

Exploring the Nature of Memory Representations Underlying Priming of Pop-out in
Visual Search

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To Inci, my muse for life.

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CHAPTER 1

INTRODUCTION

Visual search is an important piece in our psychological repertoire. We incessantly search for specific items in the environment, such as a friend in a crowded airport, a tomato in a bin of various vegetables, a red pen among many other colors. We employ several basic psychological processes to this end: we keep in memory the identity of the item being searched, we attend to locations in the scene as search attempts, and we execute the appropriate response once the target is found.

Researchers have often emphasized how and to what extent attention is employed in visual search tasks, yet, exploring the role of memory in visual search has been a secondary goal in this line of research (Woodman & Chun, 2006). Yet, the evidence that repeatedly searching for the same item across trials gradually reduces reaction times (e.g., Carlisle, Arita, Pardo, & Woodman, 2011; Reinhart & Woodman, 2013) implies that either working or long-term memory representations are being employed in visual search.

The roles of these memory systems in visual search could be explored by examining event-related potentials (ERPs) that are known to be correlates of specific

memory systems in visual search tasks. For example, if an experimental manipulation, such as the number of repetitions of a target, produces changes in long-term memory related ERPs and these changes correlate with reaction time reductions in locating the target, one could argue that long-term memory representations underlie the behavioral effect to some extent. Some recent studies (e.g., Carlisle et al., 2011; Reinhart & Woodman, 2013) applied this logic in discriminating the contributions of working and long-term memory in visual search tasks that involve searching for a target defined by a unique feature value (e.g., color; a green letter C among gray Cs).

However, these studies required participants to memorize the identity of the target item over a range of trials. In these studies the target item was described in a separate array that preceded the search array, and participants needed to remember the identity of the target between these two arrays. Alternatively, the degree to which working or long-term memory representations could facilitate visual can be tracked by using the priming of pop-out task in which information about the identity of the target is not provided in advance (Duncan, 1985; Maljkovic & Nakayama, 1994). In the priming of pop-out task, the target in each trial is defined by a unique feature value (e.g., the color red) when the distractors share a different value for that feature dimension (e.g., the color blue). In this task, after locating the target, participants respond to a secondary feature of the target, such as determining which part, bottom or top, of the target is missing. The target pops-out among distractors in priming of pop-out, provided that the feature values of the target and distractors are sufficiently different from each other (Duncan & Humphreys, 1989; Wolfe & Horowitz, 2004). Because participants do not have any information about the identity of the target before any trial, memorizing the

target is not relevant to this task. However, the main behavioral finding from this task is that when the target-defining feature (e.g., a pop-out color among same-colored distractors) repeats across trials, reaction times to respond to the secondary feature of the target (e.g., determining which part of the item is truncated) become faster (Maljkovic & Nakayama, 1994). Maljkovic and Nakayama explained this essential finding by proposing that a short-term visual memory system functioning outside of awareness (i.e., visual implicit memory) and evolved to deal with rapidly changing, complex task visual search sequences guides attention to the target and thus facilitates performance with repetitions. However, the possibility that long-term memory representations could facilitate priming of pop-out has not been evaluated yet. Recent work in visual search using ERPs showed that both long-term and short-term memory representations are formed with each repetition of the target (Carlisle et al., 2011; Reinhart & Woodman, 2013). Visual search performance is driven by short-term memory representations in the first few repetitions, however, long-term memory starts predicting performance with longer sequences (Carlisle et al., 2011; Reinhart & Woodman, 2013). In this dissertation, one of my goals is to explore the possibility that long-term memory representations underlie priming of pop-out. The idea that different memory systems are active in learning a task and that these systems predict performance in different stages of learning (Logan, 1988a, 1988b; Logan, 1990) has been used as a parsimonious explanation of the contribution of different memory systems to tasks involving repetitions of targets (Carlisle et al., 2011; Logan, 1990; Reinhart & Woodman, 2013). It is possible that priming of pop-out could be considered

as a phenomenon that could result in very efficient performance levels with repetitions establishing of long-term memories of episodes with each repetition (e.g., Logan, 1990).

