circles (2.7˚ in diameter) and squares (2.2˚ in width and height) that were red or green. A white line segment (0.6˚ length and 0.1˚ width) was presented inside each shape. The target shape always contained a vertically or horizontally oriented line segment and could appear in any one of the six possible locations. The distractor shapes always contained a 45˚ right or left tilted line segment.

The target in each display was defined as the odd-shaped item, which was either a square or circle on any given trial. There were two different sets of items. For one set of items, the target was a square and the distractors were circles. For the other set of items, the target was a circle and the distractors were squares. Within each of the sets, there were congruent and incongruent displays. A congruent display contained five distractors that were consistent in colour and shape, and a target that differed on both the colour and shape dimensions. An incongruent display contained four distractors that were consistent in both colour and shape, a singleton distractor that differed from all items in colour, and a singleton target that differed from all other items in shape. Examples of congruent and incongruent displays are shown in Figure 1.

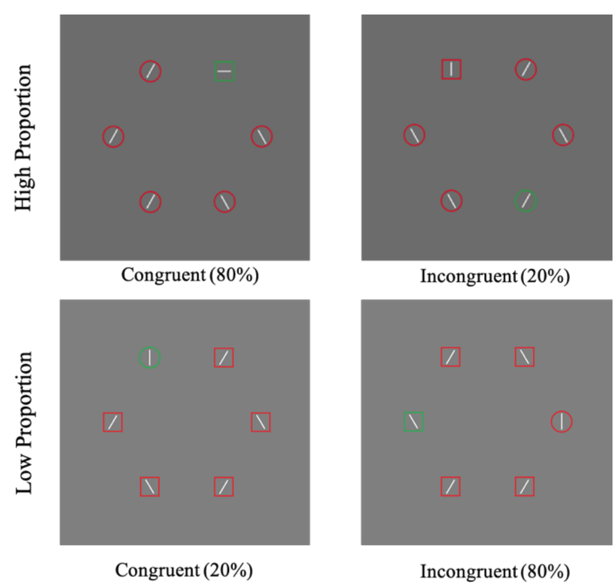

Figure 1. The top two panels display high proportion congruent (HPC) items while the bottom two panels display low proportion congruent (LPC) items. The left two panels display congruent items while the right

two panels display incongruent items.

Design

The design included two within-participant factors: congruency (congruent/incongruent) and proportion congruent (.80/.20). Proportion congruent was manipulated at the level of items. For half of the participants, proportion congruent was .80 for square singleton target items and .20 for circle singleton target items; for the other half of the participants, proportion congruent was .20 for square singleton target items and .80 for circle singleton target items. A preliminary analysis that included this counterbalancing variable as a factor did reveal several significant effects, but all of these effects could be attributed to a simple search asymmetry, with square target items producing more efficient search than circle target items (see also Crump et al., 2018). As such, we collapsed across this counterbalancing variable in all of the analyses presented below.

Procedure

Each trial began with a central dot (1˚ in diameter) for 500 ms that participants were required to fixate to initiate presentation of the search display. The search display then appeared and remained on screen until a response was made. The task for participants was to search for the odd-shaped target in each display, and then to indicate the orientation of the line segment inside the target by pressing one of two response keys. Participants pressed the 'Z' key (labeled

‘H’) for a horizontal line segment and the ‘M’ key (labeled ‘V’) for a vertical line segment. The manual response to one trial automatically triggered the next trial. Participants completed 24 practice trials, followed by four blocks of 120 experimental trials. In each block, there were 60 HPC trials and 60 LPC trials. These two item types were mixed randomly within blocks. Participants had the option of taking a short break at the end of each block of trials. In total, the experiment took approximately one hour to complete.

Results

Trials in which participants made an incorrect key response were rare, representing 3.6% of all trials. Nonetheless, mean error rates for each condition were submitted to a repeated measures analysis of variance (ANOVA) that treated congruency (congruent/incongruent) and proportion congruent (.20/.80) as within-participant factors. The analysis revealed a significant effect of congruency, F (1, 15) = 11.40, $p < 0.01$, $\eta^2 = .43$, with more errors on incongruent trials (M = 2.0%) than congruent trials (M = 1.6%). Neither the main effect of proportion congruent nor the interaction between proportion congruent and congruency reached significance (p’s > .05 in both cases). Trials on which errors were made were not analyzed further; all of the remaining analyses focused on performance for correct trials only.

Analysis of Response Times

Trials in which the RT was more than three standard deviations above or below the mean RT for that condition, and trials in which the first fixation was not aligned with the fixation dot, were excluded from analysis (a total of 8.34% of trials). Mean RTs were then calculated for each within-participant condition from the remaining observations. Mean RTs were submitted to a repeated measures ANOVA that treated congruency (congruent/incongruent) and proportion congruent (.20/.80) as factors. The analysis revealed a significant main effect of congruency, F (1,15) = 100.46, $p < .001$, $\eta^2 = .87$. Participants responded faster on congruent trials (M = 866 ms) than incongruent trials (M = 1160 ms). Of particular interest, the interaction between congruency and proportion congruent was also significant, F (1, 15) = 10.40, $p = .006$, $\eta^2 = .41$, with a larger congruency effect for HPC (M = 368 ms, $p < .001$) than LPC (M = 220 ms , $p < .001$) trials. This result constitutes a successful replication of the ISPC effect in an attention capture task (Crump et al., 2018; Thomson et al., 2014). Mean RTs for congruent and incongruent trials in the HPC and LPC conditions are displayed in Figure 2.

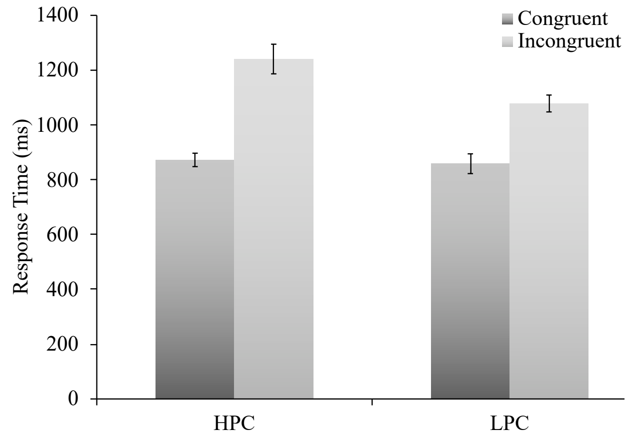

Figure 2. Mean RTs for congruent and incongruent trials in both HPC and LPC conditions. Error bars represent standard errors corrected to remove between-subject variability in overall performance (Morey, 2008).

Analysis of Eye Movement Measures

For each trial, participants were required to fixate the central dot for 500 ms to initiate presentation of the search display. For the purpose of the analyses that follow, eye movements from onset of the search display until the manual response were considered, but only on trials in which the first fixation was aligned with the centre dot at the outset of the trial.

