THE CONTRIBUTION OF VISUAL WORKING MEMORY TO PRIMING OF POP-OUT

BY

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ABSTRACT

Priming of pop-out (PoP) refers to the facilitation in performance that occurs when a target-defining feature is repeated across consecutive trials in a pop-out singleton search task. While the underlying mechanism of PoP has been at the center of debate, a recent finding (Lee, Mozer, & Vecera, 2009) has suggested that PoP relies on the change of feature gain modulation, essentially eliminating the role of memory representation as an explanation for the underlying mechanism of PoP. The current study aimed to test this proposition to determine whether PoP is truly independent of guidance based on visual working memory (VWM) by adopting a dual-task paradigm composed of a variety of both pop-out search and VWM tasks. First, Experiment 1 tested whether the type of information represented in VWM mattered in the interaction between PoP and the VWM task. Experiment 1A aimed to replicate the previous finding, adopting a design almost identical to that of Lee et al., including a VWM task to memorize non-spatial features. Experiment 1B tested a different type of VWM task involving remembering spatial locations instead of non-spatial colors. As a result, only spatial VWM load interfered with PoP, supporting the notion that VWM is involved with PoP. Based on the results from Experiment 1, Experiment 2 observed the magnitude of PoP, with manipulation of the number of items to be remembered in the VWM task. With spatial VWM load, the amount of PoP decreased with the increase of memory load. This result indicates that the concurrent spatial VWM task truly interfered with the occurrence of PoP. Experiment 3 examined whether a VWM task still affects PoP when a strong bottom-up guidance is present, and target ambiguity (Meeter & Olivers, 2006) decreases. Consistent with previous findings, the increase of set size resulted in a decrease of PoP, indicating that there was a strong bottom-up guidance based on the salience of target. Nonetheless, the dual-task interference from the spatial VWM task was consistently observed.

The result suggests that the contribution of VWM to PoP is robust, regardless of the presence of other types of guidance. Lastly, Experiment 4 directly investigated which component of a spatial VWM task interacts with PoP. To address this question, Experiment 4 observed the interaction between PoP and the VWM task with and without an inter-trial repetition of the target-related positions. Based on the finding that the repetition of position also elicited inter-trial priming (Maljkovic & Nakayama, 1996), Experiment 4 tested whether the repetition of the relative position of the target affected the effect of a spatial VWM load on PoP. As a result, while PoP interfered with a VWM load, position-based priming appeared to be independent of the VWM load as well as PoP. Such results indicate that spatial VWM exclusively contributes to PoP by swiftly deploying attention to the location of a task-relevant feature held in memory. In sum, across four experiments, PoP was affected by the concurrent spatial VWM task. Together, overall results suggest that the function of VWM contributes to the occurrence of PoP, disagreeing with the previous finding that PoP is due to the increasing gain of perceptual features, as attended in previous trials. Instead, current findings support the theory that PoP is in fact a multi-level process based on the deployment of spatial attention relying on VWM.

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CHAPTER 1. INTRODUCTION

In everyday life, the visual system constantly receives massive amounts of information, and at first glance it would seem that the system thoroughly processes all this information when a search is necessary. But in reality, the visual system cannot investigate all of the details because the human brain is highly limited in its capacity to accommodate large amounts of input. As a result, the visual system needs to prioritize the information of interest at the cost of unwanted information, a phenomenon we refer to as selection. Selection is driven in two ways: bottom-up and top-down. Bottom-up, or stimulus-driven selection is based on a particular attribute of a stimulus, regardless of the observer's intention or goal, like when your attention is captured by a coin lying in the street, glittering against a drab background. On the other hand, top-down, or goal-driven selection is based on an observer's knowledge, experience, or goals. In the example of a coin on the street, your attention may stay around the location where you found the coin, bearing the expectation of finding another coin and the knowledge of what the target (i.e. a coin) looks like.

The visual system operates various types of selection guidance to accomplish an effective and efficient search. One selection mechanism works as follows: imagine you are driving late at night on an unfamiliar road, hungry, and looking for an open restaurant. Keeping pace with traffic, you must be vigilant so as to not miss the signs of an available establishment, such as a steady flow of cars entering or exiting an area. Accordingly, you must be ready to catch any noticeable movement, flash, or sound that might indicate food is near. This type of task requires a fast, almost reflexive reaction to what you see in front of your eyes. At the same time, such a quick reaction is probably not only purely reflexive, but also guided by prior knowledge

or recent experience. For example, from experience, you have an expectation about the kind of neighborhood where you are likely to find a restaurant, though your expectations are not guaranteed to be correct. By applying such past experiences to your decision, you have a better chance to efficiently react when you encounter the expected stimuli.

Likewise, among the various types of guidance that can contribute to selection, past experience is a strong factor for guiding current behavior. A number of studies have provided solid empirical evidence that past experience can alter following attentional selection. Sometimes, the guidance of past experience is not temporally confined to any one particular moment (i.e. a trial) in the search. For example, in a series of trials of singleton search, performance on the current trial was significantly facilitated by recent responses (Maljkovic & Nakayama, 1994; 1996; 2000). In the task, participants were asked to find a target defined by a feature distinguishing it from the rest of the stimuli (e.g. its unique color) and report a second feature about the target (e.g. its shape). Not knowing what color the target would be for each trial, participants had no pre-determined criterion in mind to use to search for the target. Rather, they had to rely on the contrast between items in the current trial. This means that this type of visual search largely relies on bottom-up guidance of target salience, so the target captures attention quickly and automatically, free from the influence of top-down guidance such as memory. Considering this, it would be surprising if a trace of past experience affected such type of visual search. These findings on inter-trial priming indicate that the human visual system is highly flexible, applying various types of guidance to accomplish effective and efficient selection.

Though several characteristics of inter-trial priming have been reported and replicated, it is still a matter of debate as to what those findings can actually tell us about the nature of this effect. The cause and nature of inter-trial priming remains unclear, with several different

research groups putting forth opposing theories that have yet to be reconciled. Thus, as a contribution to the literature, the current proposal aims to investigate what type of selection mechanism plays a role in the occurrence of inter-trial priming and further, to provide a convergent theory of inter-trial priming. Exploring such a subject will eventually contribute to a clearer understanding of the visual system, especially in regards to competing theories of visual search.

1.1. The influence of past experience and inter-trial priming

As discussed above, various types of guidance drive selective attention in a search. However, such guidance is not limited just to attributes of the stimuli or obligatory task demands stemming from the current trial; indeed, it has been shown that past experience may also modulate the current selection. For example, it is well known that observers are faster at responding to a stimulus to which they previously paid attention than to a newly presented stimulus (priming: Tulving, Schacter, & Stark, 1982). Priming is extensively observed across various domains including perception, concepts and semantics, and picture naming (Tulving & Schacter, 1990; Schacter & Buckner, 1998; Wiggs & Martin, 1998). Among them, perceptual priming is known to be non-conscious, long-lasting, and graded with the number of repeated exposures. Based on such properties, it is considered to rely on a memory system separate from the explicit memory system (Tulving et al.; Wiggs & Martin). In a similar vein, findings from single cell recording and neuroimaging studies have reported a reduced response of neurons to repeated stimuli, dubbed repetition suppression (Brown, Wilson, & Riches, 1987; Baylis & Rolls, 1987; Grill-Spector, Henson, & Martin, 2006; Grill-Spector & Malach, 2001). Priming and repetition suppression share several properties in common, indicating that the two phenomena

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both rely on the lowered perceptual thresholds that seem to result from repeated exposure to certain stimuli.

More recently, it has been broadly reported that experience in one trial of visual search influences observers' behavior in the ensuing trial of the same task (Ariga & Kawahara, 2004; Goolsby, Grabowecky, & Suzuki, 2005; Hillstrom, 2000; Kristjánsson, 2006; Kristjánsson & Driver, 2008; Kristjánsson, Wang, & Nakayama, 2002; Lleras, Kawahara, Wan, & Ariga, 2008; Lleras, Levinthal, & Kawahara, 2009; Maljkovic & Nakayama, 1994; 1996; 2000). Among the inter-trial repetition effects found in the literature, one representative finding was reported by Maljkovic and Nakayama. They demonstrated a reliable advantage in performance on a singleton search task when the target was defined by the same feature across trials.

1.2. Priming of pop-out (PoP)

As in the example presented at the beginning of this article, the influence of past experience is usually observed within a sequence of complex behavior. Also, in terms of studies on visual perception, priming is often found in memory tasks such as recognition tasks. Interestingly, a similar effect has been found even in the context of quick and simple searches where selection was based on a unique feature of the stimulus (Maljkovic & Nakayama, 1994; 1996; 2000). In Maljkovic and Nakayama's experiments, participants were presented with three diamonds, with either the left or the right side of each diamond missing (for more details of the task, see Bravo & Nakayama [1992]). Among the three, one diamond had a unique color. The task was to locate the color-oddball target (e.g. a red target among green distractors) and to report which side was missing from the target. Before any given trial, participants did not know what color the target would be. In other words, the target was defined not by a specific feature,

but rather by its uniqueness, and the unique target "popped out" among the distractors. In this singleton search guided by bottom-up salience, the authors found that the search was significantly facilitated (40-100 msec) by repetition of the target-defining feature – that is, when the target's color remained the same across trials (red target followed by another red target), instead of the target switching its color across trials. This inter-trial priming effect was dubbed priming of pop-out (PoP), indicating that even an easy search depending on immediate saliency can be guided by past experience.

1.3. Characteristics of priming of pop-out

A series of studies has delineated several characteristics of PoP. First, the duration of PoP is relatively short at five to eight trials (Maljkovic & Nakayama, 1994; 1996; 2000), unlike other memory effects induced by past experience. For example, semantic priming is usually considered to have an effect for days or weeks (Squire, Shimamura, & Graft, 1987). According to Maljkovic and Nakayama (1994), the memory trace of a target feature said to influence PoP lasted for only five to eight trials, or 15 to 30 seconds. By tracing back every trial's preceding targets and then averaging the response times (RTs) of trials of the same preceding position from a particular trial, the authors found a faster response when a target of the same color was presented, compared to when the target was of a different color. Such advantage was observed when a target had the same color as the target that was presented one, two, three, four, or five trials ago. In other words, if participants had once responded to a certain target color, their response to a target of the same color five trials later was faster than their response to a different target color, regardless of the target colors seen during the intervening trials. Based on this result, Maljkovic and Nakayama proposed that PoP may rely on a type of short-lived memory, and this

short-lived memory must be different from the long-lasting memory responsible for traditional priming effects.

The second characteristic of PoP is that it does not rely on explicit, voluntary control. In one experiment, Maljkovic and Nakayama (1994) tested whether explicitly knowing the identity of the upcoming target facilitated a search. In one block, the target color stayed the same without exception, enabling participants to anticipate the color of the target in the next trial. In another block, the target color alternated between two colors on every trial, so participants were still able to predict the color of an upcoming trial. Contrasting with those two conditions, there was a block where the target color was determined with complete randomness (i.e. 50% chance of switch). If PoP occurs based on explicit predictability, search would be facilitated when participants had perfect knowledge of the upcoming target color. That is, RTs should be faster when the target color either always stayed the same, or regularly alternated from one to another, than when the target's color switched at random. In contrast to predictions, however, results of the study showed that the RTs of trials with the predictable color switch (i.e. 100% alternation) were slower than the RTs of trials with a single color (i.e. 100% stay). Between these two extremes, RTs increased linearly as the number of alternations increased. In sum, PoP was not affected by the predictability of the target color in the next trial, indicating that PoP is immune to the observer's explicit knowledge or expectations, and rather is solely driven by the repetition or switch of the target color.

This account has also been supported by results from a recall task (Maljkovic & Nakayama, 2000). In that particular study, participants were unexpectedly asked to recall the attributes of previous targets in the middle of a series of singleton search trials. The secondary recall task was administered every fifteen to twenty trials of search, asking for the feature of a

dimension (e.g. red, for color) of the target from the previous trial. If the response was correct, the next question asked for the feature of the same dimension for the target from two trials back in the series. This sequence lasted up to ten previous trials. Results showed that participants' level of recall, which requires explicit memory, was very poor while PoP remained intact. Participants generally remembered only one previous target. Together, the result supported the notion that PoP does not rely on explicit memory representations of previous trials.

In the following chapter, I will further discuss the characteristics of PoP in relation to its underlying mechanism. Though few prominent theories of attention provide a plausible explanation for how and why PoP occurs, at least a few underlying mechanisms of PoP have been proposed. The following chapter will first review various findings about PoP, then will demonstrate the candidate mechanisms based on the findings.

CHAPTER 2: UNDERLYING MECHANISM OF PRIMING OF POP-OUT

Despite the fact that PoP is generally and consistently observed in various types of visual search (Hillstrom, 2000; Kristjánsson, 2006; Kristjánsson & Driver, 2008; Kristjánsson et al., 2002; Maljkovic & Nakayama, 1994; 1996; 2000), the mechanism responsible for the effect has yet to be determined. Though PoP is a reliably measured effect, we must still question why the phenomenon exists and how it occurs. Indeed, the function of PoP is difficult to pinpoint because PoP arises from the repetition of a target-defining feature (e.g. color) that is not directly informative for the current response selection (e.g. shape). Furthermore, although multiple reliable findings illuminate the characteristics of the phenomenon, some findings are incongruent. Therefore, it is difficult to name one common mechanism involved with PoP based on those findings.

In the following sections, I will first review various findings about PoP that form the bases on which I will later suggest a possible underlying mechanism of PoP. I will then briefly summarize the account that Maljkovic and Nakayama (1994; 1996; 2000) proposed based on their initial findings. Later in the chapter, two possible mechanisms of PoP will be discussed in relation to the findings on PoP.

2.1. Findings of priming of pop-out: Stimulus-driven and goal-driven

Theories of visual search have proposed that search is an active process that takes various factors into consideration for selection. Likewise, theories of PoP argue for multiple sources of priming. Broadly speaking, findings on the source of priming can be broken down

into two major categories: the role of bottom-up guidance such as stimulus properties or the contribution of top-down guidance such as an observer's goal and intention.

A group of studies (Huang, Holcombe, & Pashler, 2004; Maljkovic & Nakayama, 1994; 1996; 2000; Meeter & Olivers, 2006) has established a theory of PoP based on the roles of stimulus and the presentation of display. This line of studies accounts for PoP as the result of stimulus-driven, automatic, and implicit attentional control. Another group of studies (Fecteau, 2007; Folk & Remington, 2007) has emphasized the role of abstract factors including task demand or an observer's intention. According to such account, PoP is modulated by goal-driven and voluntary attentional control.

2.1.1. The evidence for stimulus-driven priming of pop-out

Initial findings (Maljkovic & Nakayama, 1994) indicated that PoP relies on bottom-up selection based on the perceptual properties of the stimulus. PoP was first observed in a type of visual search where the target stood out against the background, immediately and automatically summoning attention. In addition, the response was facilitated not only by a target-defining feature but also by the repeated location of targets across trials (Maljkovic & Nakayama, 1994; 1996). Results indicate that PoP can arise from the repetition of a task-irrelevant feature like position, supporting the idea that automatic priming may be induced by any feature related to the previous target. Lastly, PoP was also quite robust, even when the observer had top-down foreknowledge, such as the target's probable identity. Based on such findings, Maljkovic and Nakayama (1994) suggested that PoP is a type of short-lived memory trace of the previous event, and that the trace automatically and involuntarily enhances the selection of the next target when the subsequent target happens to repeat a feature that matches the trace.

This account has been further supported by studies of the roles of different features in the search display. Results from several studies have commonly shown that repetition of a target-defining feature facilitates a search (Fecteau, 2007; Huang et al., 2004; Kristjánsson, 2006; Kristjánsson & Driver, 2008; Kristjánsson et al., 2002; Maljkovic & Nakayama) while a response feature does not. Based on such findings, Huang and colleagues investigated how PoP was affected in situations with a redundant feature. In their experiment, participants were asked to locate an object of unique size (target-defining feature) and to report its orientation (response feature) while ignoring the color of the items (task-irrelevant feature). Results showed a typical PoP effect in that RTs were facilitated by the repetition of the target-defining feature across trials, but not by the repetition of the response or a task-irrelevant feature. However, surprisingly, they did observe an interaction between the target's feature dimensions. In the condition where the target-defining feature was repeated, repetition of a task-irrelevant feature additionally facilitated the response. In contrast, when the target-defining feature switched across trials, repetition of the task-irrelevant feature corresponded with slower RTs. Taken together, repetition of a task-irrelevant feature modulated PoP, but the modulation was not independent of the repetition of the target-defining feature. Based on the interaction between different feature dimensions, Huang et al. proposed that a detailed episodic memory was created after a trial, and the memory trace was then matched to the display for the current search. If the match was perfect (i.e. with repetition of both the target-defining and task-irrelevant features), episodic retrieval correctly guided attention to detect a target. In contrast, when the target-defining feature was switched, repetition of a task-irrelevant feature became detrimental to the search. Due to a partial match of one surface feature (i.e. the task-irrelevant feature), the episodic memory trace from the previous trial got activated. However, the episodic memory trace of the task-irrelevant feature was apparently misleading and

deployed attention to an incorrect target, resulting in a slower search. In sum, though they admit the contribution of top-down guidance such as task-relevance, Huang et al.'s study supported the idea that reaction to the item carrying the task-irrelevant feature of the previous target was automatic and unavoidable, even when such automatic guidance was disadvantageous for performance.

Another example of stimulus-driven PoP comes from studies about the role of target ambiguity in PoP (Meeter & Olivers, 2006; Olivers & Meeter, 2006). Referring to Bravo and Nakayama (1992), the authors argued that PoP was modulated by stimulus-driven ambiguity intrinsic to a singleton search display. In Bravo and Nakayama's studies, RTs decreased as the number of distractors increased. Such a negative search slope implies that the increased number of distractors made the search quick and easy because the identical distractors tend to group together, while the target stands out against the group of distractors. In other words, the ambiguity of the target's identity decreases along with increased contrast induced by an increased number of distractors. Based on Bravo and Nakayama's findings, Meeter and Olivers observed the magnitude of PoP along with the number of distractors in a display. The authors argued that an observer may draw advantage from the repetition of target-defining feature for the purpose of decreasing the ambiguity of target, thereby PoP would decrease in an unambiguous search. As a result, the amount of priming decreased as the number of distractors increased (low ambiguity), showing that PoP is modulated by the ambiguity created by contrast among stimuli in a search display.

2.1.2. The evidence for goal-driven priming of pop-out

So far, I have reviewed several findings to support the proposition that bottom-up guidance prevails in the occurrence of PoP. However, not all characteristics of PoP can be readily explained by the features of the stimuli encountered in a search. First of all, PoP has so far been observed with a particular search task that required an observer to investigate the target with focal attention. Researchers of visual search had unanimously reported that a unique item of a singleton search "pops out", so detecting the item was easy with any number of distractors (Bravo & Nakayama, 1992; Egeth, Jonides, & Wall, 1972; Treisman & Gelade, 1980). The same rationale was used to predict that search would become easier as the number of distractors increases, due to a more distinctive target against a homogeneous background. However, not all singleton or feature searches conformed to a consistent pattern as predicted (Bravo & Nakayama; Duncan & Humphreys, 1989; Treisman & Gelade; Yantis & Jonides, 1984). While the prediction was confirmed by a task to discriminate the shape of an odd-color target, the reverse of the prediction was also found by a task to detect the presence of an odd-color target. In that task, RTs were constant regardless of the number of distractors, or even slowed with an increasing number of distractors (Duncan & Humphreys). These results suggest that the shape-discrimination task was qualitatively different from the detection task, and the difference involved the focusing of attention to a target in the discrimination task.