Additionally, the investigation of the memory systems involved in priming of pop-out task has theoretical value, essentially because the memory requirements and attentional limitations are minimal. That is, if working and long-term memory are found to be at work in a task in which their employment is not demanded, these memory systems can be argued to play a fundamental role for that psychological task. As described above, the identity of targets in priming of pop-out is defined within trials and is subject to change with each trial. The existence of a memory system that facilitates visual search in such a situation implies that this memory system is necessary to optimize performance in visual search. From an attentional viewpoint, target-defining features pop out in priming of pop-out tasks and searching for a pop-out feature has been argued to require minimal attention (Treisman & Gelade, 1980; Wolfe & Horowitz, 2004). For example, the number of distractors in simple pop-out search does not affect reaction times for locating the target (Treisman & Gelade, 1980). It has been proposed that the pop-out feature is recognized at a processing stage that requires minimal attention (Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Wolfe & Horowitz, 2004). Although, responding to the secondary feature of the target requires focused attention, this is not the case in locating the target (Bravo & Nakayama, 1992). Therefore, both memory and attentional requirements in priming of pop-out tasks are minimal, at least until responding to the secondary feature of the target. Identifying how working and/or long-term memory representations come into the picture in a case like priming of pop-out could demonstrate the very basic role of memory in visual search.

Relating Priming of Pop-out to Other Psychological Paradigms

Consistent vs. Variable Mapping & Automaticity

In the priming of pop-out task, the target and distractors might swap between trials. That is, if the target is red and distractors are green in one trial, the next trial might have the red item as the target and green items as the distractor. This feature of priming of pop-out makes it a variable mapping (VM) task in which target and distractor sets are not fixed throughout trials and swap with each other (Logan, 1988b; Schneider & Shiffrin, 1977). On the contrary, when the identity of the target and distractors is fixed between trials, the task can be evaluated as a consistent mapping (CM) task (Logan, 1988b; Schneider & Shiffrin, 1977). Automaticity of performance requires consistent mapping of targets and distractors (Kramer & Strayer, 1988; Logan, 1988b; Logan, 1990; Schneider & Shiffrin, 1977), thus the priming of pop-out task, being a VM task by design, does not allow development of automaticity. However, if the target and distractors are the same in sequences of trials, one might expect that the mechanisms that enable automaticity (e.g., acquisition of instances, Logan, 1988b) will help improve performance.

Actually, Logan (1990) showed that repetition priming and automaticity are closely related as even a few repetitions of a stimulus when the interpretation of the stimulus is kept constant can demonstrate a power law speed-up of performance, which is an indicator of automatic performance (Logan, 1988b; Schneider & Shiffrin, 1977). Because automaticity is based on long-term memory representations (e.g., instances,

Logan, 1988), any benefit of sequential repetitions of the target item in priming of pop-out might be sourced in long-term memory representations. One of the main purposes of this study is to examine this possibility. Further, it was shown that when the priming of pop-out is made a CM task in which the color (i.e., primary feature) of targets and distractors are kept constant throughout an experimental block, the number of distractors did not affect reaction times in responding to the target (Bravo & Nakayama, 1992; Maljkovic & Nakayama, 1994). On the contrary, in the VM version of the compound-search task, greater set sizes lead to faster reaction times (Bravo & Nakayama, 1992; Maljkovic & Nakayama, 1994). The pure benefit of repetition of color on speeding-up of RTs in the VM version of the compound task has not been yet evaluated. Focal attention (Bravo & Nakayama, 1992), the process by which the target is responded to in priming of pop-out, benefits from greater number of distractors in the VM version of the task, however, it is not clear whether any type of memory representations help focal attention if the color of the target is the same with the previous trial. I will examine any possible relationship between focal attention and memory representations in Experiment 1 by using set size (4, 6, or 12), type of mapping (CM vs. VM), and type of repetition (color vs. response vs. no repetition) as experimental factors.

Contextual Cueing

Chun and Nakayama (2000) identified priming of pop-out as one of the main memory mechanisms that guided attention throughout views. It is well known that the details of the world provide too much information for the perceptual system to handle

(Broadbent, 1957), thus only the gist of the scenes are processed in detail (Simons & Levin, 1997). However, this idea necessitates that the visual system needs memory mechanisms to sustain a coherent external world (Marvin M. Chun & Nakayama, 2000; Clark, 2013; Irwin & Yeomans, 1986). Chun and Nakayama (2000; also see Maljkovic & Nakayama, 1994, 1996, 2000) argued that priming of pop-out provides the short-term solution to the problem of how attention is guided (Duncan & Humphreys, 1989) with information from previous scenes. Chun and Nakayama (2000) proposed that another memory mechanism to sustain information to guide attention in the long term is contextual cueing. Contextual cueing was observed in a visual search task, which occasionally included the same spatial configurations of distractors and a target (M. M. Chun & Jiang, 1998). Chun and Jiang showed that repetitions of the same configuration throughout experimental blocks led to faster reaction times in responding to the target as compared to visual search in new configurations from the same experimental blocks. Participants did not have any explicit memory of the repeated distractor and target configurations and the effect lasted throughout 10 experimental blocks. Chun and Nakayama (2000) drew the distinction between contextual cueing and priming of pop-out in the former being the long-term memory mechanism to guide attention in future scenes in long, whereas the latter evolved to deal with short-term necessities to sustain scene information. As argued above, these two phenomena do not need to be based on different memory representations. That is, priming of pop-out might depend on the long-term memory representations (i.e., instances), especially when primary features repeat more than a few times.