Three phases of visual search. An open question is whether the ISPC effect in mean RT reflects an effect on search itself, or alternatively on processes that either preceded or follow search. The ocular capture and distractor dwell time hypotheses outlined above assume that the ISPC effect does reflect search processes, whereas the rapid categorization hypothesis assumes that the ISPC effect reflects processes that precede search. To address this question, we used eye movement data to divide RTs from each trial into three distinct phases of performance—early, middle, and late (Zhao et al., 2012). Zhao et al. linked these three phases to distinct cognitive processing stages. The early phase is defined as the time elapsed between the onset of the search display and initiation of the first saccade, and has been linked to perceptual processing that precedes overt search (Nakatani & Pollatsek, 2004; Rayner, 1998; Zhao et al., 2012). The middle phase is defined as the time elapsed between initiation of the first and last saccades of the trial, and has been described as the search phase of performance (Zhao et al., 2012). Finally, the late phase is defined as the time elapsed between the last fixation of the trial and the manual response, and has been described as the response selection stage of performance (Zhao et al., 2012). RTs on each trial for each participant were divided into these three components, and mean RTs were then calculated for each of the three phases in each of four critical conditions of our design. These mean RTs were submitted to separate repeated measures ANOVAs for each of the three phases. The relevant mean RTs are displayed in Figure 3.

For the early phase, the analysis revealed a significant main effect of congruency, $F(1, 15) = 7.28$, $p < .05$, $\eta^2 = .33$, indicating that initial saccade latency was longer for incongruent trials ($M = 332.2$ ms) than congruent trials ($M = 323.7$ ms). However, neither the main effect of proportion congruent, $F(1, 15) = .37$, $p = .55$, nor the interaction between congruency and proportion congruent, $F(1, 15) = .60$, $p = .45$, were significant. Together, these results indicate that the

ISPC effect does not emerge during the early perceptual phase of performance.

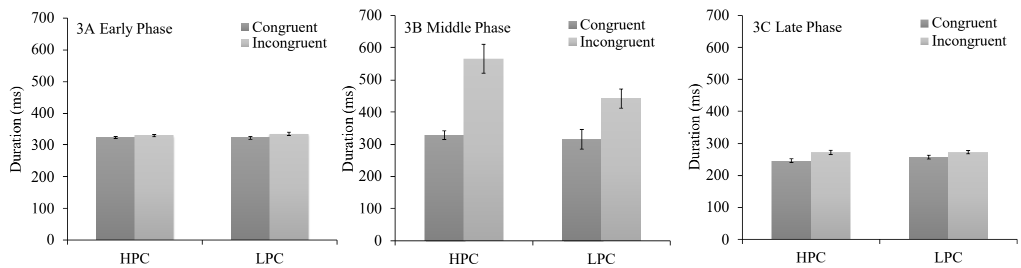

Figure 3. Mean RTs for congruent and incongruent trials in both the HPC and LPC conditions for early phase (left panel), middle phase (middle panel) and late phase (right panel) of performance. Error bars represent standard errors corrected to remove between-subject variability in overall performance (Morey, 2008).

For the middle phase, the main effect of congruency was again significant, $F\ (1, 15) = 51.33$, $p < .001$, $\eta^2 = .13$, but in this case it was qualified by a significant interaction between congruency and proportion congruent, $F\ (1, 15) = 9.75$, $p = .007$, $\eta^2 = .39$. As can be seen in Figure 3, the congruency effect was larger for HPC trials ($M = 238$ ms) than for LPC trials ($M = 126$ ms). These results indicate that the ISPC effect is clearly evident in the middle search phase of performance.

Finally, for the late phase, there was a significant main effect of congruency, $F\ (1, 15) = 8.04$, $p < .05$, $\eta^2 = .35$, indicating that response selection was longer for incongruent trials ($M = 272$ ms) than congruent trials ($M = 252$ ms). However, neither the main effect of proportion congruent, $F\ (1, 15) = 1.13$, $p = .30$, nor the interaction between congruency and proportion congruent were significant, $F\ (1, 15) = 1.13$, $p = .30$. This result indicates that the ISPC effect is not evident during the late response selection phase of performance.

Taken together, these findings point to two conclusions. First, the congruency effect occurs in each of the three phases of task performance. That is, participants were faster to process the display perceptually, search the display, and select a response on congruent trials than incongruent trials. More important, the ISPC effect—a larger congruency effect for HPC than LPC trials—emerged only during the search (i.e., middle) phase of performance. This result is inconsistent with one of the three hypotheses outlined above. According to the rapid categorization hypothesis, an ISPC effect could have resulted from rapid categorization of item type (HPC vs LPC), and consequent differences in the speed of initiation of attention shifts for the HPC and LPC item types. Clearly, there was no evidence for this hypothesis; neither the main effect of proportion congruent nor the interaction between congruency and proportion congruent were significant in the early phase analysis. The presence of an ISPC effect for the middle search phase points instead to the ocular capture and distractor dwell time hypotheses, both of which point to search itself as the locus of the ISPC effect. We turned next to eye movement analyses that focused on this middle search phase.

Scan path – First saccade. The ISPC effect emerged during the middle search phase of performance, but it is unclear when during the search phase this effect emerges. We examined this issue initially by analyzing data from the first saccade. If ocular capture is stronger for the singleton colour distractor in the HPC condition than in the LPC condition right from stimulus onset, then the first saccade ought to shift in the direction of the colour singleton distractor with higher likelihood for HPC than LPC trials.

Figure 4 shows density plots for the angular deviation of the first saccade from a linear path between the central fixation dot and the target. Each of the six plots in both rows of Figure 4 show one possible position of the distractor relative to the target, with the left most plot depicting saccade directions relative to the target when the distractor was 60° from the target, the next plot depicting saccade directions relative to the target when the distractor was $120^{\circ}$from the target, and so on. Bin size for the plots in Figure 4 is 10°, with 36 bins ranging from from 0° to 360°. For both the HPC and LPC conditions, when the colour singleton and shape singleton were the same object (congruent trials), the eyes tended to move directly to the target object (Figure 4; upper and lower far right plot). In contrast, when the colour singleton and shape singleton were different objects (incongruent trials), the eyes often shifted in the direction of the colour singleton distractor. Even when the colour singleton appeared at a location exactly opposite the target (180°), the eyes often shifted in the direction of the colour singleton.