Second, PoP was found to be independent of certain low-level changes of stimuli. For example, in their Experiment 3, Maljkovic and Nakayama (1994) observed that PoP remained intact, even when the colors of items were similar to each other. In other words, reduced low-level discriminability did not lead any change in PoP, though the change was expected to enhance stimulus-driven selection. That is, PoP was not solely modulated by bottom-up guidance.

More recent findings support the joint contribution of bottom-up and top-down guidance to PoP. Specifically, one line of research has investigated the role of an observer's goal on PoP (Fecteau, 2007; Folk & Remington, 2007; Kristjánsson & Driver, 2008). For example, Fecteau directly examined whether the current goal of a task modulated PoP. In that study, search items were all of one color except for one item of a different color. Dissociated with color, the items had the same shape except one item of a different shape. In each trial, items could keep or switch their features on both of these dimensions (shape and color). At the beginning of each trial, participants were cued regarding which feature dimension would define the singleton target. For example, if the cue pointed towards a shape dimension, the target was a shape different from the others, regardless of the presence of color singletons. After finding the target, participants were required to report the direction of a gap with respect to the target. As a result, though both shape and color singletons were present in the display, PoP was observed only with the repetition of the singleton whose dimension was cued to be relevant to the current trial. In sum, Fecteau's finding supports the idea that PoP is determined by repetition of only the task-relevant feature, and that task-relevance appears to be strongly goal-driven.

In a similar context, Folk and Remington (2007) tested feature contingency in PoP. In that study, a search display was composed of a colored target and achromatic distractors. The target's color changed unpredictably trial by trial. Prior to each trial, a colored cue was presented, varying its location. Sometimes the cue showed up in the same location as the following target. As a result, performance was enhanced when the cue and the target happened to appear in the same location. Though such spatial cuing was independent of color, there was nonetheless inter-trial priming of color. That is, when the color of the previous target and that of the current cue matched, the benefit of the spatial cue increased compared to when their colors did not match. In

another experiment, participants were required to search for a target of one of two available colors, and this instruction was effective throughout whole experiment. When researchers compared two groups of participants with different instructions, Folk and Remington found that the spatial cuing benefit was observed only for the target of the instructed color. Taken together, these results indicate that inter-trial priming (including PoP) is readily modulated by top-down control (i.e. instruction), which determines an observer's goal and intention.

In addition, Kristjánsson and Driver (2008) provided evidence to support the role of top-down guidance of PoP. Adopting a conjunction search paradigm in which both target and distractors received focused attention, the researchers showed that response was facilitated by the repetition of both target and distractors. Furthermore, when the target of the previous trial reappeared as a distractor, and vice versa, such a switch of roles was shown to be disadvantageous to the response.

Taken together, the overall results indicate that PoP does not arise from the passive encoding of all stimuli in the previous trial, but rather from a clear memory trace of the feature to be selected (the target) and the feature to be filtered (the distractor).

2.2. Possible underlying mechanisms of priming of pop-out

2.2.1. Implicit short-term memory

Since their initial findings about PoP (Maljkovic & Nakayama, 1994; 1996; 2000), several characteristics of the phenomenon have been repeatedly reported. First, PoP is a short-lived advantage, lasting only about 30 seconds. Second, PoP is immune to foreknowledge of the target's identity and to the voluntary control of memorizing previous targets. Third, PoP increases with the number of repetitions in a cumulative manner.

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Taking such findings into consideration, Maljkovic and Nakayama (1994; 1996; 2000) proposed that PoP is the result of an "implicit short-term memory" of the target that lingers after a search is completed. The authors interpreted PoP as a type of priming because it is induced merely by the repeated exposure of a target-defining feature, regardless of the feature's value to inform the next target (i.e. predictability). In a similar vein, PoP appears to them to be "implicit" – in other words, is not subject to any memory that participants could consciously recall. However, at the same time, Maljkovic and Nakayama also suggested that this type of priming has to be distinguished from typical priming, because of the relatively rapid decay of PoP.

As described above, Maljkovic and Nakayama's definition of PoP seems somewhat vague and inconsistent. Though their definition tries to inclusively embrace the main findings about PoP, it does not provide a clear sense of what the phenomenon actually is. For example, Maljkovic and Nakayama's definition does not address whether PoP is induced simply by the repeated exposure to a certain feature, or if it is driven by a memory currently cooperating with the search. Their concept of "implicit short-term memory" could be either a type of perceptual priming or the operation of short-term memory. However, it is not only confusing but also misleading to compound perceptual priming and short-term memory without a clear distinction. On one hand, perceptual priming, the lowered thresholds of perceptual identification of repeated stimuli, is considered to be a passive and automatic process. In contrast, short-term memory requires observers to encode and maintain certain information selected by a specific goal or interest.

Can we uncover what "implicit short-term memory" actually is, based on the current findings about PoP? As discussed above, the occurrence of PoP itself seems to depend on the properties of stimuli and task display in a singleton search, but at the same time, PoP seems to be

highly modulated by an observer's goal or intention. Taken together, based on the findings, PoP can be interpreted as either a top-down or a bottom-up process? In other words, each finding for PoP shows how a specific manipulation affects PoP, rather than what the underlying mechanism of PoP is. Therefore, despite a number of reliable findings, it has not been explicitly determined what mechanism directly triggers PoP or how this unknown mechanism contributes to PoP.

2.2.2. Feature gain modulation account

It seems that the current prominent theories of attention cannot readily accommodate PoP. For example, Feature Integration Theory (FIT, Treisman & Gelade, 1980), one of most often-cited theories of visual search, hardly accounts for PoP. According to FIT, a singleton search is considered to occur at the pre-attentive stage of processing. In other words, a target can be immediately detected based on its relative salience against distractors. Therefore, PoP found in singleton search causes a conundrum in the context of FIT. Since a search display is informative enough by itself to signal the presence of the target, there is no need to make use of any information from any source outside the current display (i.e. the inter-trial history of targets). Furthermore, since an observer does not have to look at and investigate each item with focused attention, there is little chance that information related to the target is well remembered.

Unlike FIT, the Guided Search Model (Wolfe, 1994; Wolfe, Cave, & Franzel, 1989), another well-established theory, provides an explanation for why and how PoP occurs in a singleton search. In this model, each location of a stimulus earns different levels of activation, either by its relative salience or by the significance of a specific feature in the task. For example, a stop sign has a high salience due to its bright color. A driver tends to pay attention to the color of any traffic sign because the whole category of color is greatly informative for driving.

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Together, at each region of a display, a level of activation is calculated. Based on the activation, the search is guided to the location of highest salience, the most likely location of a target.

Within the context of the Guided Search Model, Wolfe et al. (2003; also Mozer, Shettel, & Vecera, 2006) proposed a feature gain modulation account of PoP. As demonstrated above, the item of the biggest gained activation wins the highest rank as a target in a search. After the trial is over, the remainder of gain tied to the previous target's feature can guide attention in favor of the same feature in the following trial. As the target's feature value stays the same across trials, the residual of the gain on the feature builds up, resulting in facilitated responses.

Though the feature gain modulation account offers one plausible explanation why PoP occurs, it does not clearly specify the nature of the "gain" or how the residual gain of a certain feature induces PoP. For example, in that account, the residual gain of a previous target could be either a perceptual trace or a representation maintained in memory storage. Between the two possibilities, and considering the main idea of the Guided Search Model and feature gain modulation account, PoP seems to arise from the perceptual trace of a once-boosted activation of a previous target's feature.

However, it is noteworthy that a certain line of research has proposed that an attended item tends to be encoded into memory. For example, several studies (Fine & Minnery, 2009; Schmidt et al., 2002) have reported that an item of high bottom-up salience is prone to form a durable memory representation in working memory , a type of short-term memory. Numerous other studies adopting the attentional blink paradigm have shown that a target (an attended and selected item) is encoded as a representation in working memory (Chun & Potter, 1995; Jolicoeur, 1999; Raymond, Shapiro, & Arnell, 1992). Taken together, the findings on the

encoding of short-term memory supports the possibility that, rather than a perceptual trace, the residual gain from a previous target is in fact the information operational in PoP.

2.2.3. Visual working memory (VWM)

As shown in the concept of "implicit short-term memory" (Maljkovic & Nakayama, 1994), a type of short-term memory seems to be involved with PoP. Though visual searches have long been considered to be modulated by perceptual processing rather than memory (e.g. FIT [Treisman & Gelade, 1980]), many recent findings have begun to challenge such assumptions and increase their interest in the role of memory in visual search. In this section, I will first review such findings, then discuss the possible role of working memory in PoP.

2.2.3.1. Visual search and visual working memory

Similar to short-term memory (Atkinson & Shiffrin, 1968), the term working memory refers to a process for retaining and manipulating information for brief periods of time (Baddeley, 2000; Baddeley & Hitch, 1974; Baddeley & Logie, 1999; Irwin, 1991). Working memory is often characterized as highly limited in its capacity (Cowan, 2001; Irwin, 1991; Irwin & Andrews, 1996; Luck & Vogel, 1997). Many researchers have proposed that visual working memory (VWM) plays a crucial role in search, within its limited capacity. For example, Bundesen (1990; Duncan & Humphreys, 1989) suggested that once attention is deployed toward an item, the item would be automatically encoded in VWM and would be compared to a template of target representation. Concerning the allocation of attention to each item, Duncan and Humphreys (also Desimone & Duncan, 1995) proposed that the template of target

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representation was stored in VWM, and that it would bias attention in favor of the processing of an item similar to the target's representation.

Another group of researchers (Oh & Kim, 2004; Woodman & Luck, 2004; Woodman, Vogel, & Luck, 2001) attempted to provide further evidence as to whether VWM is required during a search. In those studies, observers performed a conjunction search while retaining certain information in memory for a change-detection task after the search. The authors predicted that if VWM played a role in search, additional VWM load would negatively affect the search. Results showed that the concurrent VWM task of spatial stimuli interfered with the search (Oh & Kim; Woodman & Luck), while the VWM task with non-spatial stimuli did not (color stimuli: Woodman et al.). Overall results suggest that there is a common mechanism shared by the search and the spatial VWM task. That mechanism is responsible for maintaining and tracking spatial locations, and such functions are indispensible to both tasks.

Results from dual task studies show no interference between search and non-spatial VWM (Oh & Kim, 2004; Woodman & Luck, 2004; Woodman et al., 2001). These studies asked the question of whether stored representations in non-spatial VWM biased observers' attention toward an item matching the representation in memory. For example, Soto et al. (2005) reported that attention was deployed to a feature (e.g. color) compatible with the representation in VWM, even when the feature was task-irrelevant. Recently, a line of research (Hollingworth, Matsukura, & Luck, in press; Hollingworth, Richard, & Luck, 2008; Richard, Hollingworth, & Luck, 2008) has suggested that non-spatial VWM plays a role in maintaining surface information about the stimulus and in quickly deploying attention to the matching feature.

In sum, it seems that VWM contributes to an efficient search. Converging evidence has shown two ways in which VWM plays a crucial role in a visual search. First, VWM stores a

template of a target which draws attention to a similar item in search display (Chelazzi et al., 1993; Desimone & Duncan, 1995; Downing, 2000; Duncan & Humphreys, 1989). Second, spatial VWM and attentional selection during a search share a mechanism for deploying attention to specific spatial locations (Oh & Kim, 2004; Woodman & Luck, 2004). In a similar vein, even non-spatial VWM plays a role in directing attention to the location of a stimulus matching the stored representation (Hollingworth et al., in press; Hollingworth et al., 2008; Richard et al., 2008; Soto et al., 2005).

2.2.3.2. Priming of pop-out and visual working memory

Though PoP has been described as "implicit short-term memory" (Maljkovic & Nakayama, 1994; 1996; 2000), it is not yet clear which memory system contributes to the phenomenon. As discussed above, the known characteristics of PoP cannot be adequately explained by just one memory mechanism. First, PoP has a short duration, implying that the memory representation may not rely on a long-lasting memory system. However, the duration of PoP is not compatible with the capacity of VWM, either. In Maljkovic and Nakayama, PoP appeared to last from five to eight trials. If participants could keep the trace of five to eight previous targets, the trace must have exceeded the known capacity of working memory (Cowan, 2001; Luck & Vogel, 1997). In addition, unlike working memory, PoP appeared to be independent of voluntary control or explicit recall. These results led Maljkovic and Nakayama (1994; 2000) to reject the well-received concept of "explicit" short-term memory. Therefore, it seems difficult to put "implicit short-term memory" into one of the existing categories of memory system, and to delineate its function in PoP.

Nonetheless, there is a link connecting PoP to VWM. As reviewed above, VWM plays a critical role for an efficient search. First, VWM stores information related to a stimulus of interest (a target template) for the purpose of efficiently responding to a similar stimulus in a future event (Desimone & Duncan, 1995; Duncan & Humphreys, 1989). Second, VWM is involved in the deployment of spatial attention in visual search (Oh & Kim, 2004; Woodman & Luck, 2004). Specifically, spatial attention is deployed in favor of locations stored in memory (Awh & Jonides, 2001; Awh, Jonides, & Reuter-Lorenz, 1998), or to the surface feature that matches the representation in memory (Hollingworth et al., in press; Hollingworth et al., 2008; Richard et al., 2008; Soto et al., 2005).

This contribution of VWM to search can also be applied to PoP. In the singleton search paradigm, there is no pre-determined target template except a requirement to locate a unique item as quickly as possible. Therefore, a feature that determines the uniqueness (e.g. color) must become critical for an efficient search. Once a target is located and further processed for a response, the target, an item which received attention, can be encoded into VWM. At this stage, the memory representation can survive beyond a trial because there is a (perhaps slight) chance that the memory representation can accelerate the deployment of attention in the next trial. Considering the previous findings on attentional deployment and VWM (Awh & Jonides, 2001; Awh et al., 1998; Hollingworth et al., in press; Hollingworth et al., 2008; Richard et al., 2008; Soto et al., 2005), in the next trial the memory representation may move the observer's attention to the location of a stimulus of the same surface color. If the stimulus to which attention is guided happens to be a target, the response would be facilitated. Otherwise, the performance would be slowed.

Though the above demonstration explains the possible role of VWM in PoP, such account lacks empirical evidence. To address the questions of whether and how VWM contributes to PoP, it is essential to directly investigate whether PoP is affected by manipulation of VWM. For example, a number of studies (Oh & Kim, 2004; Woodman & Luck, 2004; Woodman et al., 2001) tested a dual-task paradigm of search and VWM task aiming to determine whether search performance would be impaired by additional VWM load. In the next chapter, I will review a previous study (Lee, Mozer, & Vecera, 2009) that adopted the same dual-task paradigm to investigate the relationship between PoP and VWM. Based on the previous studies, an idea for a new experiment will be outlined later in the chapter.

CHAPTER 3. PREVIOUS FINDINGS AND OVERVIEW OF PRESENT STUDY

3.1. Previous evidence that VWM is not involved in PoP

Lee and colleagues (2009; also Mozer et al., 2006) directly investigated whether VWM plays a role in PoP by adopting a dual-task paradigm. In their experiments, participants were asked to maintain four colored patches in VWM while they performed a visual search. In the search task, three Landolt-C shapes were presented on the periphery, and neither the color of the target nor the color of distractors overlapped with any of the memory items. If PoP was the result of a memory of the previous target, then the priming should have decreased when the concurrent memory task loaded VWM to capacity. However, PoP was not affected by the presence of the secondary task. Based on this result, Lee et al. concluded that PoP is not driven by the top-down guidance of representations stored in VWM. Further, instead of VWM, Lee et al. proposed that feature gain modulation (Wolfe et al., 2003) is responsible for the occurrence of PoP.

3.2. Questions remaining after Lee et al. (2009)

3.2.1. Technical issues

Though Lee et al. (2009) first examined PoP in relation to VWM and feature gain modulation, there are several major reasons why their results could not provide conclusive evidence of the involvement of VWM in PoP. Lee et al. found little change in PoP in the dual task of a singleton search and a VWM task, but the null result was not sufficient to rule out the contribution of VWM to PoP. Multiple factors contribute to a null result, so it is impossible to decide whether Lee et al.'s result arises from a true absence of the difference between conditions, or uncontrolled noise. For example, in Lee et al.'s dual task condition, participants showed a low

level of accuracy in the VWM task, lower than 75% on average. Given this result, it is possible that participants in the experiment did not make an effort on the secondary VWM task to maintain close attention to the singleton search. If this interpretation is correct, the null difference between the single and dual task conditions could indicate that the two conditions were actually identical, and the VWM task had no impact on the result.

Another technical issue was that they compared the amount of priming not only between the single and dual task conditions, but also between two separate groups of participants. That is, Lee et al. first replicated PoP in a single search task (Experiment 1), and then investigated PoP with a VWM task in a separate experiment (Experiment 2) with a different group of subjects. Therefore, even though PoP was observed in both experiments, the comparison of two task conditions could not completely rule out the contribution of VWM to the occurrence of PoP. In other words, since the two experiments were conducted on two separate groups of participants, the comparison could not conclude whether the PoP observed with the load on VWM was as intact as PoP without such a load.

3.2.2. Theoretical issues

3.2.2.1. PoP and the type of VWM representation

Despite Lee et al.'s finding (2009), VWM may still play a role in PoP because they failed to test different types of representations stored in VWM. Baddeley and Hitch (1974; Baddeley, 2000; Baddeley & Logie, 1999) proposed a multi-component model of working memory, which postulates that a memory is composed of subdivisions of specified functions—such as the phonological loop, episodic buffer, and visuospatial sketchpad. Within the visuospatial sketchpad (Baddeley & Hitch), the visual memory load can be either spatial or non-

spatial. Based on this distinction, earlier studies have suggested that spatial and non-spatial representations in VWM are processed by separate mechanisms (Kim, Kim, & Chun, 2005; Kim, Kim, & Chun, 2010; Oh & Kim, 2004; Woodman & Luck, 2004). In particular, by adopting a dual-task paradigm, one line of research has demonstrated that spatial VWM loads exclusively influence the efficiency of a search (Oh & Kim; Woodman & Luck; Woodman et al., 2001). This result indicates that a spatial VWM task specifically impaired search because spatial attention in search was distracted by maintaining the spatial locations presented in the VWM task.

Lee et al. (2009) only tested the influence of loading non-spatial VWM and did not address the dissociation between dimensions of visual memory. As described above, Lee et al.'s argument was that loading VWM would significantly decrease PoP if VWM was the mechanism responsible for PoP. Their rationale was that the dual task of a singleton search and a VWM task would overflow VWM's capacity (about four: Luck & Vogel, 1997) if observers stored the information of a target's history in VWM. However, previous research adopting the dual-task interference paradigm consistently showed that a non-spatial VWM task did not affect a concurrent visual search. In other words, maxing out VWM capacity may not necessarily induce interference between attentional selection and VWM. Therefore, in order to rule out VWM's role in PoP, it will be necessary to investigate whether a spatial memory load affects PoP.