The Distractor Preview Effect

The type of decision on the popping-out target determines whether focal attention is necessary for the task (Bravo & Nakayama, 1992). For example, when the decision in pop-out visual search is presence or absence of the target, the slope of the function relating set size to RT is practically zero (Bravo & Nakayama, 1992; Treisman & Gelade, 1980; Wolfe & Horowitz, 2004). Treisman and Gelade (1980, also see Bravo & Nakayama, 1992) argued that the number of distractors did not affect RTs in finding the pop-out target because all stimuli are processed in parallel and for this reason visual search does not require focal attention. When the decision about the target involves a secondary feature, such as responding to the direction of the truncated area in the target, focal attention becomes necessary (Bravo & Nakayama, 1992; Maljkovic & Nakayama, 1994). However, the locus of attention in priming of pop-out is not clear.

Although attention is necessary to respond to the secondary feature, it might also be necessary in locating the pop-out target for the benefit of priming from previous same-color target trials. Goolsby and Suzuki (2001) explored whether attention played an extra role in priming of pop-out via encoding of the pop-out target. They interspersed trials with cues around the pop-out target preceding the search array 200 milliseconds with regular priming of pop-out trials. Their rationale was that the cue would have a detrimental effect on the extent of priming of pop-out because it would attract attention away from the color of the target. They indeed found that priming of pop-out was weaker when the target was preceded by a cue. The authors also examined whether attending to the color of an upcoming target even if it is the distractor color in the current trial will produce priming of pop-out. It did not. Goolsby and Suzuki concluded that

priming of pop-out required focused attention to the target color and cannot be acquired with passive viewing. Focal attention is also found to be necessary for the acquisition of instances (Logan, 1988b, 1998), thus Goolsby and Suzuki's findings do not rule out a possible long-term memory account of priming of pop-out. It simply rules out the ideas that attention is only necessary in responding to the secondary feature of the pop-out item and priming of pop-out can be considered as a perceptual, passive process. The proposal by Nakayama and Maljkovic (1994, 1996, 2000) that a short-term, implicit, automatically engaged visual memory system leads to priming of pop-out essentially describes such a perceptual, passive system. Thus, the relationship between how attention proceeds in priming of pop-out and how it interacts with either working or long-term memory representations is vital for a more complete understanding of that effect.

Behavioral and ERP Findings from Priming of Pop-out Research

Behavioral Findings

To reiterate, some of the most essential findings about repetition effects in the priming of pop-out task come from the seminal study of Maljkovic and Nakayama (1994). In this series of experiments, the target was often defined as the diamond shaped object that differed from other diamond shaped objects in color (e.g., the red diamond among green diamonds). The task of participants was to report which part of the diamond, up or down, was truncated. The essential finding from that study was that when the color defining the target repeated between trials participants were faster in

reporting which part of the diamond shape of the target was missing (i.e., priming of pop-out). However, this priming effect was specifically observed for the target feature (i.e., color in most of their experiments) repetitions; repeating the shape of the target, which also meant response repetitions, on the other hand, did not lead to faster reaction times. Based on this essential finding, the authors concluded that the intertrial priming was specific to the repetition of the target feature (i.e., priming of pop-out) and repeating responses did not benefit search performance at all.

Additionally, Maljkovic and Nakayama (1994) analyzed to what extent target feature repetitions from previous trials affected the search performance for the current trial (i.e., the effect of the “ $n - i$ ”th trial on the “ n ”th trial, where n is the current trial and i is the number of trials between the current and the previous trial). They found that priming of pop-out could be tracked back to the approximately seventh previous trial. They, again, did not find any hint of intertrial priming from response repetitions. In a separate experiment, Maljkovic and Nakayama tested whether the target feature intertrial priming was cumulative by repeating colors in sequences, ranging from 1 to 12 repetitions. They found that search performance, as indexed by reaction times, reached its maximum around the eighth color repetition and stayed at maximum afterwards. Based on these findings, Maljkovic and Nakayama concluded that target feature priming of pop-out was based on a perceptually driven, automatically activated visual memory system. They argued that the effect of this visual memory system could go back to approximately seven trials, indicating that this memory system has capacity limitation of approximately seven trials. Maljkovic and Nakayama also proposed that this system couldn't be controlled by conscious strategies because instructing participants to focus