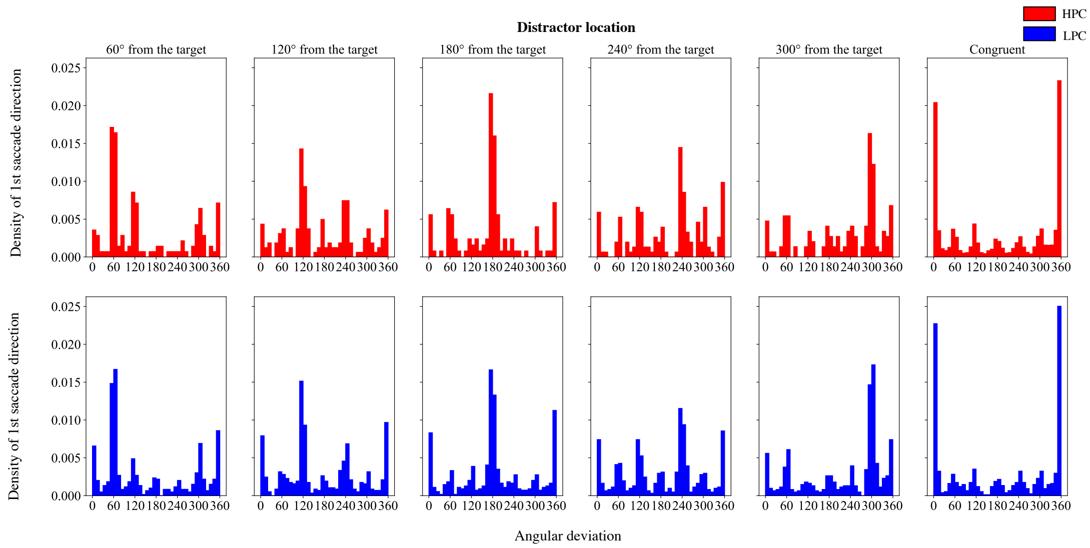

Figure 4. The effect of the colour singleton distractor on the scan path of the eyes for the initial saccade of a trial. The x-axis represents the angle of deviation of the first saccade from a linear path between the central fixation dot and the target object. The y-axis represents the density of first saccade direction. The top (red) and bottom (blue) panels show the results for the HPC and LPC conditions, respectively. The panels from left to right represent the location of the colour singleton relative to the location of the target object (60˚, 120˚, 180˚, 240˚, 300˚, 0˚/360˚).

We conducted two analyses of the data in Figure 4, one that examined the direction of the first saccade with respect to the colour singleton distractor and the other that examined the direction of the first saccade with respect to the shape singleton target. The density values in Figure 4 were converted to percentages by multiplying the height of each bar first by the bin size of 10, and then by 100. Percentages of first saccades that were directed toward either the colour singleton distractor or shape singleton target when the colour singleton distractor appeared 60°, 120°, 180° from the shape singleton target were computed by summing the percentages that corresponded to the four 10° bins that were centered on each of 60°, 120°, 180°. For example, for the 60°condition, all first saccades that fell in the four bins from 40° to 80° counted. Data from the 240° and 300° conditions in Figure 4 were combined with those from the 120° and 60° conditions, respectively, so that absolute angular deviation between the colour singleton distractor and shape singleton target served as an independent variable in the analyses.

The mean percentages of trials in which initial saccades were directed towards the colour singleton distractor for each absolute angular difference between distractor and target position (60°, 120°, 180°) in both the HPC and LPC conditions are displayed in Figure 5A, whereas the corresponding data for initial saccades directed towards the shape singleton target are displayed in Figure 5B. These data were submitted to separate repeated measures ANOVAs that treated proportion congruent and distractor position relative to target as variables.

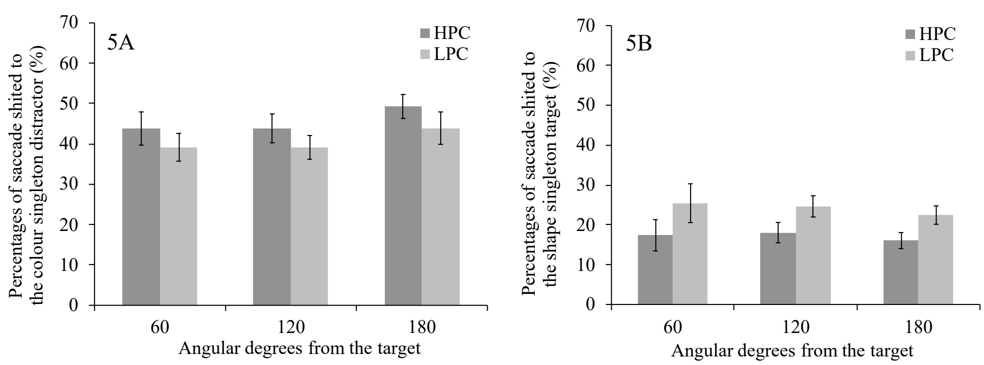

Figure 5. For each of HPC and LPC conditions, the percentages of first saccades captured by the colour singleton distractor (**5A**) or directed toward the target (**5B**) on incongruent trials when the angle between target and colour singleton distractor was 60°, 120°, or 180°.

In the analysis of first saccades directed toward colour singleton distractors, there was a significant main effect of proportion congruent, F (1, 15) = 7.05, p = .02, η^2 = .32. First saccades toward the colour singleton distractor occurred more often in the HPC condition (M = 45.7%) than in the LPC condition (M = 40.7%). Neither the main effect of distractor position, F (2, 30) = 2.34, p = .11, η^2 = .14, nor the interaction of proportion congruent and distractor position, F (2, 30) = .01, p = .99, η^2 = .001, were significant (see Figure 5A).

In the analysis of first saccades directed to shape singleton targets, there was also a significant main effect of proportion congruent, F (1, 15) = 6.28, p = .02, η^2 = .30. First saccades to the shape singleton target occurred more often in the LPC condition (24.2%) than in the HPC condition (17.2%). Neither the main effect of distractor position, F (2, 30) = 0.41, p = 0.67, η^2 = .03, nor the interaction between proportion congruent and distractor position, F (2, 30) = 0.08, p = 0.93, η^2 = .01, were significant (see Figure 5B).

Taken together, these results indicate that visual search differed for the HPC and LPC trials in a manner that influenced the initial saccade; that is, initial saccades were more likely to shift toward distractors and less likely to shift toward targets for HPC trials than for LPC trials. The fact that such an effect was found for initial saccades is noteworthy in that it indicates that visual search differs for HPC and LPC trials relatively early in the visual search process. In the following section, we describe analyses that examined corresponding effects for following saccades.