3.2.2.2. Alternative interpretation of feature gain modulation

The conclusion of Lee et al. (2009) was that a target's surface feature boosted the responsiveness to that feature (i.e. activation), and the boosted activation was carried over to the next trial (feature gain modulation: Wolfe et al., 2003). To test the feature gain modulation account of PoP, Lee et al. adopted another dual-task paradigm in which a VWM task was

replaced by a perceptual discrimination task (Experiment 4). In that particular experiment, participants were presented with a sequence of three trials composed of a singleton search, perceptual discrimination, and another singleton search. In the sequence, the color of a target was repeated or switched across trials. As a result, the repetition of the target's color facilitated the response in the second singleton search task, regardless of the target's color in the intervening perceptual discrimination task. In addition, RTs in the shape discrimination task became faster when the shape's color remained the same as the target's color in the first search trial. In other words, even between the two different tasks of a singleton search and perceptual discrimination, the repetition of the target's surface feature (color) facilitated response. This result was interpreted as a case of how boosted activation of a target's color from the first search prioritizes the same color in the following perceptual discrimination task and search task. Based on this result, Lee and colleagues proposed that PoP arises from feature gain modulation, which is based on the boosted activation of the target's feature.

However, Lee et al.'s application of feature gain modulation is somewhat unconvincing. Note that the color of the target in the perceptual discrimination task did not modulate PoP observed in the following search task. If feature gain modulation was truly responsible for this result, then the inter-trial priming observed in the second search trial should have substantially increased when the target of the perceptual discrimination task was the same as that of prior and subsequent search tasks.

This result is not only unconvincing but also open to a plausible alternative explanation. As shown above, the representation maintained in VWM can bias selection in favor of the object that seems most like the representation (Chelazzi et al., 1993; Chelazzi et al., 1998; Desimone & Duncan, 1995). Such top-down guidance of VWM actually explains well the results of Lee et

al.'s Experiment 4. Since the object that receives attention (the target) is likely to be encoded into VWM, it is probable that the target's color in the first search was remembered in VWM. Also, since the sequence of search–perceptual discrimination–search was capped by a mask display at the end, it is possible that participants postulated a connection between the search and the following perceptual discrimination tasks. As a result, a target's color in the search may have been stored in VWM, leading to attentional deployment in favor of the same color in the following trials.

Lee et al. (2009) attempted to clarify the identity and nature of the memory system underlying PoP. Nevertheless, they have not yet provided a definite conclusion in that regard, leaving important questions unanswered. First, their argument relies on the null result (i.e. an equivalent amount of priming) observed in the single and dual task conditions tested in separate groups of participants. Second, Lee et al. did not validly test VWM in relation to PoP. They failed to test the effect of different types of representations on VWM despite previous findings that spatial VWM was exclusively effective in a concurrent search. Based on such issues, the current proposal will explore the following questions: Does VWM contribute to PoP? If so, when and how does this contribution occur?

3.3. Overview of the present experiment

With these questions in mind, the present study proposes to delve into the memory mechanism underlying PoP. Specifically, the present study provides a likely answer for whether VWM plays a role in PoP, or whether PoP is entirely independent of guidance based on VWM. Through four experiments, the current study examined whether the presence or amount of PoP was affected by a concurrent VWM task. For this purpose, the present study first tested whether

PoP was impaired by an additional memory load imposed by a secondary VWM task (Experiment 1), adopting the dual-task paradigm established in a previous study (Lee et al., 2009). After establishing that VWM affects PoP, to determine under what conditions this effect obtains, the magnitude of VWM load (Experiment 2), the ambiguity of a target (Experiment 3) and the repetition of the target-related position (Experiment 4) were all manipulated.

Experiment 1 tested whether PoP was affected by a concurrent VWM task. Adopting a dual-task paradigm similar to the one employed by Lee et al. (2009), Experiment 1A attempted to replicate the null interaction between PoP and a non-spatial VWM task. In contrast, Experiment 1B replaced a feature memory task with a spatial memory task. By maintaining spatial locations instead of simply colors, it was predicted that PoP would decrease in the dual task condition because the concurrent VWM task would interfere with the localization of the target. The results of Experiment 1 were consistent with predictions, showing an interaction between PoP and a spatial VWM task. This interaction indicated that the two share a common mechanism. Further, the results supported the idea that the type of information remembered in VWM perhaps matters in the interaction with a concurrent search.

Based on the results of Experiment 1, the next question was whether the change in representation in VWM induced a proportional change in PoP. To test this question, Experiment 2 observed whether greater or lesser load impaired or facilitated priming, respectively. As predicted, the result showed that the magnitude of VWM load modulated the interference between PoP and the VWM task, thereby indicating a direct relationship between the two.

Experiment 3 tested how robust the influence of VWM load on PoP is. Based on the findings of Experiment 1, Experiment 3 explored whether the relationship between PoP and VWM was affected by the presence of a strong stimulus-driven factor. In Experiment 3, the

contrast between a target and distractors in a search was manipulated by the number of

distractors (i.e. set size). With an increased set size and accordingly increased contrast between

target and distractors (Bravo & Nakayama, 1992), the strong bottom-up salience of the search

display guided attention by itself. As a result, information other than the search display became

less useful, resulting in decreased PoP (Meeter & Olivers, 2006; Olivers & Meeter, 2006). In a

similar context, it was predicted that PoP would decrease in Experiment 3 as the set size

increased. Further, unless the role of VWM was fundamental in the phenomenon, it was

expected that the interference of VWM load on PoP would decrease or disappear. The result

turned out otherwise: Even when PoP decreased with a large set size, the interference between

PoP and VWM load was unchanged. The result suggests that the contribution of VWM is

indispensable for PoP.

Last, Experiment 4 directly investigated the relationship between PoP and spatial VWM.

The results of first three experiments suggest that spatial VWM contributes to PoP by deploying

attention to the location of a stimulus of repeated color. Such a contribution could take place in

one of two ways: spatial VWM might simply allocate spatial attention, or it may connect past

and present events by shifting spatial attention in favor of the memory representation of the task-

relevant feature. To address this question, Experiment 4 directly tested whether a spatial VWM

task interacts with position-based priming (Maljkovic & Nakayama, 1994; 1996). If the role of

VWM is limited to a spatial component, the dual-task interference between PoP and VWM

would decrease with the repetition of a target-related position, which would presumably facilitate

the fast deployment of spatial attention. In contrast, if VWM plays an integrative role to move

spatial attention specifically in favor of the memory representation of the previous target, mere

repetition of the target-related position would not affect the interaction between PoP and VWM.

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Between the two possibilities, the result of Experiment 4 supports the latter: the interference between PoP and the VWM task was constant regardless of the repetition of position. This result suggests that spatial VWM plays a role in PoP not simply by moving spatial attention, but also by allocating attention to the location of a stimulus whose task-relevant feature matches to the memory representation.

CHAPTER 4: EXPERIMENT 1— INTERACTION BETWEEN PRIMING OF POP-OUT AND

CONCURRENT VISUAL WORKING MEMORY LOAD

Experiment 1 was designed to investigate whether there is a change in PoP when VWM

is occupied by a concurrent memory task. Though the design of the experiment is similar to that

of Lee et al. (2009), the current experiment varied from Lee et al.'s design in two major ways.

First, both the single and dual task conditions were tested within the same group of participants.

Second, the task was to report the shape of the color-oddball (instead of the gap of the Landolt-

C).

Experiment 1 explored two main questions. First, it tested the relationship between PoP

and VWM. If VWM contributes to PoP, the priming effect would be attenuated by the additional

memory load imposed by the secondary VWM task. Otherwise, if VWM does not have a role in

PoP, the concurrent VWM task would have no effect on PoP, resulting in an equivalent amount

of priming regardless of memory load. The rationale underlying this prediction is as follows. If

VWM contributed to PoP, an additional VWM load must impair the process for two possible

reasons. First, the additional task load already occupies VWM to capacity, so VWM cannot

successfully maintain the representation of the previous target. Second, since the spatial VWM

task distracts spatial attention from the search, the visual system cannot quickly move attention

to the location of the repeated color. The VWM task would therefore interfere with pursuing the

trace of the previous trial, which would otherwise serve as a reference for a rapid search in the

following trial. As a result, PoP will be reduced or eliminated.

The second question was whether different types of information stored in VWM would

elicit different relationships between PoP and VWM. Literature on the role of VWM in search

has consistently suggested an exclusive contribution of spatial VWM on attentional allocation in a search. Considering this proposition, if spatial representations in VWM exclusively interfere with PoP, such interference would be observed with a spatial VWM task (Experiment 1B), but not with a non-spatial VWM task using color.

Methods

Participants. Twenty six subjects for Experiment 1A and 22 subjects for Experiment 1B performed a 50-minute-long experiment to earn either monetary reward or course credit at the University of Illinois at Urbana-Champaign. All participants were required to have normal or corrected-to-normal vision, including normal color vision. Data from participants who showed poor performance (below 80% of mean accuracy in search or 65% of mean accuracy in the VWM task) were excluded from further analysis. According to these criteria, the data for 20 participants for each experiment were submitted for further analysis.

Apparatus and Stimuli. All stimuli were generated and presented by programs written in MATLAB with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The programs ran on 3.4 GHz Pentium IV Windows PCs and the display of the experiment was presented on a 17-inch monitor running at 85 Hz with a resolution of 1024 x 768. All responses were recorded with a keyboard.

A white donut-shape fixation point (approximately 0.3°) was used at the center of a black screen. Stimuli for the singleton search consisted of circles and triangles in red or green. Each stimulus subtended approximately 0.9° at a viewing distance of approximately 50 cm. In each trial, three search items were randomly presented within an approximately 7.4° x 5.6° region of display. The display appeared in one of four quadrants, except the 2.4° x 2.4° region around the

center of the screen. The stimuli for the VWM task included four rectangular, colored patches (Experiment 1A) or two white dots (Experiment 1B). In Experiment 1A, colors of items were randomly selected among six choices (white, yellow, blue, purple, brown, and cyan). It is noteworthy that there was no overlap of color among the four items to be remembered. Each colored patch subtended approximately 0.9° and appeared at one of four fixed locations within the 2.4° x 2.4° region around the fixation point—one above, one below, one to the left, and one to the right. Also, each colored patch was centered 1.4° x 1.4° from the fixation point. In Experiment 1B, two white dots replaced four colored patches. Each dot subtended approximately 0.3° and appeared in one of 24 locations on the circumference of a circular formation, which subtended 2.4° x 2.4° around the center.

Procedure. The procedure and timing are illustrated in Figures 1A and 1B for Experiments 1A and 1B, respectively. In the single task condition of both experiments, each trial was initiated with a sign of "Ready" for one second. A white donut-shaped fixation followed, presenting at the center for 500 msec. The display for a singleton search then followed, keeping the fixation point at the center. Participants' task was to locate an item of an odd color among three items clustered in one of the four quadrants, and to report whether the target's shape was a circle or a triangle, by pressing the '>.' or '?/' key as quickly and as accurately as possible. The search display disappeared immediately after the response or after two seconds from the onset in the case of no response. When the search display disappeared in less than two seconds, a blank screen with a fixation point was presented instead of the display of the next task, to identically control the duration of the task. The blank screen with fixation remained in effect for another two seconds to make the time course consistent with the VWM task in the dual task condition.

In the dual task condition of Experiment 1A, each trial started with a sign of "Ready" for one second, as in a single task condition. Afterward, a 500-msec fixation point followed, and four colored patches were presented for one second (a memory task display) while keeping the fixation point at the center. The participants' task was to remember the colors of four rectangular patches, regardless of their locations. After 500-msec of blank screen, the singleton search display appeared. As in the single task condition, in case of a response faster than two seconds, a blank screen with the fixation point remained in effect to keep the retention interval of the VWM task consistent. A memory probe display composed of four colored patches was then presented. To indicate it was a probe display, a sign of '??' replaced the fixation point at the center. In half the trials, the display was identical to the memory task display. For the other half, one of the four colored patches changed its color from the one presented in the memory task display. The participants' task was to determine whether the probe display was the same as what they remembered: if they remembered it they pressed 'z'; if not, 'x'. If no response was recorded for two seconds, the trial was automatically terminated.

The procedure of the dual task condition in Experiment 1B was identical to that of Experiment 1A, except for the memory task. In Experiment 1B, participants were presented with two white dots (a memory task display) and were required to remember their locations for a later task. After completing the search task, participants were presented with two dots again (memory probe display) and asked to determine whether either of the two dots had changed its location from the memory task display.

In both Experiment 1A and 1B, the main manipulation was the inter-trial repetition or switch of the search target's color. In half the trials, the color of the target was the same as that of the previous trial ('repeat' condition). In the other half of the trials, the color of the current target

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and the previous target differed ('switch' condition). Participants performed two blocks of 128

trials-- one block each for the single search task and the dual task, respectively. The order of the

blocks was counterbalanced. At the beginning of each block, 20 unanalyzed practice trials were

provided. Throughout the experiment, participants were instructed to repeat "a, b, c, d" or "one,

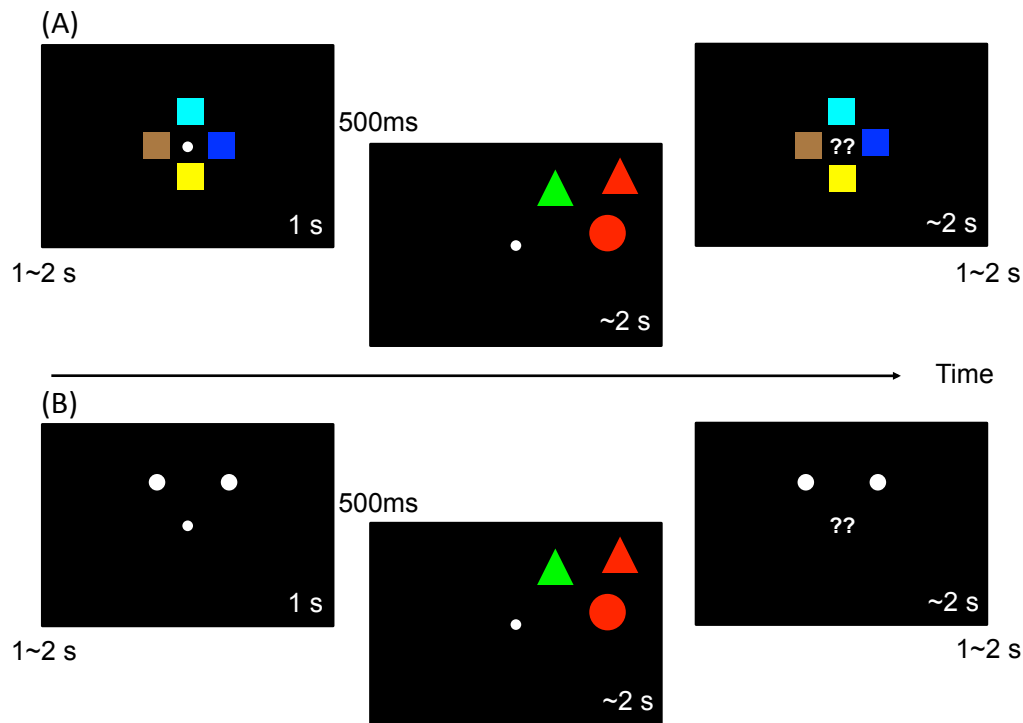two, three, four" which served as an articulatory suppression.

Figure 1. A description of the stimuli and procedure of Experiments 1A and 1B in the dual task condition. Figure 1A depicts Experiment 1A in which the VWM task was to remember the identities of four colors. Figure 1B shows Experiment 1B in which the VWM task was to remember the locations of two white dots. In both experiments, the visual search task was to find a color oddball and to report its shape. In the single task condition, only the visual search display was presented, while the time course was controlled identically to that of the dual task condition.

Results

The primary interest was the inter-trial effects in the "repeat" and "switch" conditions as measured in participants' RTs and accuracy. The amount of priming (i.e. the difference between the "repeat" and "switch" conditions) was also investigated in the single and dual task conditions. To do so, mean RT of search, accuracy of search and mean accuracy of VWM task were analyzed.

Experiment 1A. Mean RT and accuracy were analyzed with a two-way repeated-measures ANOVA, including the inter-trial repetition and task condition as factors. The results are summarized in Figure 2. Only the correct trials made within the allowable time range (150 - 2000 msec) were included for analysis[1]. In the single task condition, mean RT was 895.38 msec and 940.96 msec in the repeat and switch conditions, respectively. In the dual task condition, mean RT was 1069.89 msec and 1108.54 msec in the repeat and switch conditions, respectively. As a result of a two-way repeated-measures ANOVA on RTs (Figure 2A), there was a significant main effect of repetition, $[F(1,19) = 24.798, p < .001]$, and main effect of task, $[F(1,19) = 18.820, p < .001]$, but there was no interaction between the two conditions, $[F(1,19) < 1]$. Following planned comparisons confirmed the advantage of repetition, both in the single task, $[t(19) = 5.217, p < .001]$ and in the dual task conditions, $[t(19) = 2.666, p < .05]$. Though RTs were slower in the dual task condition, $[t(19) = 4.338, p < .001]$, the amount of priming did not differ in the two task conditions, $[t(19) < 1]$.

For the search task alone, mean accuracy was 95.61% and 93.68% in the repeat and switch conditions, respectively. In the dual task condition, mean accuracy was 91.66% and 91.67% in the repeat and switch conditions, respectively. A two-way repeated-measures

[1]The overall search accuracy was high (93.15%) and the majority of responses (96.33%) were made within the allowable time range.

ANOVA on accuracy (Figure 2B) revealed no main effect, for neither repetition, [$F_{(1,19)}$ = 1.604, p > .05], nor task, [$F_{(1,19)}$ = 3.288, p = .086], though the latter was marginally significant. Interaction between the two conditions was not significant either, [$F_{(1,19)}$ = 1.902, p > .05].

In the dual task condition, mean accuracy in the VWM task was 82.50% and 83% in the repeat and switch conditions. A paired t-test showed no difference, [$t_{(19)}$ < 1].

Experiment 1B. The data analysis for Experiment 1B was identical to that of Experiment 1A. The results are summarized in Figure 3. Only correct responses that were made after 150 msec and before 2000 msec were included for the analysis[2]. In the single task condition, mean RT was 986.59 msec and 1082.87 msec in the repeat and switch conditions, respectively. In the dual task condition, mean RT was 1082.94 msec and 1130.17 msec in the repeat and switch conditions, respectively.
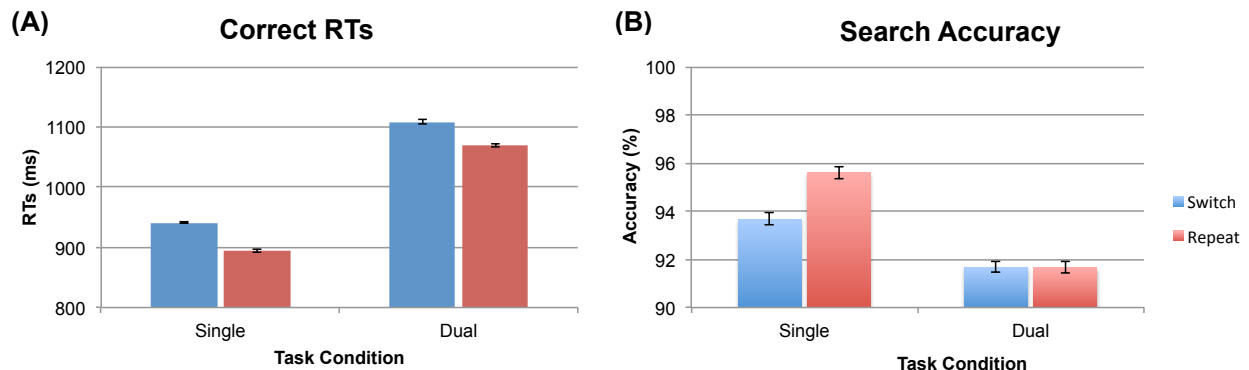

Figure 2. The results of Experiment 1A. All data were analyzed by two conditions of repetition (Repeat vs. Switch) and task (Single vs. Dual). Figures 2A and 2B demonstrate mean RT and accuracy, respectively, in the search task. Error bars are the standard errors of the amount of priming (i.e. the difference between the repeat and the switch conditions), in the single and the dual task conditions, respectively.