on repetition led to no differences in search performance. The authors did not test the possibility that long-term memories might drive performance; for example they did not evaluate the shape of the function describing the acceleration of reaction times with longer target color repetition sequences. The classical finding that improvement in performance (e.g., reaction times) with increasing number of repetitions of a task is a power function of the number of repetitions (Logan, 1988b; Newell & Rosenbloom, 1981) can be interpreted as a demonstration of the contribution of long-term memory to performance, even in tasks that involve no more than 10 repetitions of the target (Gordon D. Logan, 1990). The sequential repetition effects in the Maljkovic and Nakayama study look like that these effects can be described by a power-law function of repetition, therefore implying contribution of long-term memory representations.

In an attempt to provide a more comprehensive account of priming of pop-out, Maljkovic and Nakayama (1994, 1996) further characterized this proposed visual memory system as location-based and strictly implicit. Specifically, they showed that presenting the target in the same location with the previous trials led to faster reaction times. This location effect was gradual such that presenting targets in locations nearby the previous trials led to more facilitation compared to presenting them in distant locations, reminding the cumulative priming found for target-feature repetition (Maljkovic & Nakayama, 1994). In an additional study Maljkovic and Nakayama (2000) observed that participants were not able to recognize that targets repeated between trials, which they took as evidence for the strictly implicit nature of this memory system.

Although the visual implicit memory system put forward by Maljkovic and Nakayama (1994, 1996, 2000) looks like a complete account of priming of pop-out, it

faces some theoretical and empirical issues. From a theoretical viewpoint, the visual implicit memory system is not compatible with the classic classification of memory that involves perceptual, short-term and long-term memory systems. The advantage of the classic memory classification is that it allows all psychological tasks to employ these memory systems; therefore, it offers a more parsimonious explanation for experimental findings. The hypotheses derived from the classic models of memory allows for interactions between the different memory systems in response to changes in strategies for the task in hand or the changing demands of the task. For example, it is possible that both working and long-term memory representations are formed during a visual search task and both types of representations feed information to the response preparation systems. In this case, repetitions of a target could create enough long-term memories, or instances, so that long-term memory will be advantageous over working memory representations that are rendered futile with long repetition sequences. This approach accounted for intertrial priming in simple visual search when the effect of target repetitions was examined with well-identified ERP correlates of short and long-term memory (Carlisle et al., 2011; Reinhart & Woodman, 2013). A similar rationale can be applied to the findings from priming of pop-out.

In addition to the theoretical problem explained above, the visual implicit short-term memory account of intertrial priming also faces empirical issues. First, although Maljkovic and Nakayama (1994) failed to observe intertrial priming for response repetitions, several researchers found this effect using a very similar task to Maljkovic and Nakayama's (1994). For example, Huang et al. (2004) found that when the target feature was size, priming of pop-out effects were strongest if the responses also

repeated. Olivers and Meeter (2006) replicated this response repetition priming effect in an experiment in which the priming of pop-out task randomly alternated with simple visual search within experimental blocks. One possible explanation of Maljkovic and Nakayama's (1994) failure in finding intertrial priming of response repetition might be that the authors only checked the case of two response repetitions. It is possible that response repetition priming might require more than two repetitions. Maljkovic and Nakayama's visual implicit memory system (Maljkovic & Nakayama, 1994, 1996, 2000) was theorized not to store responses, therefore findings of intertrial priming of response repetitions would be problematic for this proposed memory system. To account for response repetition priming, this system could be modified to store response repetitions, but this modification would render the visual implicit memory system very similar to the classical conception of working memory. Contrary to the visual implicit memory system, there are intertrial priming accounts that propose what is primed with repeating stimuli is the stimulus-response mappings that are stored in long-term memory (Logan, 1990). Therefore, the classic memory systems approach is flexible enough to allow for response repetitions without resorting to any modifications to the memory systems included in the general theory.