Scan path – Successive saccades. Figure 6A represents mean percentages of incongruent trials in each of the HPC and LPC conditions in which the first, second, third, fourth, and fifth saccades were directed towards the colour singleton distractor, computed in the same manner as for the above analysis of first fixation data[1], but collapsed across the three absolute angular deviations between distractor and target (60°, 120°, 180°). These means were submitted to a repeated measures ANOVA that treated saccade serial position (first, second, third, fourth, fifth) and proportion congruent (high, low) as within-participant factors. The analysis revealed a significant main effect of saccade serial position, F (4, 60) = 65.66, $p < .001$, $\eta^2 = .81$. The percentage of trials in which the colour singleton distractor was fixated decreased from the first saccade (M = 43.2%) to the fifth saccade (M = 4.8%). The main effect of proportion congruent was also significant, F (1, 15) = 11.84, $p = .004$, $\eta^2 = .44$, but was qualified by a significant interaction between saccade serial position and proportion congruent, F (4, 60) = 7.97, p < .001, $\eta^2 = .35$. An analysis of the simple effects revealed that the eyes were significantly more likely to move toward the colour singleton in the HPC condition than in the LPC condition for the first saccade, F (1, 15) = 7.05, $p = .01$, and the second saccade, $F(1, 15) = 26.99$, $p < .001$, but not for the third, fourth, and fifth saccades (Fs < 2.1, ps > 0.1 in each case).

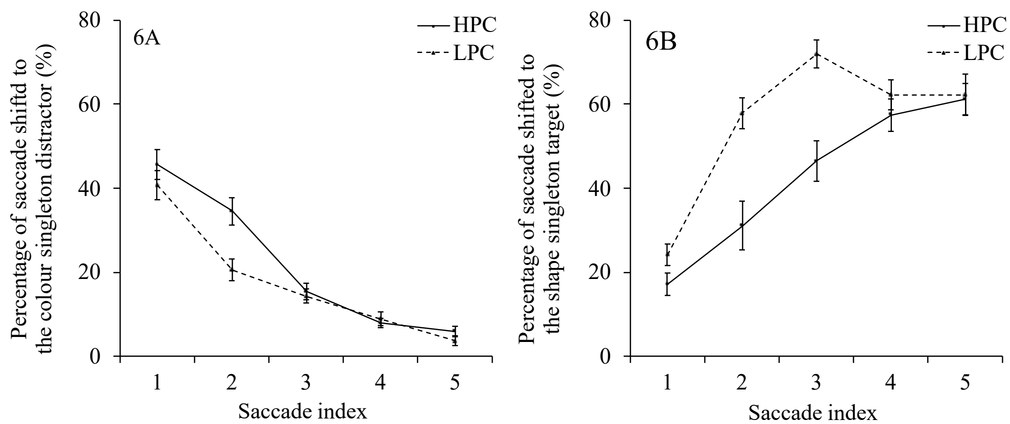

Figure 6. For each of the HPC and LPC conditions, percentage of trials in which eye movements toward the colour singleton distractor (**6A**) or target (**6B**) for the first, second, third, fourth, and fifth saccades.

The mean percentages of incongruent trials in which the first, second, third, fourth and fifth saccades were directed to the shape singleton target, rather than the colour singleton distractor, for both the HPC and LPC conditions are presented in Figure 6B. These means were submitted to a repeated measures ANOVA that treated saccade serial position (first, second, third, fourth, and fifth) and proportion congruent (high, low) as within-participant factors. The main effect of saccade serial position was significant, F (4, 60) = 33.28, $p < .001$, $\eta^2 = .69$. The percentage of trials in which a saccade was directed toward the target generally increased from the first saccade (M = 22.7%) to the fifth saccade (M = 61.8%). The main effect of proportion congruent was also significant, F (1, 15) = 20.36, $p < .001$, $\eta^2 = .58$, with a higher percentage of trials in which saccades were directed toward the target in the LPC condition (M = 55.7%) than in the HPC condition (M = 42.7%). Importantly, the interaction between saccade serial position and proportion congruent was significant, F (4, 60) = 5.99, $p < .002$, η^2

= .29. The data in Figure 6B show clearly that the percentage of trials in which saccades were directed toward the target increased at a faster rate from the first saccade to the third saccade for the LPC condition than for the HPC condition. An analysis of simple effects revealed a higher percentage of trials with saccades to the target for LPC than HPC trials for the first saccade, $F(1, 15) = 6.28, p = .02$, the second saccade, $F(1, 15) = 23.76, p < .001$, and the third saccade, $F(1, 15) = 19.39, p < .001$, but not for the fourth or fifth saccades (Fs < 0.76, ps > 0.4 in both cases).

Together, these results provide compelling evidence for the ocular capture hypothesis, according to which the colour singleton distractor pulls attention to its location more strongly for the HPC condition than for the LPC condition. This effect is present in initial saccades toward distractors (see Figure 5A), and also implied by the opposite pattern in initial saccades toward targets (see Figure 5B). Both effects are even more pronounced for the second saccade (see Figures 6A and 6B). Clearly, there is strong evidence in the eye movement data that differential ocular capture for HPC and LPC trials contributes to the ISPC effect.

Distractor Dwell Time and the ISPC effect. The results described above are consistent with the ocular capture hypothesis, that item-specific learning and memory influences the capture of overt attention by salient distractors. Next, we assessed whether differences in the dwell time of fixations on colour singleton distractors also contribute to the ISPC effect. To examine this issue, we divided the incongruent trials into two categories: (1) trials in which the colour singleton distractor was never fixated (26% of HPC incongruent trials and 35% of LPC incongruent trials); and (2) trials in which the colour singleton distractor was fixated (74% of HPC incongruent trials and 65% of LPC incongruent trials). The mean RTs for these two types of incongruent trials, together with those for congruent trials, are presented in Figures 7A and 7B.

Three results in Figures 7A and 7B are noteworthy. First, RTs are much slower on incongruent trials in which the colour singleton distractor was fixated (1288 ms) than on incongruent trials in which the colour singleton distractor was not fixated (908 ms).[2] Second, the proportion of incongruent trials in which the eyes were captured by the colour singleton distractor was higher in the HPC than LPC condition.[3] Third, and most important, RTs were 149 ms longer for HPC incongruent trials in which a saccade was made to the colour singleton (M = 1362 ms) than for LPC trials in which a saccade was made to the colour singleton (M = 1213 ms). This third point is critical; it shows that at least part of the ISPC effect owes to something other than whether or not the eyes were captured by the colour singleton distractor—the ISPC effect occurs when one considers only trials in which the eyes were captured by the color distractor for both the HPC and LPC conditions.

One possible explanation for this result is that the eyes may have remained fixated on the colour singleton distractor longer on HPC than LPC trials. To address this issue, we computed the number of saccades per trial that landed specifically on the colour singleton distractor (Figure 7C, right) and the mean fixation duration per saccade on the colour singleton distractor (Figure 7D, left), and multiplied these two values to get the mean total duration spent fixating the colour singleton distractor (Figure 7D, right). On trials in which participants fixated the colour singleton distractor, the eyes were fixated on that colour singleton 70 ms longer per trial for the HPC condition (304 ms) than for the LPC condition (234 ms).