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[2]As in Experiment 1A, the overall search accuracy was high (91.49%) and the majority of responses (94.79%) were made within the allowable time range.

Results of a two-way repeated-measures ANOVA on mean RTs (Figure 3A), show a main effect of repetition, $[F(1,19) = 48.702, p < .001]$, and a main effect of task, $[F(1,19) = 5.219, p < .05]$. There was also a significant interaction between the two conditions, $[F(1,19) = 10.031, p < .005]$. A following planned comparison revealed the evidence of PoP, both in the single task condition, $[t(19) = 6.703, p < .001]$, and in the dual task condition, $[t(19) = 4.224, p < .001]$. RTs were slower in the dual task condition, $[t(19) = 2.285, p < .05]$, and the amount of priming was smaller in that condition, $[t(19) = 2.750, p < .05]$.

In the single task condition, mean accuracy was 93.74% and 92.40% in the repeat and switch conditions, respectively. In the dual task condition, accuracy was 89.51% and 90.3% in the repeat and switch conditions, respectively. A two-way repeated-measures ANOVA on accuracy (Figure 3B) revealed a marginal main effect of task, $[F(1,19) = 3.64, p = .072]$, while there was neither main effect of repetition, $[F(1,19) < 1]$ nor interaction between the two conditions, $[F(1,19) = 1.509, p > .05]$.
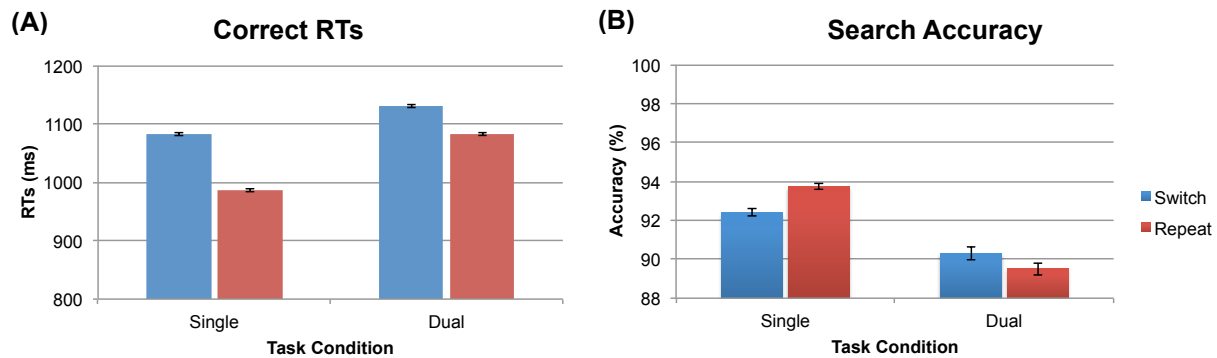

Figure 3. The result of Experiment 1B. All data were analyzed by two conditions of repetition (Repeat vs. Switch) and task (Single vs. Dual). Figures 3A and 3B demonstrate mean RT and accuracy in the search task, respectively. Error bars are the standard errors of the amount of priming.

In the dual task condition, mean accuracy of the VWM task was 88.2% and 87.29% in the repeat and switch conditions, respectively. Results of a paired t-test showed no difference, [$t(19) < 1$].

Discussion

Though Experiment 1 varied slightly from the design of previous studies, the results of Experiment 1 replicate the findings from those studies. As a sign of PoP, RTs were faster when the target's color was repeated (Maljkovic & Nakayama, 1994). Also, consistent with a previous finding (Lee et al., 2009), the amount of priming did not change along with non-spatial VWM load (Experiment 1A). In addition to such replications, a new finding indicates that PoP decreased with spatial VWM load (Experiment 1B).

While the overall results of Experiments 1A and 1B replicate PoP as Maljkovic and Nakayama (1994) reported, the results also answer two further questions about the relationship between PoP and VWM.

First, the results of Experiment 1B show that VWM affects PoP. Though PoP was reliably observed in both the single and dual task conditions, the amount of PoP substantially decreased with additional VWM load. That is, the VWM load impaired PoP, indicating that the VWM load interferes with use of the representation of the previous target in a subsequent trial. Therefore, it appears that VWM contributes to the occurrence of PoP, in contrast to the previous finding of Lee et al. (2009). Second, a comparison between Experiments 1A and 1B suggests that not all the types of VWM are involved with PoP. The result of Experiment 1A (that employed a non-spatial VWM task) exactly replicated Lee et al.'s finding. In other words, taxing VWM induced no change in PoP. In contrast to this finding, Experiment 1B, which adopted spatial

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VWM stimuli for an additional VWM load, clearly showed a decrease in PoP. Taken together, it seems that VWM contributes to PoP in a process exclusively involved with spatial VWM.

It is noteworthy that the current finding is not due to different timing between the single and dual task conditions. As described above, the time course of the procedure was controlled almost identically across conditions, except for the presence of the VWM task. Therefore, it is highly unlikely that the time course of the dual task is responsible for the decrease in PoP. Nonetheless, considering that there was an additional task and an additional response in the dual task condition, it is still possible that such a supplementary procedure slowed RTs thereby diluting the priming effect. However, two reasons argue against this possibility. First, it should be noted that the dual task condition was controlled identically in Experiments 1A and 1B. Experiment 1A differed from Experiment 1B only in the type of information memorized in the VWM task. Accordingly, it is reasonable to attribute the decrease of PoP to the increase of load in spatial VWM. Second, the pattern of weakened PoP in the dual task condition was consistently apparent regardless of whether RTs were fast or slow. In an additional analysis, all RTs for each participant were divided into two groups based on the median RT of the participant's performance (i.e. fast or slow); the two groups' amount of PoP was then compared. If the decrease in PoP was due to generally delayed RTs in the dual task condition, this decrease should be shown in the slow group only.

To test the question, a three-way repeated-measures ANOVA was conducted, with the factors of repetition, task, and RT distribution (fast vs. slow). In Experiment 1A (Figure 4A), though PoP decreased in the fast RT group, as revealed by an interaction between repetition and RT distribution, $[F(1,19) = 7.948, p < .05]$, it was consistent in both single and dual task conditions. As a result, there was no three-way interaction among variables, $[F(1,19) < 1]$. In

Experiment 1B (Figure 5A), despite an interaction between repetition and RT distribution,
$[F(1,19) = 5.349, p < .05]$ due to the decrease of PoP in the slow RT group, the pattern was
consistent in both single and dual task conditions. Therefore, there was no three-way interaction
among variables, $[F(1,19) = 2.847, p > .05]$.

Such pattern was confirmed in another three-way repeated-measures ANOVA with the
factors of repetition, task, and RT distribution of four quantile groups. In Experiment 1A (Figure
4B), RTs were slower in the dual task condition, $[F(3,57) = 9.182, p < .001]$, and PoP was
smaller in the faster quantile RT groups, as revealed by an interaction between repetition and RT
distribution, $[F(3,57) = 4.399, p < .05]$. However, such interactions were consistent in both single
and dual task conditions, $[F(3,57) < 1]$. As a result, there was no three-way interaction among
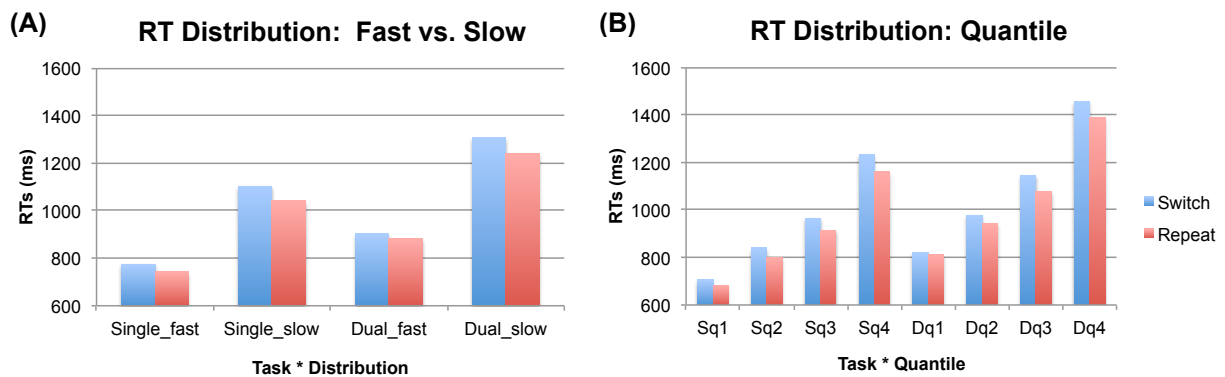variables, $[F(3,57) < 1]$.

Figure 4. The distribution of correct RTs in Experiment 1A. Figure 4A demonstrates the distribution of mean RTs of
two RT groups (Fast vs. Slow) in the repetition and task conditions. Figure 4B shows a more detailed distribution of
four quantile RT groups.

In Experiment 1B (Figure 5B), except an interaction between repetition and task conditions, $[F_{(3,57)} = 6.416, p < .05]$, RTs $[F_{(3,57)} < 1]$, or the amount of PoP $[F_{(3,57)} = 1.627, p > .05]$ did not differ across single and dual task conditions. Therefore, there was no three-way interaction among variables, $[F_{(3,57)} = 1.657, p > .05]$. Generally speaking, the pattern of PoP in each RT distribution was identical, regardless of the task.

Though the question of whether VWM load affects PoP has been tentatively answered, there is a remaining question as to whether the contrast between Experiment 1A and 1B truly arises from an intrinsic difference between the representations stored in VWM. For example, it is possible that the task difficulty of the non-spatial VWM task and the spatial VWM task was not equivalent, causing an unexpected discrepancy between the two experiments.
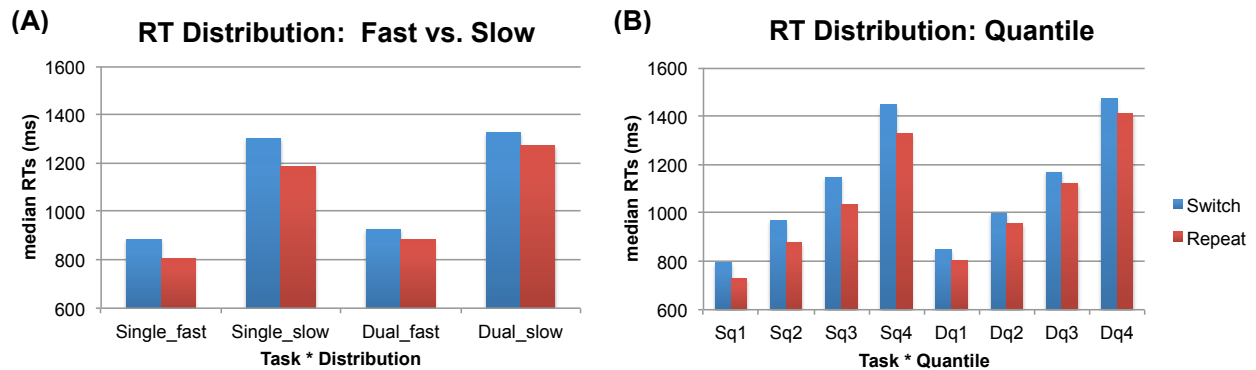

Figure 5. The distribution of correct RTs in Experiment 1B. Figure 5A demonstrates the distribution of mean RTs of two RT groups (Fast vs. Slow) in the repetition and task conditions. Figure 5B shows a more detailed distribution of four quantile RT groups.

Indeed, the mean accuracy of the VWM task in Experiment 1B was much higher than in Experiment 1A. This result indicates that the VWM task in Experiment 1B may have been easier than the one in Experiment 1A. As a consequence of the challenging VWM task, participants in Experiment 1A could have opted out by not paying close attention to the VWM task, thereby leaving PoP unaffected. Such a strategy of giving up on the VWM task could have also occurred in the previous study by Lee et al. (2009), where the accuracy of their non-spatial VWM task was as low as 74.6% (Lee et al., Experiment 2A) with no sign of an effect of the VWM task on PoP.

The question is quite fundamental. If task difficulty is responsible for the unaffected PoP in the dual task condition, it would support the notion that a VWM representation has a part in PoP, regardless of the type of to-be-remembered information. Otherwise, if task difficulty is not responsible, it would indicate that a property exclusively related to the spatial VWM task is essential in PoP. To answer this question, Experiment 2 investigated how a concurrent VWM task with a different amount of load affects the presence and magnitude of PoP.

CHAPTER 5: EXPERIMENT 2—INTERACTION BETWEEN PRIMING OF POP-OUT AND

AMOUNT OF VISUAL WORKING MEMORY LOAD

As discussed above, the result of Experiment 1 left the question of whether a concurrent

spatial VWM task exclusively interfered with PoP. If this is true, it would suggest that a memory

mechanism related to spatial representation contributes to the occurrence of PoP. Alternatively, it

is possible that participants opted out of a particular VWM task due to its difficulty, leaving PoP

unaffected. If this alternative account is true, it would imply that the information stored in VWM

is useful for PoP regardless of the type of information.

Exploring this question, Experiment 2 tested whether VWM load modulated the presence

and magnitude of PoP in a concurrent search task. To manipulate the load, participants were

tested with two separate blocks of dual task composed of a search and a VWM task with a varied

load in each block. As in Experiment 1, Experiment 2 adopted two different VWM tasks, one for

storing non-spatial information (Experiment 2A), and another for storing spatial information

(Experiments 2B and 2C). If the role of VWM in PoP is limited to a spatial component,

increased VWM load would further interfere with PoP in Experiment 2B and 2C, while leaving

PoP unaffected in Experiment 2A. Instead, if both spatial and non-spatial VWM play a role in

PoP, all three experiments would demonstrate further dual-task interference on PoP with the

higher VWM load.

Methods

Participants. Twenty three, 25, and 31 new subjects participated in Experiments 2A, 2B, and 2C,

respectively. All participants were required to have normal or corrected-to-normal vision,

including normal color vision. After excluding the data of participants who showed poor

performance (i.e. below 80% of mean accuracy in search or 65% of mean accuracy in the VWM

task), the data for 18, 20, and 20 participants in Experiment 2A, 2B, and 2C respectively, were

submitted to further analysis.

Apparatus and Stimuli. All were identical to Experiment 1. As in Experiments 1A and 1B,

Experiment 2A employed a non-spatial color VWM task in the dual task condition while

Experiments 2B and 2C adopted spatial VWM tasks.

Procedure. All are identical to Experiment 1 with two exceptions (Figure 6). First, all

experiments included two blocks of dual task that were composed of a search and a VWM task.

Second, in each experiment and each block, the number of items varied in the VWM task. In

Experiment 2A, participants were asked to remember and respond to one colored patch or four

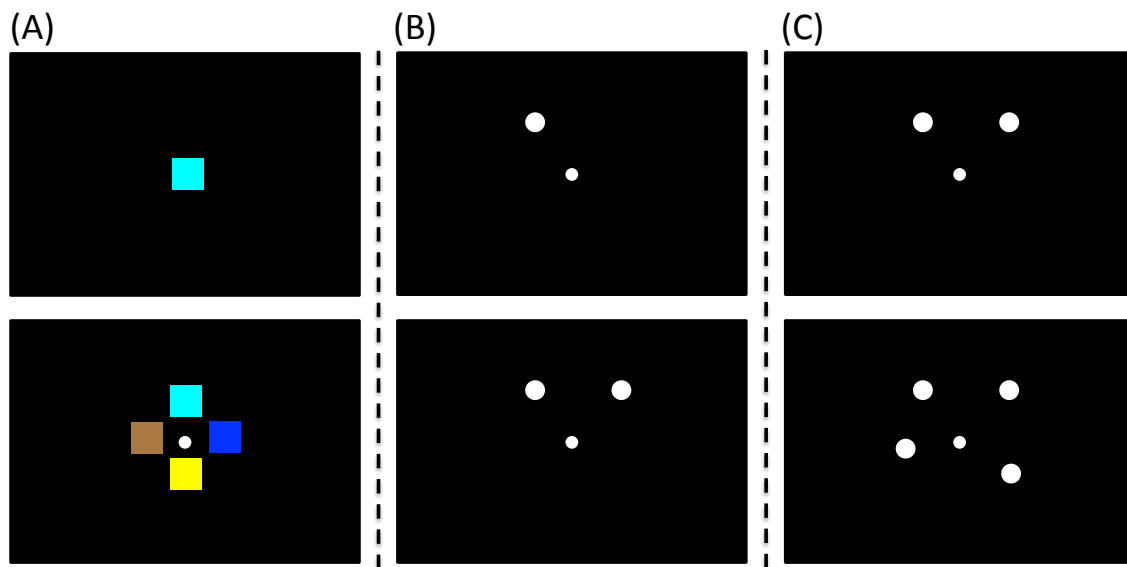colored patches in separate blocks (load 1 vs. load 4).

Figure 6. A description of VWM task of various loads in Experiment 2. Figure 6A, 6B, and 6C depict Experiments
2A, 2B, and 2C, respectively.

In a similar way, Experiment 2B asked participants to remember and respond to the location of one dot or those of two dots (load 1 vs. load 2). Experiment 2C presented two dots or four dots, asking participants to remember the locations (load 2 vs. load 4). Across all three experiments, the order of the two blocks was counterbalanced.

Results

Mean RTs, accuracy of search and mean accuracy of VWM task were analyzed with a two-way repeated measures ANOVA, adopting the conditions of repetition (repeat vs. switch) and VWM load (low vs. high load) as factors.

Experiment 2A. The results are summarized in Figure 7. Fewer than 4% of trials were eliminated due to too short (< 150 msec) or too long (> 2000 msec) RTs. In the low load condition, mean correct RT was 943.1 msec and 969.37 msec in the repeat and switch conditions, respectively. In the high load condition, mean correct RT was 1016.53 msec and 1047.45 msec in the repeat and switch conditions, respectively.
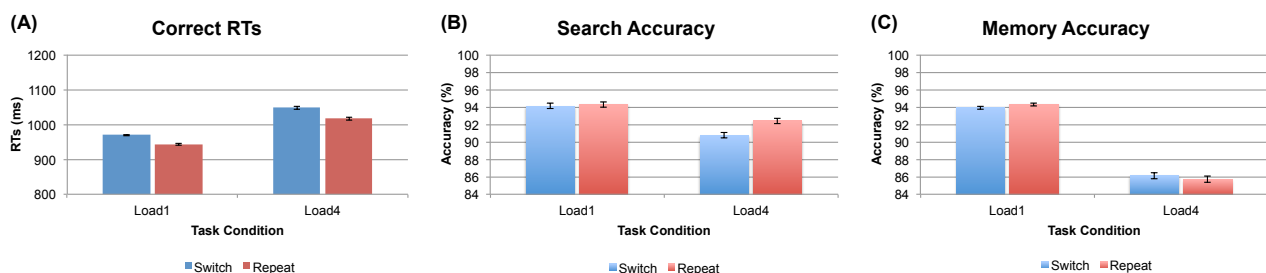

Figure 7. Results of Experiment 2A (non-spatial VWM task). All data were analyzed by two conditions of repetition (Repeat vs. Switch) and load (Low vs. High). Figures 7A and 7B demonstrate mean RT and accuracy of search task, respectively. Figure 7C shows mean accuracy of VWM task. Error bars are the standard errors of the amount of priming.