A second empirical problem the visual implicit memory account faces is that it is agnostic to some basic findings from the priming of pop-out paradigm. For example, in their first experiment, Maljkovic and Nakayama (1994) found that reaction times decreased with the greater number of distractors when the repetition or the switch of the target feature was random. The visual implicit memory account does not have any explanation for this finding. A perceptual memory system that allows for parallel

accumulation of evidence for all items in a search array could account for this finding by proposing that some aspects of perceptual representations used in visual search are rendered more efficient by either working or long-term memory representations. For example, if the “target found” decision requires one bit of information in a display with two distractors, the same decision might require 0.7 bit of information when there are nine distractors. Assuming that intertrial priming might increase (Ratcliff, Van Zandt, & McKoon, 1999) the starting point of information accrual, the negative correlation between number of distractors and reaction times could be explained by appropriating a perceptual memory system that works with parallel accrual of information. In the visual search literature, perceptual memory systems have been proposed to underlie the within trial visual search effects such as the slowing of reaction times with increasing number of distractors (Treisman & Gelade, 1980). Yet, perceptual memory could also be playing a fundamental role in priming of pop-out through changes in information accrual. These ideas could be tested with ERPs through relating the changes in the early, perception related ERPs and later ERPs that are indicative of priming of pop-out to reaction times.

A third issue the visual implicit memory approach faces is the possibility that a special memory system is not required to account for the finding that repeating only the position of the target, while allowing for changes in the primary and secondary (i.e., color and deciding which part of the target was truncated, respectively) features, led to strong intertrial priming. Information about spatial location is proposed to be stored in working memory and this information is probably used in visual search. For example, the findings from the Woodman and Luck (2004) study showed that visual search

slowed down when participants were required to remember the spatial locations of items in a concurrent, but independent spatial working memory task. That is, holding spatial location information in working memory interferes with visual search probably because this memory system is employed in visual search. Thus, intertrial priming of location could be explained by spatial working memory. Further, long-term memory may underlie intertrial priming of location when the number of repetitions increases because long-term memory representations were found to include location information (Logan, 1998). The possible roles of working and long-term memory could be identified with comparing of working and long-term memory related ERPs during a priming of pop-out task with target position repetitions.

ERP Findings

The use of ERPs in the analysis of intertrial priming, including priming of pop-out, is a fairly novel approach. However, most ERP studies of priming of pop-out focused on the extent to which priming of pop-out facilitates attentional selection of the target rather than identifying memory components that make the facilitation of attentional selection possible. Although the focus of the studies I propose are not attention-related ERPs, these ERPs are still relevant because attention is the system that the memory systems serve during visual search. That is, both working and long-term memory storage of target information help visual search by guiding attention to the target. Thus, identifying how attention-related ERPs change in response to repetition of the target feature and/or responses can help me in specifying in which ways working and long-term memory representations can guide visual search (Duncan & Humphreys, 1989).

Most ERP studies of priming of pop-out have focused on an attention related ERP component called the N2pc to explore how priming of pop-out is reflected in attention. This component is observed during the deployment of attention to items in a search array (Steven J. Luck, 2006). It is measured by subtracting the activity shortly after 200 milliseconds from the electrodes over the parietal cortex, contralateral to the visual field, from the activity in the ipsilateral electrodes over the same cortex (Steven J. Luck & Hillyard, 1994; G. F. Woodman & Luck, 1999). One common view of what N2pc signifies is that it reflects an attentional filtering mechanism that suppresses the further processing of distractors around the attended stimulus (Steven J. Luck, 2006; Steven J. Luck, Woodman, & Vogel, 2000). This view is supported by the finding that N2pc disappears when there are no distractors competing for processing (Steven J. Luck & Hillyard, 1994). Additionally, when distractors are necessary for defining the target as it is the case in singleton search, no N2pc is observed (Steven J. Luck & Hillyard, 1994). In this case, filtering out distractors would result in failure of the task of finding the item that differs from distractors (Steven J. Luck, 2006). These features of N2pc can make it an appropriate tool in determining to what extent working and long-term memory representations guide attention.

Recently, Olivers and Hickey (2010) examined N2pc in priming of pop-out. The search task in this study consisted of a target defined by a salient color (e.g., red or green), presented among gray non-targets. In addition to gray non-targets (i.e., all gray distractors), some blocks included distractors in either red or green (i.e., colored distractor). The authors predicted that target feature repetitions would facilitate attentional selection of the target more when there were distractors with salient colors in

contrast to trials with all grey distractors. Participants' task was to detect the direction (e.g., left or right; secondary feature) of an arrow placed in the target. Participants were informed about the color of the target before the blocks with color distractors. No significant priming of pop-out was observed in trials with all grey distractors whereas the trials including color distractors led to significant priming of pop-out, indicating that target feature repetitions were more beneficial when there was more competition for attentional selection (Olivers & Hickey, 2010). The effect of target feature repetition was quantified by comparing N2pc for target feature repetitions and switches in both all gray and salient distractor trials. Similar to the behavioral findings, N2pc for target feature repetitions with salient distractors were higher in amplitude compared to the N2pc feature repetitions with all gray distractors. The effect of target feature repetition on N2pc was replicated in studies where one of the distractors had a task-irrelevant feature in addition to the target and response defining features (Hickey, Olivers, Meeter, & Theeuwes, 2011). In this study, target feature repetition benefited visual search more when one of the distractors had a task-irrelevant feature. The differential benefit of target repetition with different distractor types was reflected in N2pc amplitude such that target feature repetition when there was a distractor with a task-irrelevant feature led to an increase in N2pc amplitude, compared to the N2pc observed for target feature repetition trials with all task-relevant distractors.