This 70 ms difference accounts for less than half of the 149 ms difference in mean RTs depicted in Figures 7A and 7B. As such, although a longer dwell time on the colour singleton distractor in the HPC condition accounts for some of the ISPC effect, some other factor must also contribute to the ISPC effect. The fixation data in Figure 7C also point to this idea. Note that the difference in total number of saccades on trials in which the colour singleton distractor was fixated was larger in the HPC condition ($M = 5.42$) than the LPC condition ($M = 4.75$). The corresponding difference in saccades that landed on the colour singleton distractor was much smaller in magnitude ($M = 1.4$ for HPC; $M = 1.2$ for LPC). In other words, additional saccades were generated in the HPC condition relative to the LPC condition that were directed to locations other than the colour singleton distractor. This result is consistent with the idea that control over search that directs fixations to the shape singleton is generally weaker in the HPC condition than in the LPC condition, which leaves attention susceptible to capture by the colour singleton distractor but to capture by other distractors as well.

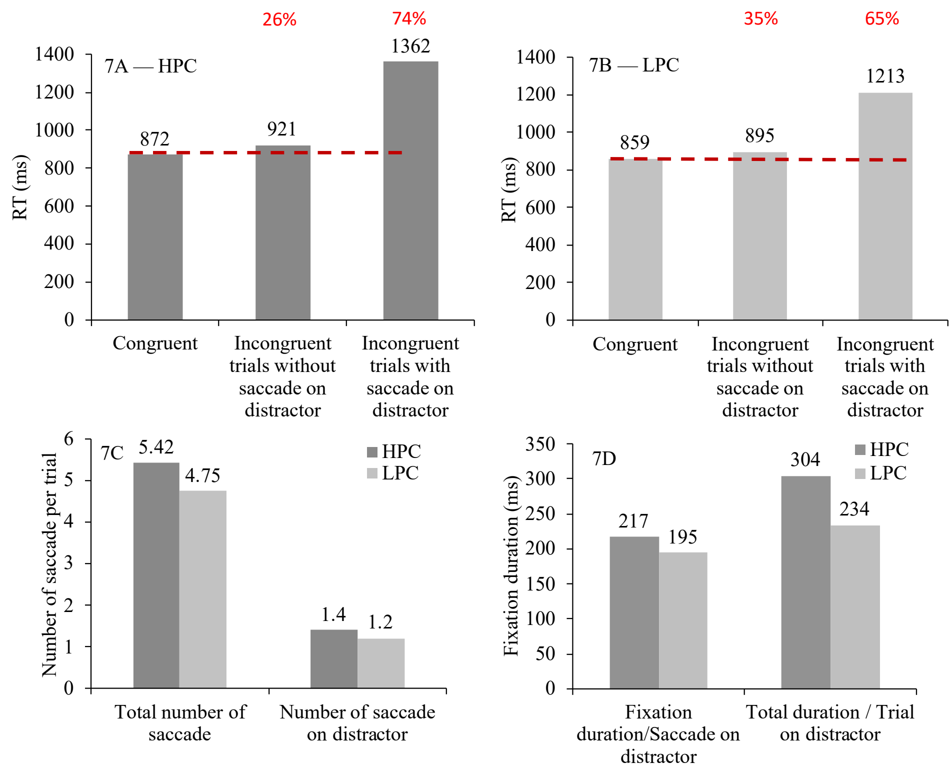

Figure 7. Analysis of the ISPC effect in terms of saccade frequency and duration on trials. Figures 7A and 7B display mean RTs for congruent trials, and incongruent trials with and without capture by the colour singleton distractor. Figure 7C shows total number of saccades, and number of saccades on the color distractor for incongruent trials in which capture by the colour singleton did occur. Figure 7D shows the mean fixation duration per saccade and mean total fixation duration per trial on distractors for trials with capture by the colour singleton.

In summary, in accord with the distractor dwell time hypothesis, more time was indeed spent fixating colour singleton distractors in the HPC condition than in the LPC condition. This result implies that the ocular capture hypothesis on its own does not offer a complete explanation of the ISPC effect. At the same time, the longer dwell time on colour singleton distractors for HPC than LPC trials accounts for less than half of the 149 ms difference between HPC and LPC trials in which colour singleton distractors were fixated. As such, the distractor dwell time hypothesis also fails to offer a complete explanation of the ISPC effect. A theoretical proposal that integrates these findings is offered in the General Discussion.

General Discussion

In the present study, we examined the ISPC effect in attention capture (Crump et al., 2018; Theeuwes, 1991, 1992; Thomson et al., 2014). Our specific goal was to study the mechanisms that contribute to the ISPC effect by monitoring participants' eye movements. The overall RTs replicated the ISPC effect in attention capture reported in earlier studies; the congruency effect was larger for HPC trials than LPC trials (Crump et al., 2018; Thomson et al., 2014). Using eye movement measures to carve RT into three phases of performance, we found that the ISPC effect occurs for the middle search phase, and not for either the early perceptual phase or for the late response selection phase. Eye movement measures also showed that participants were more likely to shift their eyes toward the colour singleton distractor for HPC trials than LPC trials on the first saccade, and even on the second saccade (Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999). Participants were also more likely to shift their eyes to the shape singleton target for LPC trials than HPC trials on the first, second, and third saccades. On incongruent trials that did result in a shift of the eyes to the colour singleton distractor, the time spent fixating the colour distractor was 70 ms longer for HPC than LPC trials. However, this 70 ms of additional dwell time on distractors accounted for less than half of the 149 ms RT difference between HPC and LPC trials.

The ISPC Effect: Attention Capture or Distractor Dwell Time?

These results allow us to evaluate the three hypotheses for the ISPC effect put forward at the outset of this article. First, there is little evidence for the rapid categorization hypothesis, as there was no difference in performance between HPC and LPC items in the early perceptual phase, and no hint of an ISPC effect in this measure. Importantly, the ISPC effect was limited to the middle search phase of performance. This result is noteworthy as it the first demonstration of an ISPC effect measured in overt shifts of the eyes. Second, there was strong evidence for the ocular capture hypothesis. The eyes shifted towards the colour singleton distractor more often on HPC than LPC trials, and toward the shape singleton target more on LPC than HPC trials. These effects were present in the first saccade and increased in size for the second saccade. The proportion of trials in which a fixation landed on the colour singleton distractor was also larger for HPC than LPC trials. Together, these results are consistent with the idea that the colour singleton exerted a stronger pull on overt attention for HPC than for LPC trials. Third, there was also strong evidence for the distractor dwell time hypothesis. Focusing only on trials in which the eyes did shift to the colour singleton distractor, the eyes remained fixated on the colour singleton 70 ms longer for HPC than LPC trials. This result suggests that colour singleton distractors not only exerted stronger ocular capture for HPC than LPC trials, but they also elicited longer fixation dwell times following ocular capture for HPC than LPC trials.

One interpretation of these results is that item-specific learning affects at least two processes that contribute to the ISPC effect, one that influences ocular capture and another that influences the dwell time of the eyes on salient distractors. However, we favour an alternative theoretical approach in which both of these results are accommodated in a single framework that focuses on links between item-specific learning, goal-driven attention processes, and attention capture.