Results of the two-way repeated-measures ANOVA on RTs showed a significant main effect of repetition, $[F(1,17) = 15.675, p = .001]$ and a marginal main effect of load $[F(1,17) = 4.296, p = .054]$, but no interaction between the two conditions, $[F(1,17) < 1]$. Following planned comparisons showed that RTs of the repeat condition were faster than RTs of the switch condition, $[t(17) = 3.959, p = .001]$. This sign of PoP was present in the low load condition, $[t(17) = 2.742, p < .05]$ and marginally present in the high load condition, $[t(17) = 2.011, p = .06]$. Though mean RTs were slower in the high load condition, $[t(17) = 2.073, p = .054]$, the amount of priming did not differ in the two load conditions $[t(17) < 1]$.

In the low load condition, mean search accuracy was 94.3% and 94.12% in the repeat and switch conditions, respectively. In the high load condition, mean accuracy was 92.41% and 90.75% in the repeat and switch conditions, respectively. A two-way repeated-measures ANOVA on search accuracy revealed only a marginal main effect of repetition, $[F(1,17) = 3.503, p = .079]$. There was neither a main effect of load, $[F(1,17) = 1.132, p > .05]$ nor an interaction, $[F(1,17) < 1]$.

Mean VWM accuracy of the low load condition was 93.56% and 93.92% in the repeat and switch conditions, respectively. In the high load condition, accuracy was 83.74% and 86.14% in the repeat and switch conditions, respectively. A two-way repeated-measures ANOVA on VWM accuracy showed a main effect of load, $[F(1,17) = 11.093, p < .05]$. No other effect was significant, $[F(1,17) < 1]$. A subsequent paired-t test revealed that the main effect was due to higher accuracy in the low load condition, $[t(17) = 3.331, p < .05]$, regardless of repetition.

Experiment 2B. Results are summarized in Figure 8. Fewer than 3% of trials were eliminated due to too short (< 150 msec) or too long (> 2000 msec) RTs. In the low load condition, mean

correct RT was 915.15 msec and 948.49 msec in the repeat and switch conditions, respectively. In the high load condition, mean correct RT was 879.64 msec and 921.23 msec in the repeat and switch conditions, respectively.

A two-way repeated-measures ANOVA on RTs revealed a main effect of repetition, $[F(1,19) = 17.917, p < .001]$, but neither a main effect of load, $[F(1,19) = 1.32, p > .05]$ nor an interaction, $[F(1,19) < 1]$. Following planned comparisons showed faster RTs in the repeated condition, $[t(19) = 4.233, p < .001]$, in both load conditions. No other comparison was significant.

In the low load condition, mean search accuracy was 93.15% and 92.85% in the repeat and switch conditions, respectively. In the high load condition, mean accuracy was 93.82% and 92.18% in the repeat and switch conditions, respectively. A two-way repeated-measures ANOVA on accuracy showed no main effect of repetition, $[F(1,19) < 1]$, no main effect of load, $[F(1,19) = 1.308, p > .05]$, and no interaction, $[F(1,19) < 1]$.
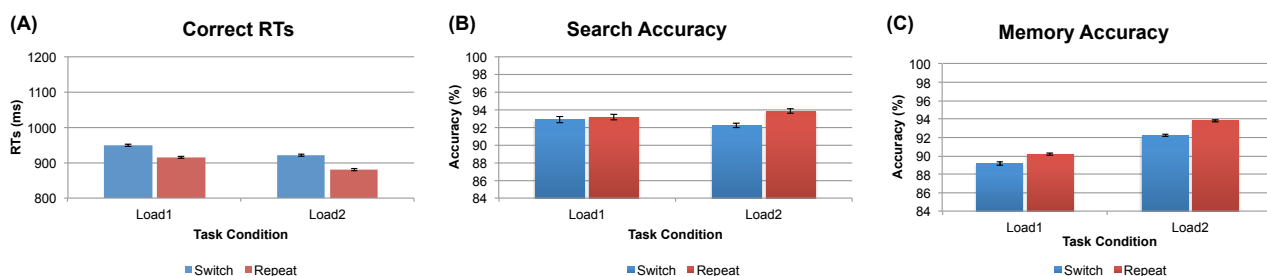

Figure 8. Results of Experiment 2B (spatial VWM task). All data were analyzed by two conditions of repetition (Repeat vs. Switch) and load (Low vs. High). Figures 8A and 8B demonstrate mean RT and accuracy of search task, respectively. Figure 8C shows mean accuracy of VWM task. Error bars are the standard errors of the amount of priming.

Mean VWM accuracy of the low load condition was 90.2% and 89.15% in the repeat and switch conditions, respectively. In the high load condition, accuracy was 90.71% and 91.08% in the repeat and switch conditions, respectively. A two-way repeated-measures ANOVA revealed no main effect of repetition, $[F(1,19) < 1]$, no main effect of load, $[F(1,19) = 1.798, p > .05]$, and no interaction, $[F(1,19) = 2.665, p > .05]$. No other effect from a paired t-test was significant, $[t(1,19) < 1]$.

Experiment 2C. Results are illustrated in Figure 9. Fewer than 2% of trials were eliminated due to too short (< 150 msec) or too long (> 2000 msec) RTs. In the low load condition, mean correct RT was 924.86 msec and 991.06 msec in the repeat and switch conditions, respectively. In the high load condition, mean correct RT was 814.66 msec and 838.03 msec in the repeat and switch conditions, respectively. A two-way repeated-measures ANOVA on RTs revealed a main effect of repetition, $[F(1,19) = 20.835, p < .001]$, a main effect of load, $[F(1,19) = 21.942, p < .001]$, and an interaction between the two, $[F(1,19) = 8.213, p < 0.01]$. In following planned comparisons, RTs were faster in the repeat condition, $[t(19) = 4.565, p < .0001]$ both in the low load condition, $[t(19) = 4.705, p < .0001]$ and the high load condition, $[t(19) = 2.267, p < .05]$. RTs were also faster in the high load condition, $[t(19) = 4.684, p < .001]$ with a smaller amount of priming, $[t(19) = 2.866, p < .05]$.

In the low load condition, mean search accuracy was 93.36% and 92.68% in the repeat and switch conditions, respectively. In the high load condition, mean accuracy was 93.59% and 92.79% in the repeat and switch conditions, respectively. A two-way repeated-measures ANOVA of search accuracy showed neither main effect of repetition, $[F(1,19) = 1.898, p > .05]$, load, $[F(1,19) < 1]$, nor interaction, $[F(1,19) < 1]$.

Mean VWM accuracy of the low load condition was 92.29% and 90.95% in the repeat and switch conditions, respectively. In the high load condition, VWM accuracy was 87.43% and 87.11% in the repeat and switch conditions, respectively. A two-way repeated-measures ANOVA on VWM accuracy revealed a main effect of load, $[F(1,19) = 5.833, p < .05]$, but neither a main effect of repetition nor an interaction was significant, $[F(1,19) < 1]$. According to a following planned comparison, the accuracy was higher in the low load condition, $[t(19) = 2.415, p < .05]$.

Discussion

As discussed above, Experiment 2 tested whether the result of Experiment 1 was truly due to interference by a concurrent VWM load. Results of Experiment 1 left two questions. First, considering the relatively low accuracy of the VWM task in Experiment 1A, there was a possibility that participants gave up on performing the VWM task, resulting in no influence of the task on PoP. Second, considering the task-switching required by the dual task paradigm, the decrease of PoP observed in Experiment 1B could have been due to generally impaired performance in that condition.

In order to address these questions, Experiment 2 aimed to test whether the dual-task interference corresponded to the increase or the decrease of VWM load. Across three experiments, PoP was measured with a concurrent non-spatial (Experiment 2A) and spatial (Experiment 2B, 2C) VWM task. In the VWM task, loads were manipulated by the number of items to be remembered.

As a result, non-spatial VWM load had no effect on PoP (Experiment 2A). Despite the increase of VWM load (as indicated by the decreasing accuracy of the VWM task), the amount

of PoP was constant across low and high VWM load conditions. In contrast, the increase of spatial VWM load decreased PoP (Experiment 2C). The effect was truly driven by the different level of VWM load. The load effect on PoP was also observed in a load effect on accuracy in the VWM task (Experiment 2C), while there was no load effect on PoP when a different load had no impact on accuracy (Experiment 2B)[3]. Taken together, these results suggest that a concurrent VWM load interfered with PoP, and only the spatial VWM load induced such dual-task interference on PoP. Further, these findings suggest that only spatial VWM contributes to PoP.

The remaining question is why spatial VWM is recruited for PoP, while non-spatial VWM appears not to relate to PoP. Such dissociation between spatial and non-spatial VWM has already been reported in dual-task studies adopting a VWM task and conjunction search (Oh & Kim, 2004; Woodman & Luck, 2004; Woodman et al., 2001). Though those studies commonly assume that additional VWM load would fill up VWM's capacity, the overflow of VWM's capacity did not always interfere with the efficiency of search. That is, a search became inefficient with a spatial VWM load (Oh & Kim; Woodman & Luck), but it was unaffected by a non-spatial VWM load (Woodman et al.).
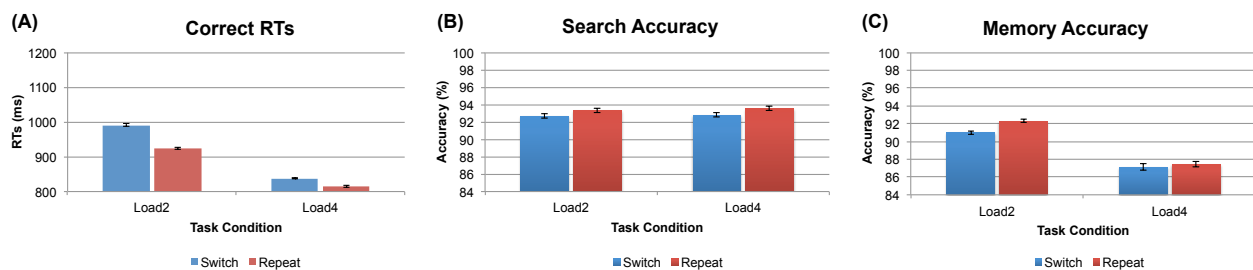

Figure 9. Results of Experiment 2C (spatial VWM task). All data were analyzed by two conditions of repetition (Repeat vs. Switch) and load (Low vs. High). Figures 9A and 9B demonstrate the mean RT and accuracy of search task, respectively. Figure 9C shows the mean accuracy of the VWM task. Error bars are the standard errors of the amount of priming.

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[3] In Experiment 2B, the VWM load of one or two locations yielded no difference in RTs, accuracy, or the amount of PoP. Considering the high accuracy in the VWM task, it is possible that the load of one or two locations was equivalently easy, so performance equally topped out.

A line of research regarding the interaction between spatial VWM and search (Oh &

Kim, 2004; Woodman & Luck, 2004) has proposed that the dual-task interference may be due to

an increasing need for attentional allocation rather than a shortage of memory capacity.

According to this account, though both spatial and non-spatial VWM load filled up the memory

store, only the spatial VWM task required an extra shift of attention to the remembered locations.

Ahn and Kim (2005) directly investigated the account by manipulating the relative position of

the two tasks in the dual task paradigm. In one condition, memory items appeared in one

quadrant of a screen, and the search item showed up in the same quadrant. In another condition,

the stimuli of the two tasks were presented in two separate quadrants. The efficiency of search

was more impaired in the second condition than in the first condition. Results indicate that the

second condition was more detrimental to the efficiency of search because attention had to move

to stimuli presented across quadrants.

In sum, the results of Experiments 1 and 2 support the notion that VWM and attentional

selection in PoP are related to each other, considering that additional VWM load conflicted with

priming. Specifically, the overall result of Experiment 2 shows that such interference was

observed only with a spatial VWM load. Recalling previous findings on the relationship between

search and spatial VWM, the interference seems to reflect the need for an extra shift of attention

rather than the overflow of VWM capacity. Later in the present study, Experiment 4 will further

explore why only spatial VWM load interferes with PoP, and further, how VWM plays a role in

PoP.

CHAPTER 6: EXPERIMENT 3—INTERACTION BETWEEN PRIMING OF POP-OUT AND

VISUAL WORKING MEMORY LOAD

WITH MANIPULATION OF THE AMBIGUITY OF TARGET

Experiments 1 and 2 reported the presence (Experiment 1) and the magnitude (Experiment 2) of the interference between PoP and VWM load. Based on these findings, Experiment 3 investigates the robustness of the role of VWM in an efficient search. The present experiment aims to explore the question of whether the effect of VWM load on PoP interacts with other types of guidance engaged in the task. For example, we can imagine a situation where there is strong guidance based on the properties of the stimuli or display of a search. Since the visual system flexibly draws upon the most efficient means of search based on the information at hand (Navalpakkam & Itti, 2006; 2007), observers would rely on adequately strong guidance rather than their memory of the previous target. Hence, observers would need much less help from the mechanism involved with PoP, resulting in decreased PoP. With the decrease of PoP, it is likely that the presence of strong stimulus-driven guidance would intrude on the contribution of VWM to PoP, too. However, if VWM is a fundamental underpinning of PoP, the effect of VWM load would remain constant, regardless of the presence of other selection guidance.

In the context of a singleton search, one factor of stimulus-driven salience is the ambiguity of the target, which is determined by the set size of the search. In theories of attention (e.g. FIT), singleton or feature searches are considered efficient regardless of set size. However, Bravo and Nakayama (1992) reported that the efficiency of a singleton search was affected by its set size—namely, the efficient search was even further facilitated by an increase of set size. This result was interpreted to indicate that the target's salience grew as the number of distractors

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increased because the target was better contrasted (i.e. unambiguous) against a homogeneous background composed of distractors.

Regarding the relationship between PoP and the ambiguity of target, Meeter and Olivers (2006; Lamy, Bar-Anan, Egeth, & Carmel, 2006; Olivers & Meeter, 2006) observed that PoP decreased with a large set size. In that study, the set size was either three or twelve, and the amount of PoP was significantly smaller in the latter condition. This result implies that observers in an "unambiguous" search highly relied on the stimulus-driven guidance of the current display, discounting the value of information from previous targets. In contrast, in the "ambiguous" search, observers may have leveraged the maximum advantage of previous targets when the salience of the current target was not obvious enough to guide the observer by itself.

In reference to the previous finding, it would be worthwhile to test how ambiguity of target interacts with the influence of VWM load on PoP. The question of interest is whether the stimulus-driven salience of the target affects not only PoP itself but also the role of VWM in PoP. In an "ambiguous" search, the guidance from an increased stimulus-driven salience would replace the guidance of the memory of previous targets. Thus, the mechanism involved with PoP would not be required as much as in an "ambiguous" search. In this situation, if the contribution of VWM is a necessary condition for the occurrence of PoP, it would remain constant by default. Therefore, a concurrent VWM task would still interfere with PoP, regardless of the ambiguity of the target in the search. In contrast, if the role of VWM in PoP is replaceable, the role of VWM should decrease along with a decrease of PoP. As a result, in an "unambiguous" search, the concurrent VWM task would no longer conflict with the role of VWM in PoP, which would be indicated by a comparable amount of priming in the single and dual task conditions.
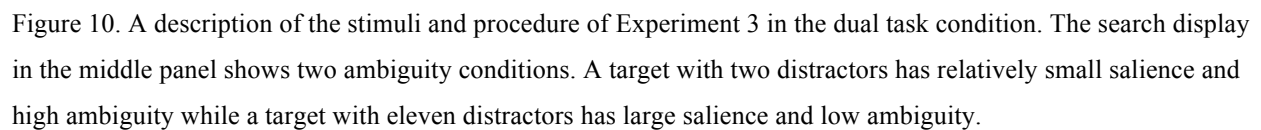
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Methods

Participants. Twenty six subjects participated in Experiment 3. All participants were required to have normal or corrected-to-normal vision, including normal color vision. After excluding the data of participants who showed poor performance (i.e. below 80% of mean accuracy in search or 65% of mean accuracy in VWM task), the data for 20 participants were submitted to further analysis.

Apparatus and Stimuli. All were identical to Experiment 1B.

Procedure. All were identical to Experiment 1B with a few exceptions in the search display (Figure 10). In both single and dual task conditions, the search display was presented with one target and two distractors (high ambiguity) or eleven distractors (low ambiguity). Therefore, there was one more independent variable in Experiment 3 than in Experiment 1B. In addition to the inter-trial repetition of the target color (repeat vs. switch) and the type of task (single task vs. dual task), the level of target ambiguity (i.e. 'ambiguous' and 'unambiguous') was tested. In this 2 x 2 x 2 design, the repetition condition was shuffled within one block out of four different blocks. Two blocks were composed of the search task alone with set sizes of either three ('single-high ambiguity') or twelve ('single-low ambiguity'), and two blocks of the dual task with set sizes of three ('dual-high ambiguity'), or twelve ('dual-low ambiguity').

The order of the four blocks was counterbalanced with four combinations—(1) single-high / single-low / dual-high / dual-low, (2) single-low / single-high / dual-low / dual-high, (3) dual-high / dual-low / single-high / single-low, and (4) dual-low / dual-high / single-low / single-high. In each block, participants performed 96 trials in addition to 10 practice trials at the beginning.

Results

Results are summarized in Figure 11. Fewer than 1% of trials were eliminated due to too short (< 150 msec) or too long (> 2000 msec) RTs. In the 'single-high ambiguity' condition, mean correct RT was 794.88 msec and 874.87 msec in the repeat and switch conditions, respectively. In the 'single-low ambiguity' condition, mean correct RT was 595.07 msec and 636.76 msec in the repeat and switch conditions, respectively. In the 'dual-high ambiguity' condition, mean correct RT was 805.59 msec and 857.42 msec in the repeat and switch conditions, respectively. Lastly, in the 'dual-low ambiguity' condition, mean correct RT was 681.93 msec and 698.73 msec in the repeat and switch conditions, respectively.

Figure 10. A description of the stimuli and procedure of Experiment 3 in the dual task condition. The search display in the middle panel shows two ambiguity conditions. A target with two distractors has relatively small salience and high ambiguity while a target with eleven distractors has large salience and low ambiguity.

Results of a three-way repeated-measures ANOVA on RTs showed a significant main effect of repetition, [$F(1,19) = 51.357$, $p < .001$], a marginal main effect of task, [$F(1,19) = 3.052$, $p = .097$], and a main effect of target ambiguity, [$F(1,19) = 76.664$, $p < .001$]. Among the three variables, no three-way interaction was observed, [$F(1,19) < 1$]. Note the interaction between repetition and task, [$F(1,19) = 8.066$, $p = .001$], between repetition and target ambiguity, [$F(1,19) = 7.275$, $p < .05$], and between task and target ambiguity, [$F(1,19) = 7.71$, $p < .05$]. In sum, PoP was decreased by additional VWM load. And, even though PoP itself was decreased in the "ambiguous" search, the dual-task interference was not modulated by the ambiguity of target.

In the 'single-high ambiguity' condition, mean search accuracy was 96.88% and 93.64% in the repeat and switch conditions, respectively. In the 'single-low ambiguity' condition, mean search accuracy was 98.25% and 97.95% in the repeat and switch conditions, respectively. In the 'dual-high ambiguity' condition, mean search accuracy was 94.67% and 93.5% in the repeat and switch conditions, respectively. Lastly, in the 'dual-low ambiguity' condition, mean search accuracy was 95.64% and 94.69% in the repeat and switch conditions, respectively.