Töllner and colleagues (2010) investigated ERPs in a priming of pop-out task where the type of target defining feature changed between trials (e.g., from color to shape). In their version of the priming of pop-out task, the target-defining feature shifted between color and shape between trials (i.e., target feature dimension shifts; Müller et

al., 1995). In two third of the trials, participants were informed about whether the target feature was shape or color by presenting the name of the target feature dimension before trials. However, this cue was valid in 80% of these trials. The remaining one third of trials included only a neutral cue as presented by the word "NEUTRAL". The task of the participants was to determine the direction of the orientation of the gratings inside the items, regardless of whether the target feature was color or shape. The authors compared valid, invalid, and neutral cue trials to investigate whether the knowledge of the target feature would alter the processing for the compound-search task, as measured by ERPs. Unfortunately, Töllner et al. did not report behavioral or ERP data for whether the type of cues interacts with target feature or response repetitions. However, the authors found that valid cues led to a more pronounced negativity around the 400 milliseconds time window in central electrodes. They also found that when both the target feature and response repeated, it led to more positive ERPs around 300 milliseconds in central electrodes, compared to when neither of the target feature and response repeats. A different picture emerged when the authors evaluated response-locked ERPs in the central electrodes: repetitions of response, regardless of target feature repetitions, led to more negative ERPs just before response execution (i.e., lateralized readiness potential, LRP). Based on these findings, the authors proposed that repetitions of target feature and responses exert effects in different stages of processing. They argued that priming between trials in the priming of pop-out task is not a unitary phenomenon and should be treated differently with respect to repetitions of the target feature (i.e., priming of pop-out) and response. The overall picture emerged from this study essentially argues against a single, specialized memory system, such as the

visual implicit memory system, that is proposed to exert its effects at specific stages of processing (Maljkovic & Nakayama; 1994, 1996, 2000). Working and long-term memory representations, on the other hand, could inform visual search at different stages of processing (Carlisle et al., 2011; Reinhart & Woodman, 2013) and allow for intertrial priming of both target feature and responses (Logan, 1990).

The more positive ERPs observed in Töllner et al. (2010) study for target feature repetitions is reminiscent of the P3b component that is commonly observed in the frontal, central, and parietal midline electrodes in response to “oddball” stimuli in a sequence of “standard” stimuli (Donchin, 1981; Donchin & Coles, 1988; Polich, 2007; Vogel, Luck, & Shapiro, 1998). The P3b component is often taken as an indicative of updating working memory that keep track of regularities in stimuli presentation (Donchin, 1981; Donchin & Coles, 1988; Polich, 2007). The P3b could be utilized as a measure of working memory in priming of pop-out because the repetitions of target features can be evaluated as a form of regularity in the environment. According to this idea, a switch in the target feature should first lead to a large P3b because working memory needs to be updated in this case. However, the P3b should decline with further repetitions, as the working memory will not update. Therefore, the reductions in P3b with repetitions could be taken as the diminishing of working memory representations. Further, to determine how working memory representations facilitate visual search through facilitation of attentional selection, the changes in the amplitude of P3b may be correlated with the increased difficulty in attentional selection of the target, as indexed by N2pc. Finally, The P3bs could also be compared with ERP measures of long-term

memory to determine whether working or long-term memory representations guide visual search with repetitions.

Such an attempt at comparing the roles of working and long-term memory representations, as measured by ERPs, in simple visual search came from our laboratory. Reinhart and Woodman (2013) instructed participants in a simple visual search task to search for the same target in sequences of one to seven repetitions. One slight modification to simple visual search was that the participants needed to remember the target over a 1,000 milliseconds long retention interval. The authors observed that the ERP measure of working memory, contralateral delay activity (CDA) (Vogel & Machizawa, 2004), decreased when participants repeatedly searched for the same target. It was argued that the CDA in this task indexed the storage of attentional templates (i.e., templates with information for the identity of the target) that guides the visual search (Carlisle et al., 2011). In contrast to the decrease in CDA with repeatedly searching for the same target, a positive component measured from central midline electrodes around 170 milliseconds, namely P170, became more negative with repetitions. The authors interpreted this interplay between CDA and P170 as handing out of working memory representations guiding the visual search, as indexed by CDA, to long-term memory representations that are established with repeated searches for the same target, as indexed by P170. This finding is in line with the classical approaches to memory by proposing a distinction between working and long-term memory representations as formed by target repetitions. This finding further shows how important the memory systems are to visual search and the classical classification of the memory systems are able to explain an important portion of priming of pop-out. The