Item-specific goal learning and control of attention capture

We propose an item-specific goal learning and control account of the results of the present study. Fundamental to this account is the idea that attention capture is mediated by goal-driven attentional control settings (Folk et al., 1992). The goal of participants in the present study was to attend to the shape singleton target, and we assume that the strength of attention capture from the colour singleton target varied inversely with the strength of this goal-related representation. Whereas prior studies examining this issue have focused on attentional control settings defined by a priori task demands (Folk et al., 1992), the ISPC effect studied here constitutes an attention capture effect that varies across conditions despite a priori task demands being constant across conditions. For the ISPC effect to be explained by reference to attentional control settings, those control settings must vary after search display onset, and in accord with item-specific prior experience that differentiates the HPC and LPC items.

To understand how this might occur, consider that finding a singleton shape target on HPC trials does not depend critically on an active task goal representation (i.e., attend to the shape singleton target). This is the case simply because the shape singleton target can often be found on HPC trials by relying on the signal from the salient colour singleton. As a consequence, the task goal representation (attend to the shape singleton target) and the perceptual representation of HPC items are often not co-active. Following the Hebbian learning principle that co-active representations increase the strength of association between those representations, it follows that the association between the task goal representation and HPC perceptual representations tend not to be strengthened over the course of the experiment (see also Verguts & Notebaert, 2008). In contrast, finding the shape singleton target on LPC trials does depend critically on an active task goal representation, as the colour singleton distractors usually lead attention astray. As a result, the task goal representation and the perceptual representation of LPC items are often co-active, and tend to be strengthened over the course of the experiment.

Now, given the different association strengths between the task goal representation and the perceptual representations of HPC and LPC items, we assume that onset of HPC and LPC items results in different on-line re-activation of the task goal representation. Specifically, onset of LPC items will result in a higher strength of on-line re-activation of the task goal representation than is the case for HPC items. Strong re-activation of the task goal representation for LPC trials counters attention capture by the colour singleton distractor, whereas weak re-activation of the task goal representation for HPC trials fails to counter attention capture by the colour singleton distractor, which together produce the ISPC attention capture effect.

The item-specific goal learning and control account offered here can account for all of the eye tracking results described in the present study. The tendency to fixate the colour singleton distractor more for HPC than LPC items, and to fixate the shape singleton target more for LPC than HPC items, both follow directly from the idea that attention capture depends on activation of the task goal representation (attend to the singleton shape), and on-line re-activation of the task goal representation is weaker for HPC than LPC items. The longer dwell time of fixations on the singleton colour distractor for incongruent HPC than incongruent LPC items also follows from weaker on-line activation of the task goal for HPC items—weak activation of the task goal works counter to the required re-orientation of attention from where it is (oriented to the singleton colour) to where it should be (oriented to the singleton shape). Finally, the higher number of overall (non-singleton distractor) fixations for incongruent HPC items than for incongruent LPC items also fits with the idea that re-activation of the task goal representation is weaker for HPC than for LPC items.

Conclusion

In the present study, the ISPC attention capture effect was observed in RTs, and for the first time in eye movements of participants. This effect was reflected in a greater likelihood of eye movements toward the colour singleton distractor on HPC than LPC trials, a greater likelihood of eye movements toward the shape singleton target on LPC than HPC trials, and longer dwell times for fixations on colour singleton distractors of HPC than LPC trials. All of these findings fit the idea that attention capture depends on activation of goal-related representations, and that activation of goal-related representations differs for the two item types. We have proposed that this differential activation of goal-related representations results from item-specific learning processes that strengthen the link between goal representations and LPC items and/or weaken the link between goal representations and HPC items. All told, the present study demonstrates how item-specific learning and memory processes can involuntarily modulate control over attention capture.

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Footnotes

[1] Percentages are based on all trials within each of the HPC and LPC conditions with at least n saccades, where n is the saccade index for that condition. For example, the relevant data for saccade index 3 are the percentages of HPC and LPC trials in which at least three saccades were made and the third saccade shifted toward the target.

[2] Two ANOVAs were conducted to confirm that the ISPC effect was driven primarily by performance for incongruent trials on which the eyes fixated the colour singleton distractor. In the first analysis, mean RTs were submitted to a repeated measures ANOVA that treated trial type (Congruent, Incongruent without saccade on distractor) and proportion congruent (HPC, LPC) as within-participant factors. This analysis revealed no significant effects. In a second analysis, mean RTs were submitted to a repeated measures ANOVA that treated trials type (Congruent, Incongruent with saccade on distractor) and proportion congruent (HPC, LPC) as within-participant factors. The analysis revealed a significant main effect of trial type, $F\ (1, 15) = 130.33, p < 0.001, \eta^2 = .89$, with slower RTs for incongruent than congruent trials. More important, there was a significant interaction between trial type and proportion congruent, $F\ (1, 15) = 6.04, p = .027, \eta^2 = .29$, with a larger congruency effect for HPC trials ($M = 490$ ms) than for LPC trials ($M = 354$ ms). Together, these results demonstrate that the ISPC effect was driven by incongruent trials in which participants made a saccade to the colour singleton distractor.

[3] In principle, this difference in trial proportions itself could produce an ISPC effect. However, the contribution of these trial proportions to the ISPC effect reported here was actually quite small, with the effect instead driven by the difference between the HPC and LPC conditions in RT for incongruent trials in which a saccade was made to the colour singleton distractor (149 ms; see Figures 7A and 7B).

Chapter 5: General Discussion

A typical visual context contains more information than we can process at one time. The human visual system therefore requires an attention system that selects relevant visual information for further processing while ignoring the remaining information. Traditionally, visual selective attention has been considered to be driven either by voluntary, top-down processes that select goal-relevant information or by automatic, bottom-up processes that select particularly salient stimulus features (Buschman & Miller, 2007; Corbetta & Shulman, 2002; Theeuwes & Belopolsky, 2010). However, this dichotomous theoretical framework fails to explain a growing amount of empirical evidence in which visual selection can be accounted for neither by observers' current goals nor by physical salient visual features. To address this issue, it has been suggested that selection history be identified a third class of processes affecting attentional selection (Awh, Belopolsky, & Theeuwes, 2012; Kim & Anderson, 2019; Theeuwes, 2019). On the one hand, although selection history effects appear to be involuntary, they can mediate the influence of bottom-up, stimulus-driven selection influences (Crump, Milliken, Leboe-McGowan, Leboe-McGowan, & Gao, 2018; Jacoby, Lindsay, & Hessels, 2003; Thomson, Willoughby, & Milliken, 2014). On the other hand, although selection history constitutes a form of 'control' over bottom-up selection, selection history effects can work either for or against observers' current intentional goals (Anderson, Laurent, & Yantis, 2011; Kim & Anderson, 2019). As such, it seems clear that selection history processes are distinct from both the bottom-up and top-down selection processes that have predominated in theoretical discussions of attentional selection for many years, and should be regarded as a third class of processes affecting selection attention.