A three-way repeated-measures ANOVA on search accuracy revealed a significant main effect of repetition, [$F(1,19) = 11.403$, $p < .005$], task, [$F(1,19) = 7.132$, $p < .05$], and target ambiguity, [$F(1,19) = 5.468$, $p < .05$]. However, no three-way interaction was observed, [$F(1,19) = 1.093$, $p > .05$]. None of two-way interactions, between repetition and task, [$F(1,19) < 1$], between repetition and ambiguity, [$F(1,19) = 1.349$, $p > .05$], and between task and target ambiguity, [$F(1,19) = 1.676$, $p > .05$] was significant, either.

Mean VWM accuracy of the "dual-high ambiguity" condition was 96.08% and 95.2% in the repeat and switch conditions, respectively. In the "dual-low ambiguity" condition, accuracy was 95.04% and 93.65% in the repeat and switch conditions, respectively. Results of a two-way

repeated-measures ANOVA on VWM accuracy showed a marginal main effect of repetition, $[F(1,19) = 3.178, p = .091]$, but not a main effect of set size, $[F(1,19) < 1]$. The interaction between the two conditions was not significant, either, $[F(1,19) < 1]$.

Discussion

The purpose of Experiment 3 was to investigate the extent to which VWM interacts with PoP. To test the stability of the VWM load effect on PoP, the present experiment introduced a new source of selection guidance, the salience of a target based on its ambiguity. A previous finding (Meeter & Olivers, 2006; Olivers & Meeter, 2006) demonstrated that PoP substantially decreased in a search of low "ambiguity" generated by increased set size. Such interaction between PoP and target ambiguity indicates that inter-trial history may have less impact on search when there is another type of strong selection guidance.
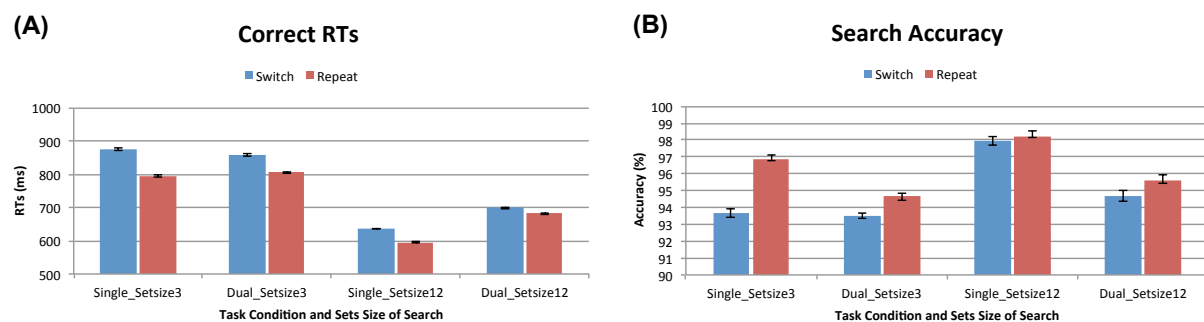

Figure 11. Results of Experiment 3. All data were analyzed by three conditions of repetition (Repeat vs. Switch), task (Single vs. Dual), and ambiguity manipulated by set size--set size 3 and 12 correspond to the ambiguous and unambiguous search, respectively. Figures 11A and 11B demonstrate mean RT and accuracy in the search task, respectively. Error bars are the standard errors of the amount of priming.

Based on this finding, Experiment 3 examined whether the interaction between PoP and VWM load is modulated by the presence of the stimulus-driven guidance of an "unambiguous" search. That is, if the contribution of VWM is a necessary condition for the occurrence of PoP, the interaction between PoP and VWM has to be invariably constant as long as any amount of PoP is observed. As a result, the dual-task interference should remain unaffected by the set size of search.

There is actually a confounding effect in the design and hypothesis of Experiment 3. Considering the previous finding on PoP and target ambiguity (Meeter & Olivers, 2006; Olivers & Meeter, 2006), both RTs and PoP were supposed to substantially decrease in an "unambiguous" search, leaving little room to further decrease in the dual task condition. Therefore, in that type of search, the chance to observe any dual-task interference would be quite slim.

Indeed, results of Experiment 3 replicated previous findings of Meeter and Olivers (2006) such as speeded RTs and substantially decreased PoP in an "unambiguous" search. Nonetheless, our results revealed that the pattern of dual-task interference on PoP remained constant regardless of the ambiguity of target. Consistent with the findings of Experiment 1B and 2C, PoP was even further decreased in the dual task condition. Though the amount of priming was quite small in both single and dual task conditions due to the increased target saliency in the "unambiguous" search, the dual-task interference was proportionally comparable to that in the "ambiguous" search. Together, results of Experiment 3 show that the interaction between PoP and VWM is quite robust, indicating that the contribution of VWM to PoP is inevitable.

The dual-task interference in Experiment 2C was scaled along with the magnitude of VWM load, whereas the interference was not affected by the ambiguity of target in Experiment 3.

However, despite the discrepancy, the results of Experiments 2C and 3 were not contradictory. PoP may occur by virtue of the contribution of VWM, so a high load on VWM would further interfere with the process through which PoP takes place, as observed in Experiment 2C. On the other hand, even when an alternative source of selection guidance intrudes on PoP, it would not affect the very process through which VWM contributes to the occurrence of PoP, as Experiment 3 proposes.

CHAPTER 7: EXPERIMENT 4A—INTERACTION BETWEEN PRIMING OF POP-OUT

AND CONCURRENT VISUAL WORKING MEMORY LOAD WITH THE MANIPULATION

OF TARGET-RELATED POSITION (1)

Though Experiments 1 and 2 show interference between PoP and VWM load, the interaction was only observed with a spatial VWM load, but not with a non-spatial one. Based on this observation, Experiment 4 investigates why spatial VWM exclusively interacted with PoP, aiming to explore how VWM contributes to PoP.

Literature on the interaction between attentional selection and VWM (Oh & Kim, 2004; Woodman & Luck, 2004) has proposed that the allocation of spatial attention is the common process required for a search and a spatial VWM task. Such proposition is in line with the concept of "spatial rehearsal" (Awh & Jonides, 2001; Awh et al., 1998). In their work about the close link between spatial attention and VWM, Awh and colleagues showed that keeping a location in VWM facilitated the processing of stimuli presented at the location, which was similar to the function of spatial attention (Posner & Cohen, 1984). In this account, the role of spatial VWM was like maintaining spatial attention on a location stored in memory.

However, the function of spatial VWM in PoP may not be about simply keeping attention to the locations held in memory. As aforementioned, Soto et al. (2005; also see Han & Kim, 2009; Woodman & Luck, 2007) reported that a feature stored in VWM captured attention when it reappeared in the following search. This suggests that attention is driven to the location of a feature matching the memory representation. Similarly, another line of research (Hollingworth et al., in press; Hollingworth et al., 2008; Richard et al., 2008) showed that a saccade landed faster and more accurately to a feature matching the memory representation. A similar finding was

reported in the context of PoP, too. McPeek, Maljkovic, and Nakayama (1999; also see the discussion of Maljkovic & Nakayama, 1996) reported that saccades landed more quickly on the target whose color or position was repeated across trials[4]. Taken together, these findings indicate that spatial VWM plays a role in attentional selection by deploying attention to the location of the feature matching the memory representation. In the same context, the contribution of spatial VWM to PoP may occur in two steps, by maintaining a feature relevant to the task (e.g. color in the present study) and by allocating spatial attention in accord with the feature. Experiment 4 aimed to test such hypothetical role of VWM in PoP. In order to test the hypothesis, Experiment 4 investigated the interaction between PoP and a VWM load with and without the repetition of target-related positions.

The repetition of position has been reported as another source of inter-trial priming, which is considered to be independent of PoP (i.e. inter-trial priming based on the repetition of a target-defining feature). In Maljkovic and Nakayama (1996), a search was facilitated when a target showed up at or near the position at which the previous target appeared (Figure 12). Such position-based priming did not interact with color-based PoP. That is, RTs were faster when the target's position repeated than when it switched, regardless of whether or not the target color switched. This result suggests that there may be two separate sources of inter-trial priming: repetition of a target-defining feature and repetition of target position.

In addition to the priming based on repetition of absolute position, Maljkovic and Nakayama (1996) found priming based on repetition of the relative position (Figure 13). In their Experiment 3, three items of search were presented in a horizontal row. The hemispheric side of the search display was repeated or switched, with keeping or switching the relative position of the target among the three items in the row. Therefore, there were three conditions of repetition

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[4]Bichot and Schall (1999) reported a similar result in conjunction search.

of target-related positions: the repetition of hemispheric side as well as relative position, the repetition of only relative position, or neither. As a result, the authors found priming induced by the repetition of both absolute and relative positions. The priming was largest when the search display remained in the same hemispheric side and the same relative position across trials. There was also reliable priming based on the repetition of only relative position. This result suggests that position-based priming was not based on a retinotopic coordinate, but based on an object or landmark-oriented coordinate that is more abstract than the retinotopic one (Maljkovic & Nakayama).

The finding of position-based priming (Maljkovic & Nakayama, 1996) indicates that the repetition of target position is advantageous for administering the deployment of spatial attention. If the role of VWM in PoP is devoted to allocating spatial attention in general, the repetition of position would be beneficial for the process. Hence, the relationship between PoP and VWM would be positively affected by repetition of the target position. In contrast, if the role of VWM in PoP is to deploy attention to the location of a task-relevant feature held in memory, the repetition of a task-relevant feature but not position (which is task-irrelevant) should affect PoP. Therefore, the relationship between PoP and VWM would not be affected by the repetition or switch of target position.

Following this rationale, Experiment 4 investigated whether the dual-task interference between PoP and spatial VWM load interacts with the repetition of position. To observe position-based priming, two spatial components of search were manipulated: the relative position of a target among three items and the quadrant in which a search display appeared.
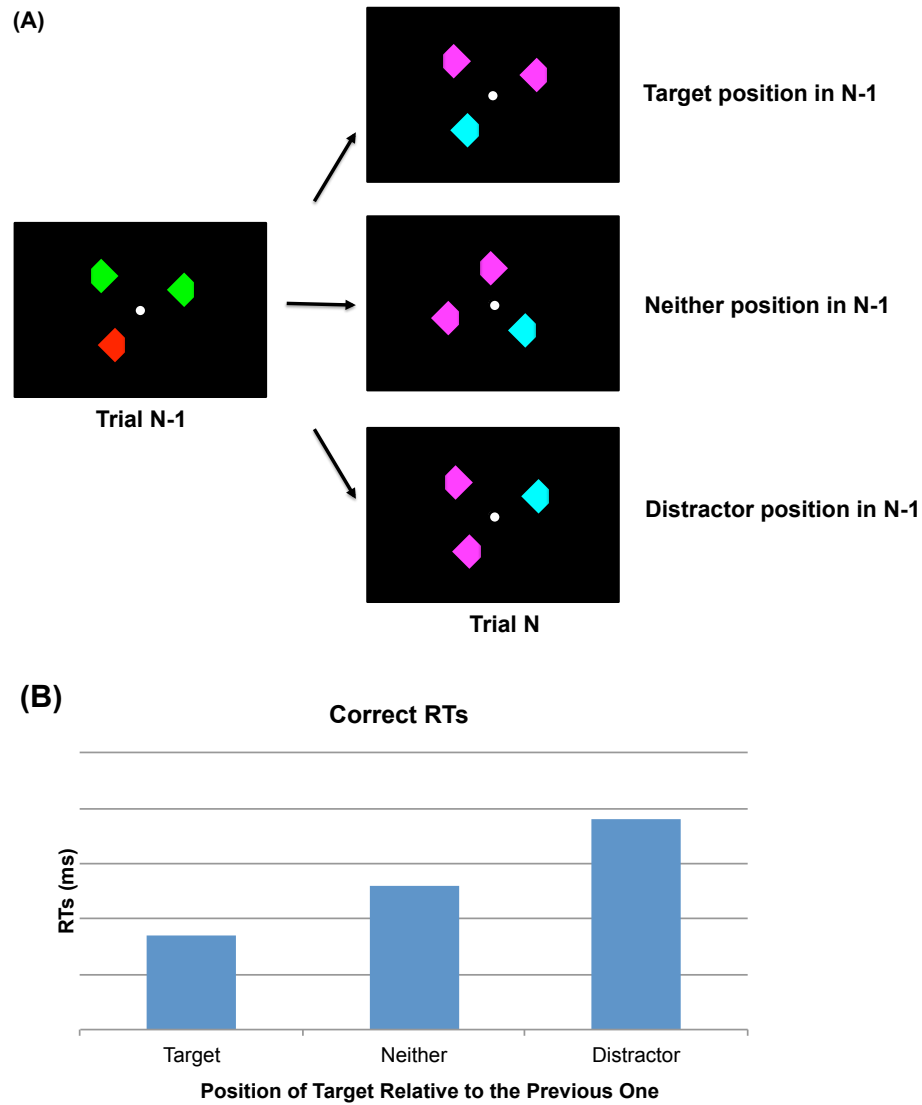
Figure 12. A schematic description of the design and results of Experiments 1 and 2 of Maljkovic and Nakayama (1996). As shown in Figure 12A, in a sequence of two consecutive trials, the target of trial N showed up either at the position of the previous target or at the position of one of the previous distractors. The repetition of position was independent of that of color. Compared to baseline RTs (i.e. "neither position" condition), search became faster when the target's location was repeated, while search was slowed when the target's location was switched (Figure 12B).
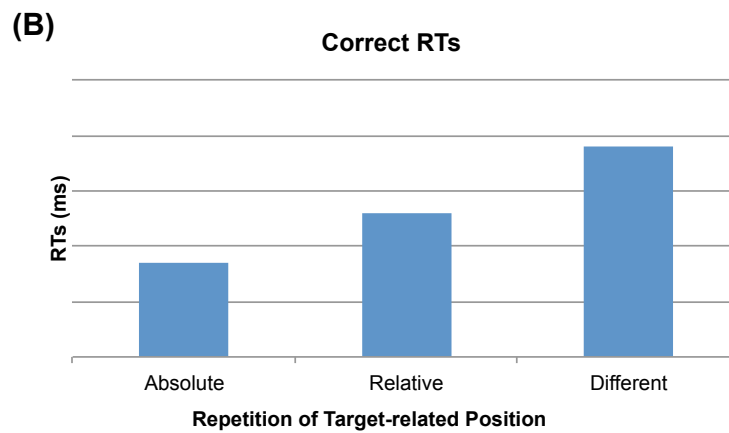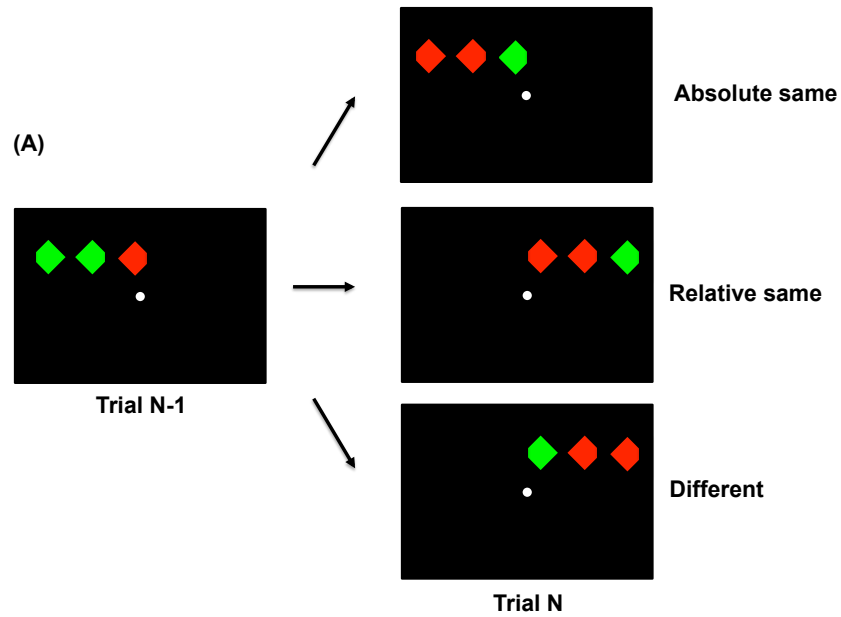
Figure 13.A schematic description of the design and result of Experiment 3 of Maljkovic and Nakayama (1996). In a sequence of two consecutive trials, the position of target in relation to the previous trial was one of three (Figure 13A): the absolute same position, the relative same position, or neither. As a result, search was most facilitated by the repetition of absolute position and moderately facilitated by the repetition of only relative position (Figure 13B).

In this design, there were three potential sources for position-based priming. First source was the repetition of both relative position and the quadrant corresponding to the repetition of "absolute position", as dubbed by Maljkovic and Nakayama (1996). In addition, there was the repetition of relative position alone or the repetition of quadrant alone. Considering that position-based priming is observed with the repetition of either absolute or relative position (Maljkovic & Nakayama), it was expected that position-based priming would occur with the repetition of absolute or relative position. Assuming the presence of position-based priming, of particular interest was whether the position-based priming would interact with the dual-task interference between PoP and additional VWM load. To address this question, PoP was observed with and without the repetition of position, and in the single and dual task conditions. If the role of spatial VWM in PoP is related to the deployment of spatial attention in general, the repetition of position would be advantageous to the process (especially in the dual task condition), and the dual-task interference would be mitigated by the repetition of position. Otherwise, if VWM contributes to PoP by deploying attention exclusively to the stimulus matching the representation of a task-relevant feature, the repetition of position would not interact with the relationship between PoP and VWM.

Methods

Participants. Twenty five subjects participated in Experiment 4A. All participants were required to have normal or corrected-to-normal vision, including normal color vision. After excluding the data of participants who showed poor performance (i.e. below 80% of mean accuracy in search or 65% of mean accuracy in VWM task), the data for 20 participants were submitted to further analysis.

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Apparatus and Stimuli. All were identical to Experiment 1B with one exception. In the search

task, the three search items were presented in a horizontal row at the center of one of the

quadrants. The group of stimuli in the horizontal row subtended approximately 5.5°.

Procedure. All were identical to Experiment 1B with a few exceptions in the search display.

First, in addition to the repetition of target color (repeat vs. switch) and type of task (single task

vs. dual task), the repetition of target-related positions was manipulated. There were four ways to

repeat the target-related positions (Figure 14): the repetition of both quadrant and relative

position ('absolute'), the repetition of relative position ('relative'), the repetition of quadrant

('quadrant'), and neither ('neither'). The repetition of color and position were randomly and

independently assigned within a block of single task or dual task. In each block, participants

performed 192 trials in addition to 20 trials of practice at the beginning. The order of blocks was

counterbalanced.

Results

Fewer than 1% of trials were eliminated due to too short (< 150 msec) or too long (>

2000 msec) RTs. The mean RT and accuracy of all conditions appear in Table 1. Results are

summarized in Figure 15.

A three-way repeated measures ANOVA was then conducted with the variables of color

repetition (2), task (2), and position repetition (4). As a result, a main effect of color repetition,

$[F(1,19) = 36.761, p < .001]$ and a main effect of position repetition, $[F(1,19) = 19.483, p <$

$.001]$, but no main effect of task, $[F(1,19) < 1]$ was observed. A three-way interaction was not

significant, $[F(1,19) < 1]$. Among the three variables, an interaction between color repetition and

task was significant, $[F(1,19) = 8.230, p < .001]$, while interactions between color repetition and position repetition and between task and position repetition were not significant, $[F(1,19) < 1]$.