priming of pop-out task could show a similar interplay between working and long-term memory representations with target feature repetitions. Additionally, because the response is determined by a secondary feature in priming of pop-out and this requires the focusing of attention to the target unlike simple pop-out search, this interplay could be correlated with attention related ERP components in addition to reaction times.

The ERPs explained up to this point provide a good set of tools to explore the role of different memory systems in priming of pop-out. The P170, an early ERP component that has been identified as a correlate of long-term memory (Carlisle et al., 2011; Diana, Vilberg, & Reder, 2005; Reinhart & Woodman, 2013; Tsivilis, Otten, & Rugg, 2001), could be employed as a means to determine how the long-term memory system begins guiding visual search by allowing more instances of the target feature in memory. The P3b, on the other hand, is responsive to the changes in the presentation sequence of items and is commonly interpreted as a correlate of updating working memory in response to changes in stimuli sequences (Donchin, 1981; Donchin & Coles, 1988; Polich, 2007). Intertrial target feature priming could stem exclusively from working memory representations when successive target feature repetitions are limited to two. If this is the case, the P3bs for target feature switches should be significant and should be correlated with the slowing of reaction times with the feature switch. However, target feature repetitions could show priming beyond successive repetitions. This possibility could be explored by taking the “i”th previous trial with the same target feature and comparing the ERPs of this previous trial with the current one (see Maljkovic and Nakayama, 1994, for a behavioral implementation of this rationale). If long-term memory representations of the target feature facilitates priming of pop-out, then P170s from “i”th

previous trial should be correlated with reaction times. The contribution of long-term memory could further be tested with the sequential repetitions of target features, while the response feature is allowed to vary within the sequence. The length of the sequence should determine the role of working and long-term memory representations in visual search, leading to more negative P170s with longer repetition sequences (Carlisle et al., 2011; Reinhart & Woodman, 2013). The P3b, as a supposed correlate of working memory, should also be responsive to length of target feature repetition sequences such that its amplitude will increase in target feature switches with shorter repetition sequences (e.g., the amplitude of the P3b observed after a sequence of three repetitions should be higher than a P3b after a sequence of seven repetitions).

P3b as a Measure of Updating Working Memory

Examining the antecedent conditions of an ERP component is necessary to understand its role in information processing (e.g., Donchin, 1981; Donchin & Coles, 1988) and thus its possible use in understanding priming of pop-out. From its discovery on, one essential antecedent of P3b has been identified as the subjective probability of a relevant item. Infrequent target items elicit greater P3bs; for example if the task of participants is to count the number of infrequent high-pitched tones interspersed between frequent low-pitched tones, these infrequent targets will elicit strong P3bs (Donchin & Coles, 1988; Duncan-Johnson & Donchin, 1982; Halgren et al., 1980; Squires, Petuchowski, Wickens, & Donchin, 1977; Sutton, Braren, Zubin, & John, 1965). Further, the probability of presentation of low frequency stimuli determines the amplitude of P3b; as the rarity of the target item increases, so does the amplitude of

P3b (e.g., Squires et al., 1977). It is the subjective probability rather than objective probability that determines the amplitude of P3b, because P3b amplitude is sensitive to the immediate history of stimulus presentation rather than the objective probability that is used to determine the frequency of targets. For example, Squires et al. (1977) found that targets preceded by four consecutive non-targets produced more positive P3bs compared to targets preceded by one or two consecutive non-targets, although the probability of targets were the same throughout the blocks in which these sequences were presented. Lastly, ignored stimuli do not elicit P3b (Duncan-Johnson & Donchin, 1977; Gopher & Donchin, 1986): when Duncan-Johnson and Donchin instructed participants to solve a puzzle and not to pay attention to any of the tones presented, neither infrequent nor frequent tones produced P3bs.