This thesis examined two attentional effects thought to tap into selection history processes. One such effect is contextual cueing (Chun & Jiang, 1998). The experiments in Chapters 2 and 3 examine whether selection history processes responsible for the contextual cueing effect depend on a one to one associative learning between a repeated distractor context and target, and whether relational working memory is involved in implicit learning that drives the contextual cueing effect. The second selection history effect studied here is the item-specific proportion congruent attention capture effect. The experiment described in Chapter 4 addressed how selection history mediates attention capture effects by tracking observers' eye movements.

Beyond One-to-One Associative Learning in the Contextual Cueing Effect

One of the debates over the mechanism responsible for the CCE focuses on whether it reflects facilitation of attentional guidance or facilitation of response selection. According to an associative learning account, participants learn an association between a repeated distractor context and target location, resulting in attention being directed to the target location when observers encounter the same distractor context again (Brady & Chun, 2007; Chun & Jiang, 1998). Moreover, participants appear to learn not just distractor–target associations but also associations among distractors within the search context (Beesley, Vadillo, Pearson, & Shanks, 2015). In contrast, according to a response selection account, the CCE is driven by non-search factors rather than an improvement in search efficiency (Kunar, Flusberg, Horowitz, & Wolfe, 2007). These two theoretical accounts of the CCE are not mutually exclusive; some researchers hold the view that both attentional guidance and response selection contribute to the CCE (Schankin, Hagemann, & Schubö, 2011; Sewell, Colagiuri, & Livesey, 2018; Zhao et al., 2012).

In the first empirical chapter, we re-examined the mechanism responsible for the CCE by using a multiple target location paradigm. If one-to-one context-to-target associative learning is the only mechanism responsible for the CCE, then the CCE ought to be smaller when multiple targets are paired with a single repeated distractor context. In such situations, a cost should occur when the distractor context cues attention to the wrong target location. In a series of experiments, each repeated distractor context was associated with multiple possible target locations. Experiment 1 was a replication of the classical contextual cueing paradigm, and a large CCE was observed with one repeated distractor context associated with one specific target location (1C-1T). The CCE was also evident (although smaller in magnitude) when one context was associated with two possible target locations (2C-2T). This result is similar to those reported by Chun and Jiang (1998) where a modest CCE (about 40 ms) was found in the last epoch of trials, and by Zellin, Conci, von Mühlenen, and Müller

(2011) where a CCE of 36 ms was found. Surprisingly, a reliable CCE occurred when each repeated distractor context was associated with four possible target locations (4C-4T). Importantly, the magnitude of the CCE found in the 4C-4T condition was comparable to that in the 2C-2T condition. Moreover, Experiment 5 used a within-subject design to compare 1T-1C and 4C-4T conditions and replicated the results from the corresponding between-subject experiments.

Unlike prior multiple target studies of the CCE (e.g, Experiment 6 of Chun & Jiang, 1998; Zellin et al., 2011), the present study created multiple associations between repeated distractor contexts and target locations without increasing the total number of target locations. This aim was achieved by randomly switching target locations between the repeated distractor contexts within those groups. This method of increasing the number of associations between repeated distractor contexts and targets without increasing the total number of target locations is a unique recipe in our designs, and very likely contributed to the CCE when one repeated distractor context was associated with up to four target locations.

Prior research had demonstrated that contexts associated with target locations can modulate learning that integrates relocated targets into already learned distractor contexts (Zellin, Mühlenen, Müller, & Conci, 2013). The reuse of target locations between multiple repeated distractor contexts appears also to have contributed to the results of the present study. Participants appear capable of extracting multiple levels of available statistical information and using that information to modulate search behaviour when encountering a repeated context in the future (Zellin et al., 2013). This flexible contextual learning allows observers to learn associations among distractors as well as associations between distractor contexts and target locations (Beesley et al., 2015). Most notably, learning of the repeated distractor context here contributed to robust CCEs found in the 2C–2T and 4C–4T conditions.

In conclusion, the first empirical chapter demonstrates for the first time that a CCE can be obtained when one repeated distractor configuration is associated with up to four possible target locations, provided that target locations are also shared by the other repeated distractor contexts. This study implies that contextual cueing could involve mechanisms beyond "one-to-one" context–target attentional guidance.

Associative Working Memory in Contextual Cueing Effect

As mentioned above, the attentional guidance account (Chun & Jiang, 1998) assumes that participants learn an association between repeated distractor context and target location through repeated exposure of contextual information. This learned association then guides observers' visual attention to the target location when encountering the same context information in the future. The attentional guidance account implies that a relational binding processing may be involved in the contextual learning that underlies the CCE. However, no prior studies have examined the whether associative working memory is involved in this contextual learning. In the second empirical chapter, we addressed this question in two different ways. One way was to require participants to do a contextual cueing visual search task which holding a stimulus in working memory. The rationale for this method is that performing the working memory task and visual search task concurrently may render relational working memory resources unavailable to support contextual learning in the visual search task. A second way this issue was addressed was to require participants to complete the visual search and working memory tasks separately, and then to measure the correlation between the magnitudes of the CCE and working memory performance. The rationale was that there should be a positive correlation between the magnitude of the CCE and the working memory performance if these two effects depend on the same cognitive resources.

The results from the three experiments of Experiment 1 of Chapter 3 were clear: a concurrent relational binding working memory task does not significantly weaken spatial context learning. In Experiments 1 to 3, participants conducted visual search either under non-relational binding working memory conditions or under relational binding working memory conditions. A CCE was observed independent of whether the visual search task was carried out concurrently with a non-relational binding or relational binding working memory task. These findings show that occupying working memory with a working memory task that requires relational binding does not impair contextual learning. The results from Experiment 2 showed that there was little correlation between the magnitude of the CCE and working memory task performance. Taken together, the results in

Chapter 3 indicate that resources required for relational binding may not be involved in the contextual learning that underlies the CCE.

These results are in line with Vickery, Sussman, and Jiang (2010), who found that contextual cueing was unaffected by a concurrent working memory task. Our results are important for understanding the underlying mechanisms of contextual learning. The attentional guidance account (Chun & Jiang, 1998) suggests that once participants learn an association between repeated distractor context and target location, the contextual information may serve as a cue that guides attention, allowing visual search to be done on the basis of memory retrieval rather than serial deployment of attention (Brady & Chun, 2007; Chun & Jiang, 1998; Vickery et al., 2010). Although memory traces for spatial contextual information can persist for at least one week (see Experiment 3, Chun & Jiang, 2003), our results suggest that learning and retrieving context information exerts little demand on attention or working memory. The retrieval of contextual information seems to proceed automatically, bypassing the working memory system.