Since no interaction was found between the two types of repetition, all position conditions were collapsed in the analysis of color repetition, and vice versa (Figure 16). In the analysis of color repetition, a two-way ANOVA revealed a main effect of repetition, $[F(1,19) = 67.856, p < .001]$ and a significant interaction between repetition and task, $[F(1,19) = 4.336, p = 0.051]$, but no main effect of task, $[F(1,19) < 1]$. A planned comparison confirmed that RTs were faster in the repeat condition than in the switch condition, $[t(19) = 11.642, p < .001]$, indicating the presence of PoP. Priming substantially decreased in the dual task condition, $[t(19) = 5.478, p < .001]$, as consistently observed in previous experiments.
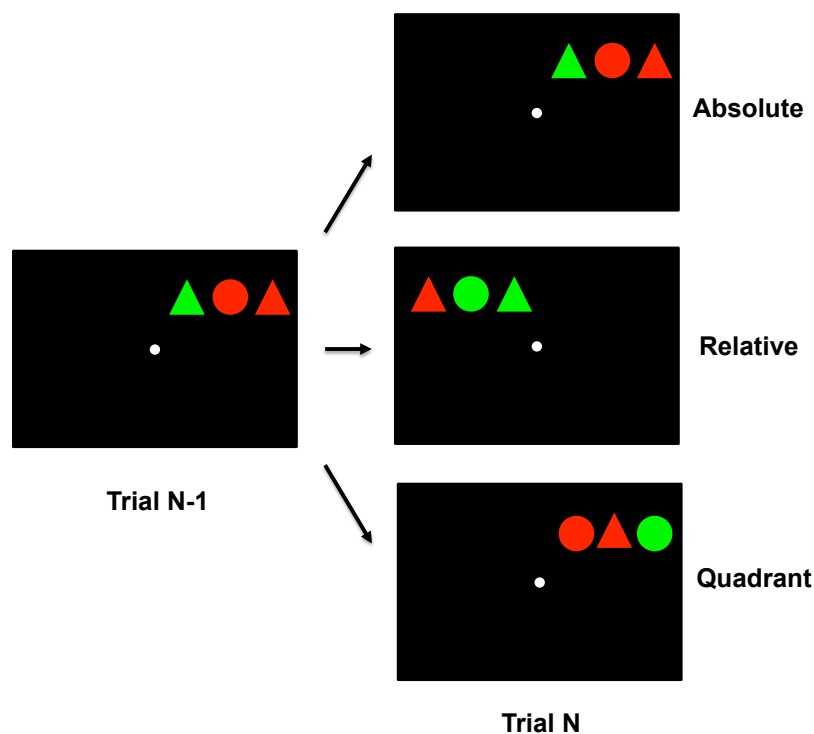

Figure 14.A schematic description of the repetition of target-related positions of Experiment 4A. The "Absolute" condition shows the repetition of both relative position (left) and quadrant. The "Relative" condition illustrates the repetition of relative position alone, while the "Quadrant" condition illustrates the repetition of quadrant alone.

Table 1. Mean RT (msec) and accuracy (%) of Experiment 4A broken down by conditions

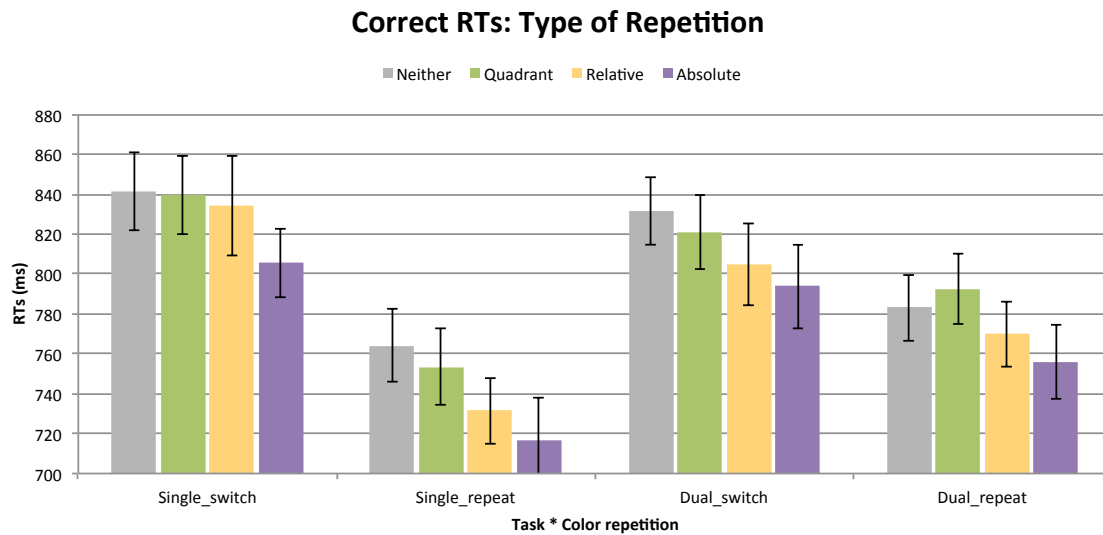| Task Type			Single Task		Dual Task	
			Color			
			Repeat	Switch	Repeat	Switch
Position	**Repeat**	**Absolute**	717.04 (96.76)	805.67 (95.46)	755.77 (95.70)	793.80 (97.86)
		Relative	731.59 (96.12)	834.03 (94.48)	769.71 (95.71)	804.73 (95.52)
	Switch	**Quadrant**	753.58 (95.86)	839.48 (93.58)	792.77 (96.67)	821.20 (95.61)
		Neither	763.97 (97.02)	841.51 (94.57)	783.09 (95.89)	831.40 (95.24)

Correct RTs: Type of Repetition

Figure 15. Results of Experiment 4A. All data were analyzed by three conditions of repetition (Repeat vs. Switch), task (Single vs. Dual), and position repetition (Neither, Quadrant, Relative, and Absolute), respectively. Error bars are the standard errors of mean RT.

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In the analysis of position repetition, a two-way ANOVA between task (2) and position repetition (4) showed a main effect only of position repetition, $[F(1,19) = 5.692, p < .01]$, but neither a main effect of task nor an interaction between two variables were observed, $[F(1,19) < 1]$. A post-hoc analysis indicates that the main effect of position repetition arose from the faster RTs in the absolute and relative conditions compared to the quadrant and neither conditions.
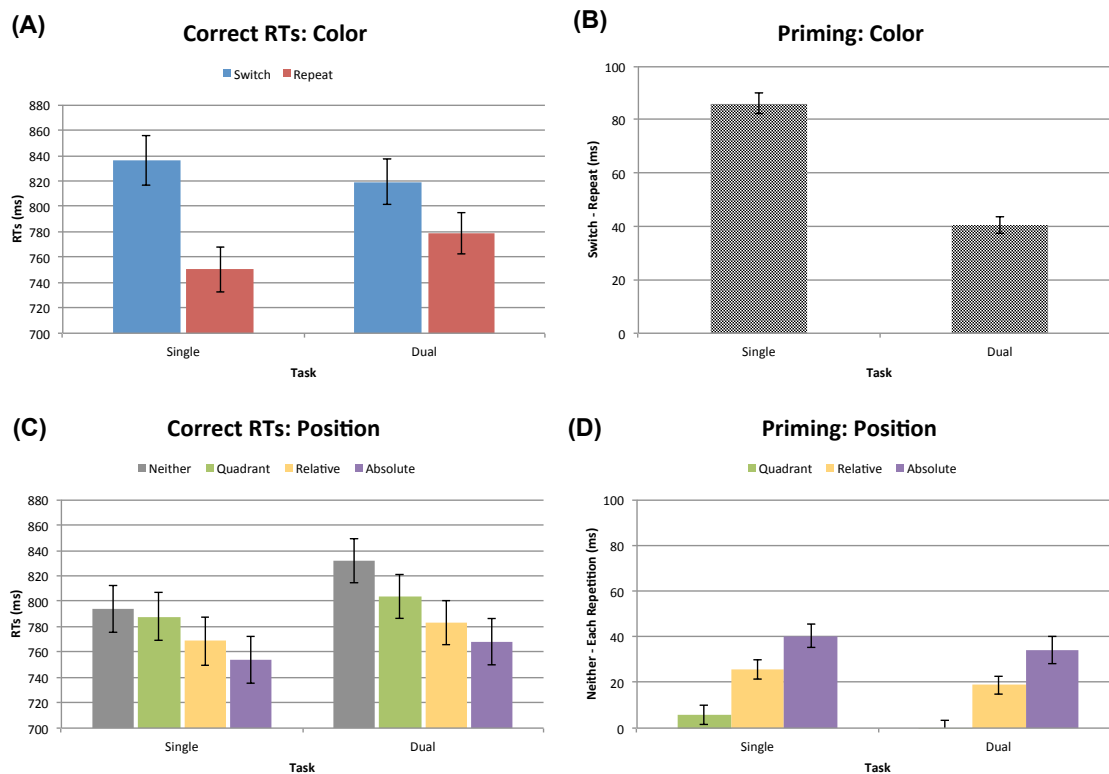

Figure 16. Figure 16A and 16C demonstrate mean RTs of the color repetition condition and the position repetition condition, respectively. Error bars are the standard errors of mean RT. Figure 16B and 16D demonstrate the amount of priming (i.e. the difference between the switch and the repeat conditions), respectively. Error bars are the standard errors of the amount of priming.

In the following planned comparison, RTs of the absolute condition were faster than the quadrant condition, [$t(19) = 2.817$, $p < .05$] and the neither condition, [$t(19) = 4.217$, $p < .001$]. RTs of the relative condition were also faster than those of the quadrant condition, [$t(19) = 3.178$, $p < .01$] and the neither condition, [$t(19) = 3.566$, $p < .01$]. The difference between absolute and relative conditions was not significant, [$t(19) = 1.307$, $p > .05$], nor was the difference between quadrant and neither conditions, [$t(19) < 1$].

Accuracy Analysis. As in the RT analysis, a three-way repeated measures ANOVA was conducted with the variable of color repetition, task, and position repetition. Results revealed neither any main effect, [$F(1,19) < 1$] nor a three-way interaction, [$F(1,19) < 1$]. Among two-way measures, color repetition and task conditions showed a marginally significant interaction, [$F(1,19) = 4.063$, $p = .058$] while no other effect was significant, [$F(1,19) < 1$]. The marginally significant interaction was mainly due to higher accuracy in the color repeat condition, especially in the single task condition, [$t(19) = 3.017$, $p < .01$]. Mean VWM accuracy was 93.6% and 93.9% in the color repeat and switch conditions, respectively. The difference was not significant, [$t(19) < 1$].

Discussion

The main question of Experiment 4A was to uncover the special role of spatial VWM in PoP. Previous findings about visual search and spatial VWM suggest that VWM may be devoted to maintain spatial information and to allocate spatial attention, as shown in the concept of spatial rehearsal of VWM (Awh & Jonides, 2001; Awh et al., 1998). On the other hand, the function of spatial VWM may be restricted to deploy attention to the location of a specific feature held in memory with the purpose of pursuing a task-relevant feature.

To test the hypothetical role of spatial VWM in PoP, Experiment 4A investigated whether the repetition of target-related position affects the relationship between PoP and the VWM task. As a result, both PoP (Maljkovic & Nakayama, 1994) and position-based priming (Maljkovic & Nakayama, 1996) were observed. Search was facilitated with the repetition of target color, and also with the repetition of the absolute or relative position of the previous target. Consistent with previous findings, PoP and position-based priming appear to be independent.

PoP and position-based priming were dissimilar in their interaction with spatial VWM load, too. In the case of PoP, the priming was observed both in the single and dual task conditions, but the amount of priming substantially decreased when an additional VWM load was present. This result replicates the findings of the previous experiments in this study (Experiment 1B, 2C, and 3), indicating a close link between PoP and spatial VWM. In contrast, position-based priming was not affected by the presence of a concurrent VWM load. Together, the results of Experiment 4A indicated that PoP and position-based priming are independent of each other, while PoP is closely involved with spatial VWM. Thus, results support the notion that spatial VWM may play a role in PoP by allocating spatial attention to the location specified by the memory of a target-relevant feature.

Despite the evidence of the dissociation between PoP and position-based priming, Experiment 4A had several problems in its design. Though no interaction was observed among color repetition, task, and position repetition, this could have been due to large variation among the conditions. By introducing a new variable, position repetition, the design created three variables and 16 conditions. Thus, it may have been difficult to find a distinctive pattern among this number of conditions, even if such a pattern existed. Furthermore, since the probability of position repetition was much less than that of position switch (1:2 for the repetition of relative

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position), the conditions had inconsistent sample sizes. For example, the sample size of the "absolute repetition" condition was only about 25 trials across the whole experiment. These two factors could have induced large variance, clouding an effect that in fact exists.

Since no interaction was observed between the color and position repetition conditions, the different conditions of each type of repetition were collapsed in the analysis of color repetition. That is, within the color-repeat or color-switch condition, the data from all four position-related conditions were pooled. Such pooling could have been another source of unpredicted variance. Considering this possibility, a follow-up analysis was conducted. To directly compare the color and position repetition conditions, the analysis selected the mean RT of each condition with no repetition (i.e. no color-switch nor neither position) as the common baseline. For comparison, priming in the color repetition, absolute position repetition, and relative position repetition conditions (excluding trials with more than one type of repetition) was calculated, by subtracting each condition's mean from the baseline, thereby creating a measure of how much each condition facilitated search.

As a result (Figure 17), a 2 x 3 repeated measures ANOVA of task (single and dual task) and type of priming (color, absolute position, and relative position) revealed only a main effect of type of priming, [$F(1,19) = 5.037$, $p < .05$], while no effects were found for task or the interaction between task and type of priming, [$F(1,19) < 1$]. Based on a post-hoc analysis, color-based priming was compared to absolute and relative position-based priming. Between the color and absolute position priming, only a main effect of task was observed [$F(1,19) = 4.96$, $p < .05$]. Between the color and relative position-based priming, there was a main effect of the type of priming, [$F(1,19) = 10.485$, $p < .005$] and an interaction, [$F(1,19) = 5.929$, $p < .05$]. A main effect of task was not significant, [$F(1,19) < 1$]. In sum, the analysis of priming supports PoP and

position-based priming as two fundamentally different phenomena. Hence, the interaction

between PoP and spatial VWM is not modulated by the repetition or switch of target-related

positions.

CHAPTER 8: EXPERIMENT 4B—INTERACTION BETWEEN PRIMING OF POP-OUT AND CONCURRENT VISUAL WORKING MEMORY LOAD WITH THE MANIPULATION OF TARGET-RELATED POSITION (2)

Experiment 4A provided evidence that PoP and position-based priming are dissociative, and that the contribution of spatial VWM is unique to PoP. However, in that experiment, design problems possibly added noise to the result.
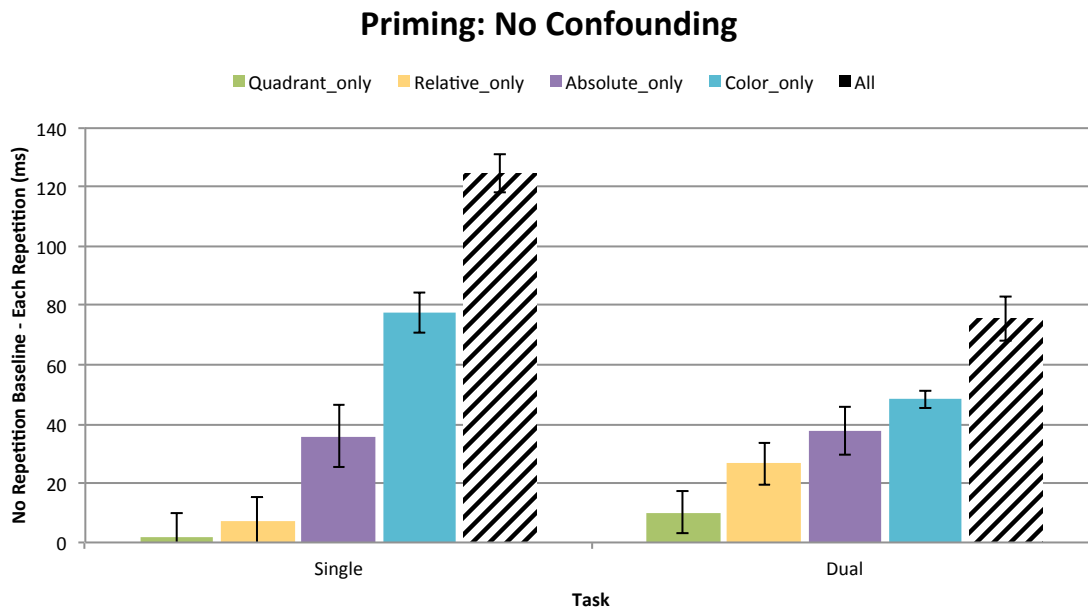

Figure 17. Priming observed in each condition of Experiment 4A. The "All" condition refers to the mean RT from trials of both color and position repetitions. Excepting the "All" condition, each condition included only one type of repetition. Priming was calculated by subtracting the mean RT of each repetition condition from the common baseline RT (i.e. the mean RT of trials with neither color nor position repetition). Error bars are the standard errors of the amount of priming.

Therefore, Experiment 4B again investigated whether position-based priming interacts with the dual-task interference between PoP and spatial VWM, this time with a change in the search display (Figure 18). In Experiment 4B, only relative position was repeated or switched across trials, reducing the variance from the inconsistent sample sizes among conditions. Importantly, the search display of Experiment 4B introduced a much higher location uncertainty to the search, increasing the chance that observers gain a strong advantage from the repetition of relative position.
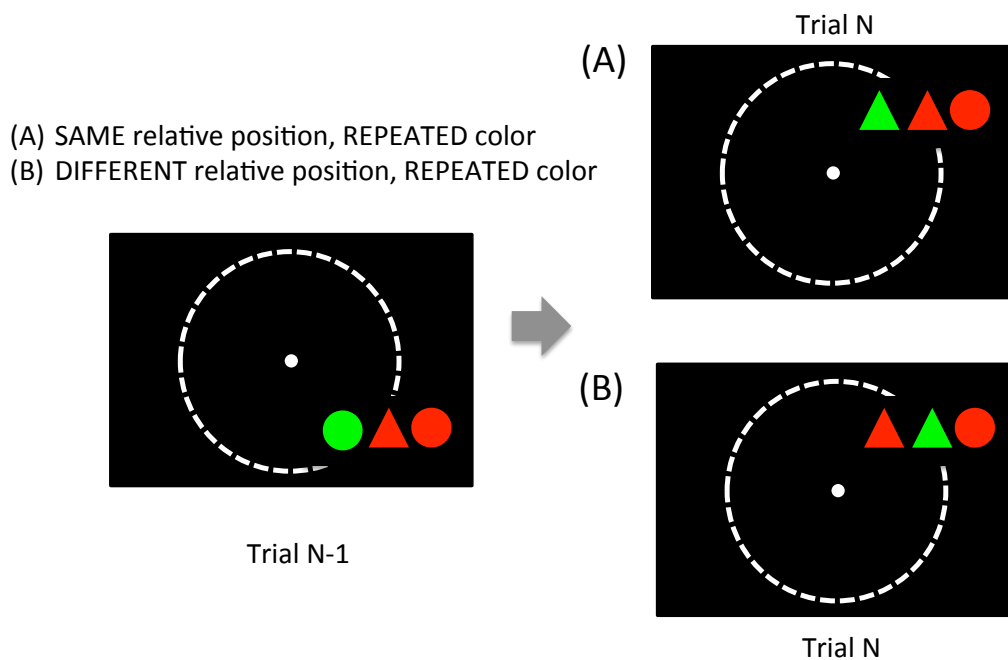

Figure 18. An illustration of a search display in Experiment 4B. Figure 18A corresponds to the "Both" condition in which both color and position are repeated. Figure 18B corresponds to the "Color" condition in which only color is repeated.

Methods

Participants. Twenty seven subjects participated in Experiment 4B. All participants were required to have normal or corrected-to-normal vision, including normal color vision. After excluding the data of participants who showed poor performance (i.e. below 80% of mean accuracy in search or 65% of mean accuracy in VWM task), the data for 20 participants were submitted to further analysis.

Apparatus and Stimuli. All were identical to Experiment 4A with one exception. The group of search stimuli was presented at one of 24 locations distributed on the circumference of an invisible circle, which subtended approximately 6.5°.

Procedure. All were identical to Experiment 4A with one exception in the search display. Having 24 locations at which a search display appeared (instead of four) made it highly unlikely that a display would be presented at the same position as in the previous trial. As a result, no condition corresponded to the repetition of "absolute" position, leaving "relative" position as the only position variable to repeat or switch across trials. Considering both color and position in the search display, there were four possible conditions of repetition or switch: repetition of "both" color and position, repetition of "color", repetition of "position", and repetition of "neither" color nor position.

Results

Fewer than 1% of trials were eliminated due to too short (< 150 msec) or too long (> 2000 msec) RTs. The mean RT and accuracy of all conditions appear in Table 2. A two-way repeated measures ANOVA was then conducted with the variables of repetition (4) and task (2). Results are summarized in Figure 19.

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Table 2. Mean RT (msec) and accuracy (%) of Experiment 4B broken down by conditions

Task Type		Single Task		Dual Task	
		Color			
		Repeat	Switch	Repeat	Switch
Position	Repeat	840.40 (94.58)	812.99 (95.75)	850.68 (93.33)	816.59 (93.54)
	Switch	841.83 (93.01)	854.87 (94.47)	866.89 (92.40)	856.95 (93.18)

They show a main effect of repetition, $[F(1,19) = 10.45, p < .001]$, but neither a main effect of task, $[F(1,19) < 1]$, nor an interaction, $[F(1,19) = 1.576, p > .05]$. Following planned comparison among different types of repetition showed that RTs were faster in the position condition than in both repetition, color repetition, and neither repetition conditions, respectively, $[t(19) = 3.413, p < .05]$, $[t(19) = 5.172, p < .001]$, $[t(19) = 4.958, p < .001]$.
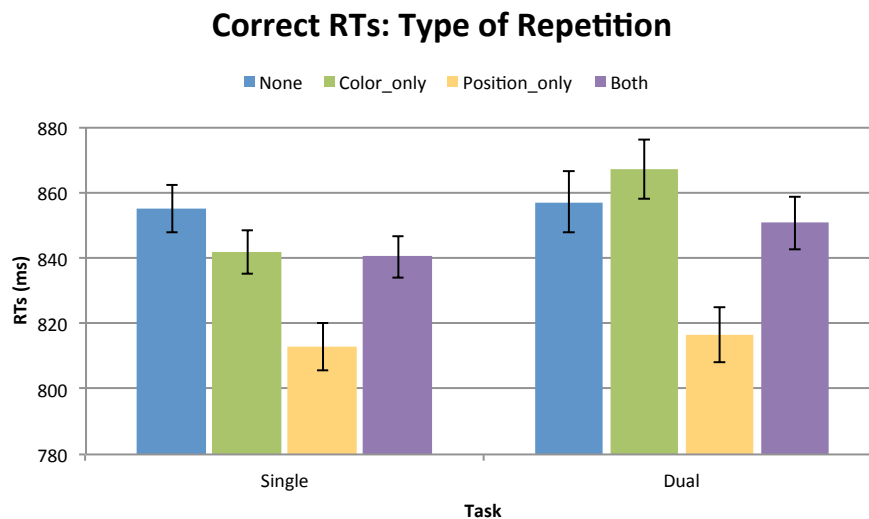

Correct RTs: Type of Repetition

Figure 19. Results of Experiment 4B. All data were analyzed by two conditions representing type of repetition (None, Color, Position, and Both) and task (Single vs. Dual). Error bars are the standard errors of mean RT.

Since no interaction was found between four types of repetition, all position conditions were collapsed in the analysis of color repetition, and vice versa (Figure 20). A two-way ANOVA of color repetition and task showed a main effect of repetition, $[F(1,19) = 5.951, p < .05]$ and a significant interaction between repetition and task, $[F(1,19) = 5.291, p < .05]$, but no main effect of task, $[F(1,19) < 1]$. A planned comparison confirmed that RTs were slower in the repeat condition than in the switch condition, $[t(19) = 2.440, p < .05]$, indicating the reversed pattern of PoP. This pattern of negative priming was only found in the dual task condition, $[t(19) = 2.883, p < .05]$.

A two-way ANOVA of position repetition and task demonstrated only a main effect of repetition, $[F(1,19) = 11.558, p < .005]$, but no main effect of task, $[F(1,19) < 1]$ nor interaction, $[F(1,19) = 1.153, p > .05]$. A planned comparison confirmed that RTs were faster in the repeat condition than in the switch condition, $[t(19) = 3.4, p < .005]$, indicating the presence of position-based priming.

With the mean RT of the neither condition as baseline, priming was calculated for the repetition of color alone and position alone. Results of a two-way ANOVA of the type of repetition and task showed a significant main effect for type of repetition $[F(1,19) = 26.746, p < .0001]$ and an interaction, $[F(1,19) = 4.603, p < .05]$, but there was no main effect of task, $[F(1,19) = 1.012, p > .05]$. A planned comparison revealed that position-based priming was larger than color-based priming in both single and dual task conditions, $[t(19) = 5.172, p < .001]$.

Accuracy Analysis. As in the RT analysis, a two-way repeated measures ANOVA was conducted with the variables of repetition type and task. Results revealed only a marginal main effect of repetition type, $[F(1,19) = 2.386, p = .079]$, but no other effect, $[F(1,19) < 1]$. The marginally significant main effect was due to a higher rate of accuracy in the position repetition

condition than in the color repetition condition, [t(19) = 3.748, p = .001]. Mean VWM accuracy was 94.6% and 93.9% in the color-based repeat and switch conditions, respectively. The difference was not significant, [t(19) < 1].

Discussion

Experiment 4B tested the same question as Experiment 4A with possibly reduced variance and with a search display of high location uncertainty. Results were somewhat surprising. For example, RTs were comparable regardless of the repetition or switch of color. This absence of PoP was never observed across the seven previous experiments of the present study. One possible explanation is that the presentation of the search display with high location uncertainty highly prioritized position-related information. In Experiment 4B, the group of three search stimuli could show up at any one of 24 positions in contrast to the other experiments in which the group was presented in one of four quadrants. Therefore, to reduce uncertainty, participants might have developed a strategy to devote more attention to searching for the position of stimuli than to their color.

Figure 20. Results of Experiment 4B. Figure 20A demonstrates the priming of color repetition or position repetition, calculated by subtracting the mean RT of each repetition condition from the mean RT of the "Neither" repetition condition. Error bars are the standard errors of the amount of priming. Figure 20B and 20C demonstrate mean RTs of color repetition condition and position repetition condition, respectively. Error bars are the standard errors of mean RT.

Previous findings (Fecteau, 2007; Folk & Remington, 2007) have shown that observers are capable of swiftly switching their focus from one feature dimension to another, according to the task relevance of each feature dimension. In those studies, PoP was observed only with the repetition of a task-relevant feature. Likewise, in the current experiment, it is likely that participants selected to pay attention to the repetition of position at the cost of PoP.

In addition to the absence of PoP, RTs were slowed even in the repetition condition with additional VWM load. Despite the absence of PoP, such negative priming indicates that spatial VWM may be linked closely with the process of locating and responding to the repeated feature across trials.

Consistent with the finding of Experiment 4A, the effect of position repetition was independent of that of color repetition. Search was facilitated by the repetition of relative position, regardless of the concurrent VWM load.

Taken together, it appears that VWM contributes to allocating attention to the location of a repeated target-relevant feature, while it is not involved with the speeded response to a stimulus at the location of the previous target. Therefore, overall results of Experiment 4 suggest that the function of spatial VWM is sensitive to task-relevance, serving to trace a task-relevant feature repeated across trials.

CHAPTER 9: CONCLUSIONS AND DISCUSSION

9.1. Overview

The current study aimed to explore the underlying mechanism of the well-known inter-trial history effect, PoP (Maljkovic & Nakayama, 1994; 1996; 2000). Though the mechanism of PoP has long been debated, prominent theories of attention and a number of empirical findings have reached no conclusion on the matter. Although the initial findings of PoP (Maljkovic & Nakayama) propose a type of short-term memory contributing to PoP, the nature of this mechanism has not been clearly addressed. Another account proposes a feature gain modulation mechanism (Wolfe et al., 2003) which suggests that PoP arises from a residual gain associated with a feature of the previous target, but the nature of the gain is still in question.

Therefore, investigating the mechanism responsible for PoP will shed light on the phenomenon. Moreover, considering the large influence of past experience in our everyday behavior, uncovering the underlying mechanism of PoP will have great significance in understanding how the visual system implements the guidance of past experience for efficient behavior.

The present study examined whether PoP is involved with VWM, a type of memory to actively maintain and manipulate information for brief periods of time. VWM has been suggested to have a close association with a concurrent attentional selection, as shown in a series of studies adopting the dual task paradigm composed of visual search and a VWM task (Oh & Kim, 2004; Woodman & Luck, 2004). Despite the previous finding that VWM plays a crucial role in search, a study on the relationship between PoP and VWM (Lee et al., 2009) reported that additional VWM load did not affect PoP. The present study questioned this finding and

demonstrated technical and theoretical problems of Lee et al.'s experiments. Bearing those

problems in mind, the present study thoroughly investigated the relationship between PoP and

VWM load with a modified version of the dual task paradigm inspired by Lee et al.

Experiment 1 was designed to test whether additional VWM load had an impact on PoP.

Given the finding that only the spatial VWM task significantly interfered with a concurrent

search (Oh & Kim, 2004; Woodman & Luck, 2004), Experiment 1 tested whether spatial and

non-spatial VWM loads had different patterns of interaction with PoP. Results showed an

disruptive interaction between PoP and spatial VWM load (Experiment 1B), while there was no

interaction between PoP and non-spatial VWM load (Experiment 1A). Such dual-task

interference was replicated in Experiment 2, and the close relationship between PoP and spatial

VWM was further demonstrated by the fact that the interference was graded with the magnitude

of the VWM load. Overall results suggest that the mechanism responsible for PoP and VWM

share a common process, so additional VWM load overburdens the process. In addition, the

results indicate that only spatial VWM plays a role in PoP, which is consistent with other

findings on the relationship between visual search and VWM.

Based on the findings of Experiments 1 and 2, Experiments 3 and 4 investigated the

nature of the association between PoP and VWM. Experiment 3 tested the robustness of the

relationship between the two by presenting a strong stimulus-driven guidance in the search

display. Reduced target ambiguity is known to intrude on PoP (Meeter & Olivers, 2006; Lamy et

al., 2006; Olivers & Meeter, 2006); therefore it was expected to affect the process correlated with

PoP. As a result, while PoP substantially decreased in the "unambiguous" search, the dual-task

interference between PoP and VWM load remained unaffected. This result indicates that the role

of VWM is indispensible for the occurrence of PoP, rather than mutually correlated and varied with PoP.

Experiment 4 directly investigated why spatial VWM exclusively contributes to PoP. Based on the finding that spatial VWM plays a role to allocate spatial attention (Awh & Jonides, 2001; Awh et al., 1998), Experiment 4 tested whether the role of spatial VWM in PoP is restricted to deploy spatial attention only for a task-relevant feature. The dual-task interference between PoP and VWM was observed with and without the repetition of target-related positions, a result which supports previous findings on position-based inter-trial priming (Maljkovic & Nakayama, 1996). Although the repetition of target position facilitated the deployment of spatial attention in search, such advantage was independent of either PoP or the effect of spatial VWM load. This result was interpreted as evidence that spatial VWM plays a role in PoP by biasing spatial attention in favor of a repeated task-relevant feature.

9.2. Priming of pop-out and spatial visual working memory

The results of Experiments 1 and 2 showed that the spatial VWM task exclusively interacts with PoP. One may find this result surprising for two reasons. First, PoP is often observed in a singleton search in which a target is defined by a feature. Therefore, if the previous target is stored in memory, a non-spatial feature memory system should be related to PoP, as Lee et al. (2009) assumed. Second, interference induced by the concurrent spatial VWM task has been reported in a conjunction search (Oh & Kim, 2004; Woodman & Luck, 2004). Indeed, those studies propose that spatial VWM plays a role in a search by deploying spatial attention, based mainly on a conjunction search in which focused attention scrutinizes the location of each stimulus (e.g. FIT, Treisman & Gelade, 1980).

However, such questions can be readily explained by findings on the relationship between attentional selection and VWM. In singleton search, a target receives focused attention[5], thereby giving its feature a chance to be encoded in memory (Schmidt et al., 2002). Once a memory representation is constructed, the representation guides attention to a matching stimulus (Chelazzi et al., 1993; Chelazzi et al., 1998; Duncan & Desimone, 1995). In sum, the function of spatial VWM in PoP is not simply storing and maintaining the color or spatial location in memory. Rather, spatial VWM seems to be involved with an integrative process to remember the task-relevant information and to allocate spatial attention in accord with that information.

A similar idea is found in the discussion of Maljkovic and Nakayama (1996). According to their "gaze reorientation" hypothesis, PoP and position-based priming depend on a representation in a "short-term memory", which is the basis of re-orienting eye gaze to an object or location involved in a sequence of actions. Later eye movement data (McPeek et al., 1999) supported the gaze reorientation hypothesis by showing that saccades to a target were faster and more accurate when the target color was repeated across trials. This result indicates that the underlying mechanism of PoP contributes to rapidly reorienting the observer's gaze to recently foveated target.

A line of research on transsaccadic memory (Hollingworth et al., 2008; Richard et al., 2008) reported similar findings. In their studies, while participants were maintaining a color, the same color reappeared at a different location from where it was previously presented. Though participants at first moved their saccades to the location of the initial presentation, they quickly and accurately corrected saccades to the location of the stimulus matching their memory

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[5]Though the target is defined by a single feature, singleton search is not pre-attentive. The discrimination task of the paradigm requires focused attention to be allocated at the location of target. This is supported by the result of McPeek et al. (1999; Also Bravo & Nakayama [1992]) that shows the involvement of focused attention in singleton search.

representation. Recently, Hollingworth et al. (in press) also showed that saccades to an abrupt onset were faster and more accurate when the onset matched the memory representation. This result suggests that such gaze correction may even contribute to a quick and simple type of attentional selection like a singleton search. Taken together, these findings suggest that the role of spatial VWM in PoP is presumably to guide attention to the stimulus of a repeated task-relevant feature. By virtue of this type of guidance, the visual system may obtain the chance to pursue and process an object in a stable manner[6].

9.3. Underlying mechanism of priming of pop-out: Two possible mechanisms

The results of four experiments in this study converge to propose a close relationship between PoP and VWM. Indeed, theoretically and empirically, it seems quite convincing that VWM plays a critical role in PoP. However, it does not seem that VWM is the only underlying mechanism of PoP, considering that some findings on PoP hardly can be explained by the function of VWM. For example, PoP is independent of voluntary control or explicit knowledge about the target (Maljkovic & Nakayama, 1994; 2000), suggesting that at least some portion of the priming must be involved with a memory system different from VWM.

As shown in position-based priming which is independent of PoP and VWM, there might be multiple sources of inter-trial priming. Considering the possible function of PoP to guide a sequence of action (Maljkovic & Nakayama, 1996), a portion of the priming may be involved with a reflexive and automatic guidance. Recent work about the role of eye movement in a multi-component activity (e.g. tea making; Land, Mennie, & Rusted, 1999; Land & Hayhoe, 2001) has

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[6]Consistent with this account, it has been largely suggested that transsacadic memory (corresponding to working memory) serves to obtain perceptual stability and object correspondence by integrating separate retinal images (e.g. Hayhoe, Lachter, & Feldman, 1991; Hollingworth et al., 2008; Irwin, 1991).

suggested that eye movement contributes to action in two ways: actively planning how to execute the next action and passively responding to the environment. Similarly, PoP may be driven by both the guidance based on VWM and the guidance based on a passive response to a repeated stimulus.

The present study suggests that spatial VWM guides spatial attention to the task-relevant feature matching a memory representation. A missing link here is where the memory representation is maintained. Given that a feature (i.e. non-spatial) VWM task does not interfere with PoP (Experiments 1 and 2), there must be another mechanism corresponding to the memory representation. One possible mechanism is a "gain" proposed by the feature gain modulation account (Wolfe et al., 2003). Though the account does not clearly address what the gain is, it may correspond to a reduced response threshold to a repeated feature.

A recent brain-imaging study exploring the neural basis of PoP (Kristjánsson et al., 2007) provides evidence to support the collaboration of different sources of guidance in PoP. With PoP, the authors found repetition suppression (i.e. a reduced response to a repeatedly presented stimulus; Grill-Spector et al., 2006) in inferior temporal areas as well as in fronto-parietal areas. Inferior temporal areas are known to process object-related information such as color or shape (e.g. Grill-Spector et al., 1998; Grill-Spector & Malach, 2001), while the fronto-parietal network is believed to control spatial attention (Kastner & Ungerleider, 2001; LaBar et al., 1999). Thus, results indicate that at least two separate mechanisms may contribute to PoP, by priming the repeated feature and by deploying spatial attention to the location of the primed feature in the current display.

9.4. Conclusion

We often encounter a situation where we incorporate recent experience into our current behavior. In that process, we also orchestrate various sources of guidance to fulfill a behavioral goal. Though we intuitively assume the active process of attentional selection based on recent experience, very little of this process has been clearly addressed. The current study aimed to develop the theories of inter-trial priming by uncovering the mechanism that contributes to PoP. Further, the present study intended to advance the existing theory of attention to a more comprehensive one, by filling the gap found in the literature.

The results of the present study offer the first solid evidence in support of the contribution of VWM to PoP. This finding is profoundly significant in several aspects. First, the current results supported the idea that PoP is at least partially driven by top-down attentional control such as VWM, rather than bottom-up processes such as a lingering perceptual trace. Second, results of the present study suggest a unique relationship between attentional selection and spatial VWM. Consistent with previous findings, overall results imply that VWM allocates spatial attention to a target-relevant feature based on the memory representation. Lastly, the present study serves an example of the flexibility of the visual system. Previous findings on visual search have shown that attentional selection is a dynamic process, strategically adopting a variety of bottom-up and top-down guidance to accomplish the most adaptive behavior. Consistent with such findings, the results of the present study suggest that PoP may be guided by a variety of processes including VWM. That is, even a seemingly automatic and minute behavior may in fact be in fact the result of a sophisticated process for efficient response to the environment.

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