Our current results also support the general theoretical framework that differentiates explicit and implicit learning, with the latter being more robust to interference of many stressors, including the availability of attention and working memory resources (Reber, 1989; Vickery et al., 2010). Our study provides strong empirical evidence that, as is typical of implicit spatial learning effects, the contextual cueing effect does not rely heavily on the relational working memory.

Item Specific Proportion Congruent Learning Could Modulate Attention Capture

Unlike the first and second empirical chapters that used an implicit spatial learning method, in Chapter 4 we used an item-specific proportion congruency (ISPC) method to study selection history processes. In particular, we used an ISPC method that focused on attention capture using the additional singleton paradigm (Crump et al., 2018; J. Theeuwes, 1992; Jan Theeuwes, 1991; Thomson et al., 2014). Prior studies had shown that implicit learning involving that association between item type and proportion congruent can modulate the magnitude of attention capture (Crump et al., 2018; Thomson et al., 2014). Our specific goal in Chapter 4 was to examine the mechanisms that contribute to this ISPC effect by monitoring participants' eye movements.

In principle, the ISPC effect could be driven by a rapid categorization of items as belonging to either high proportion congruent (HPC) or low proportion congruent (LPC) item type once the visual display presented, and consequent differences in the speed of initiation of attention shift for the HPC and LPC item types. However, we found that there was no difference in performance between HPC and LPC items in the early perceptual processing phase that precedes ocular movement, arguing against the rapid categorization hypothesis. Instead, our results showed that the ISPC effect occurred after the initiation of ocular movement. Participants were more likely to shift their eyes toward the colour singleton distractor for HPC trials than LPC trials on the first saccade, and even on the second saccade (see also Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999). Meanwhile, participants were more likely to shift their eyes toward the shape singleton target for LPC trials than HPC trials on the first, second and third saccades. Moreover, focusing solely on trials in which participants shifted their eyes to the color singleton distractor, we found that participants fixated on the colour singleton distractor 70 ms longer for HPC than LPC trials, supporting the distractor dwell time hypothesis. However, this 70 ms of additional dwell time on distractors accounted for less than half of the 149 ms ISPC effect found in a corresponding RT measure.

We proposed an item-specific goal learning and control account for all the results of the present study. Goal-driven attentional control settings can mediate attention capture (Folk, Remington, & Johnston, 1992). The goal of participants in the current study was to search for the shape singleton target. For the HPC trials, participants could often find the shape singleton target by relying on the signal from the salient colour singleton. Thus, the task goal representation (i.e., find the odd shape) did not necessarily have to be active on HPC trials to perform the task. Consequently, we conjecture that the perceptual representation of HPC items and the task goal representation were often not co-active on HPC trials. In contrast, finding the shape singleton target on LPC trials did depend on an active task goal representation. As a result, the task goal representation and the perceptual representation of LPC items were much more likely to be co-active. Following the Hebbian learning rule that co-active representations strengthen the association between those representations (Hebb, 2005), the association between the task goal representation and perceptual representation of items would tend to be strengthened for the LPC trials but not for the HPC trials over the course of experiment (Verguts & Notebaert, 2008). Consequently, onset of LPC items may have strongly cued the retrieval of the task goal representation, which in turn reduced attention capture by the colour singleton distractor. In contrast, onset of HPC items would have only weakly cued the retrieval of the task goal representation, thus failing to counter attention capture by the colour singleton. We propose that these two influences on stimulus-cued task goal activation together produced the ISPC effect on attention capture.

Future Directions

The current research leaves several questions unanswered to be addressed in future studies. For example, when considering the finding of our multiple targets study and prior studies, it seems likely that both attentional guidance and non-search factors, such as response selection, contribute to the CCE. However, little is known about when attentional guidance will be the dominant process underlying the CCE and when non-search factors will instead be dominant. What factors might influence whether one or the other set of mechanisms will be dominant in determining the CCE? Are individual difference in implicit learning on the one hand, or differences in experimental task demands on the other hand, likely to play a larger role in determining which processes are dominant in the CCE? Also, given the distinction between explicit and implicit learning, it would be interesting to determine whether the multiple target finding in the present study depends at all on participant awareness of statistical regularities.

With respect to the second empirical study, the results indicated that relational working memory was not involved in implicit contextual learning. Given that the relational working memory task was explicit, it would be interesting to examine whether an implicit task that taps working memory might impact implicit contextual learning. Hassin, Bargh, Engell, and McCulloch (2009) provided evidence of the existence of implicit working memory. In a future study, it would be interesting to adopt this form of implicit memory task to examine further the relation between implicit working memory and implicit contextual learning. A future study might also examine brain activity when performing the working memory task and the implicit contextual learning task. If the activation areas of the cerebral cortex caused by the two tasks do not overlap, it would provide further evidence that implicit working memory and implicit contextual learning depend on separate resources.

Finally, the ISPC attention capture paradigm also constitutes a useful tool to study selection history mechanisms. However, additional research might be conducted to explore the link between this selection history effect and other well studied selection history phenomena. For example, participants may be trained jointly with reward and item-specific proportion congruency. This method would allow researchers to explore whether adding a reward to HPC trials (especially high rewards for HPC incongruent trials) could weaken or even eliminate the

ISPC effect. If this were the case, it would provide evidence that the two effects are related forms of selection history effect, and more broadly that selection history does constitute a useful third category of process that controls attention selection.

Conclusion

This thesis examined two phenomena of selection history: the contextual cueing effect and the item-specific proportion congruent attention capture effect. The novel and innovative findings from this thesis are: (1) selection history can exert its influence on the attentional control of selection in a much more flexible manner than has been documented in prior studies, as evidenced by search facilitation even when one repeated context is associated with four possible target locations, provided that the four target locations are also shared by other repeated contexts; (2) in implicit spatial contextual learning, selection history appears to influence attentional selection without relying on working memory resources; and (3) selection history can mediate attention capture in a pop out search task through item-specific learning and memory. Together, these findings suggest that selection history is mediated by incidental learning in a variety of ways, and can produce a variety of different forms of influence on attentional selection.

The two phenomena of the selection history covered in this thesis, the contextual cueing effect and item-specific proportion congruent effect, demonstrate that human beings are capable of extracting the regularities embodied in the visual environment through different forms of associative learning, improving the visual search performance. Specifically, evidence from the multiple target study suggests that observers could learn the association between distractor configuration and target location in a flexible manner to allow more efficient attention selection. The evidence from the item specific proportion congruent learning suggests that observers could also learn the association between item settings and proportion congruency and facilitate attentional control. Although observers do not have awareness to this learned associative information, the recent experiences of specific attentional deployment can module subsequent attentional allocation, which in line with existing frameworks that emphasize the role of associative learning and memory in the deployment of attention (Logan, 1988, 2002).

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