These antecedent conditions together could signify that P3b is elicited by a group of neurons that assess whether it is necessary to update working memory to deal with an ongoing task (Donchin, 1981; Donchin & Coles, 1988; Kok, 2001; Polich, 2007). According to this perspective, frequent targets elicit smaller P3bs because they do not require working memory to be updated. On the contrary, infrequent targets necessitate a modification of working memory to integrate the information provided by these rare events. Non-targets or ignored stimuli do not produce P3b (Duncan-Johnson & Donchin, 1977) because non-targets do not bring any relevant information for the task and consequently will not modify working memory. Additionally, if a stimulus gains predictive value for the target item in an oddball task (i.e., the conditional probability of the target is high when the predictive stimulus is presented), the amplitude of P3b for that stimulus is modulated by its predictive validity (Jost, Conway, Purdy, & Hendricks, 2011). That is,

the statistical regularity in the presentation pattern is learned and predictive value of stimuli is represented in working memory to be ready for the target item (Daltrozzo & Conway, 2014). P3b is likely to index also this form of working memory update.

Latency of P3b is often taken as indicating completion of stages of information processing prior to response execution and selection (Gopher & Donchin, 1986; McCarthy & Donchin, 1981; Squires et al., 1977). Therefore, the relationship between reaction time and P3b latency depend on which stage of processing is experimentally manipulated. When stimulus evaluation processes are manipulated, such as introducing noise to stimulus presentation, P3b latencies and reaction times increase both (Kutas, McCarthy, & Donchin, 1977; McCarthy & Donchin, 1981). However, response preparation manipulations such as stimulus-response incompatibility (e.g., responding with the left button to the stimulus "RIGHT") increase reaction times but do not influence latency of P3b (McCarthy & Donchin, 1981).

P3b was repeatedly found to be indicating of the workload of ongoing tasks (Isreal, Wickens, Chesney, & Donchin, 1980; A. F. Kramer, Wickens, & Donchin, 1983; Wickens, Kramer, Vanasse, & Donchin, 1983). Manipulations increasing difficulty of the ongoing task, such as crowded displays or order-of-control in a target tracking and control task, lead to greater P3bs (A. F. Kramer et al., 1983). When secondary tasks are introduced to a difficult task, the P3b shown to secondary task diminish if the primary task becomes too difficult (Isreal et al., 1980; A. F. Kramer et al., 1983). The total amplitude of P3b seems to be stable and reciprocally distributed across tasks with prioritization of the primary task. Additionally, amplitude of P3b is responsive to the interaction between the number of items to be memorized for a task and whether

identity of targets and distractors remain constant or swap (i.e., consistent vs. variable mapping, CM vs. VM). Strayer and Kramer (1990) found that set size in Stenberg memory search task where participants memorize a set of targets and respond whether a test item belongs to the target set modulated P3b amplitude only in VM condition. When target and distractors sets were kept constant, the P3b amplitude did not track set size. It should also be noted that the P3b does not index the maintenance of items in working memory (e.g., Vogel & Machizawa, 2004); it is rather an index of the effort of the visual or auditory system shows to deal with the ongoing task (Kahneman, 1973) and whether the existing working schemata should be updated for the task to be accomplished (Donchin & Coles, 1988; Gopher & Donchin, 1986).

The picture that emerges with exploring the factors that influence the amplitude and latency of P3b is clear: P3b is very likely to be produced by a network of neurons that assesses the frequency information and task demands of the ongoing task, controls distribution of mental resources to the ongoing tasks and takes account prioritization order of tasks, requires attention to stimuli (Donchin, 1981; Donchin & Coles, 1988; Polich, 2007). The processes that P3b could be used to monitor are completed after categorization of stimuli and before response preparation and execution (Kutas et al., 1977; McCarthy & Donchin, 1981). Therefore, P3b amplitude and latency can be used to explore how previous visual search episodes influence working-memory based processing of a current visual search episode.

P3b has been employed in answering questions about the nature of visual search. For example, Luck and Hillyard (1990) used P3b latency and amplitude to test whether visual search was parallel or serial in cases where the target popped out or not.

In half of the trials, the target possessed a feature that was absent in the distractors (i.e., pop-out target) or excluding a feature that distractors included. Targets were present in half of trials of each condition. Luck and Hillyard examined the effect of set size on RT, P3b latency, and amplitude. They found linear set size effects on mainly P3b amplitude in non-pop-out trials, despite decreases in accuracy with larger set sizes. More relevant to my discussion, Luck and Hillyard also evaluated the effects of the outcome of the previous trial (i.e., target is present or not) on current trials. They reasoned that presence of the target in the previous trial determined the subjective probability of the presence of the target in the current trial. They argued that if the previous trial included the target, the subjective probability of the target should be increased and the first few search attempts with negative results in serial search should produce larger P3bs. Their prediction was confirmed in non-pop-out target trials: when the previous trial was positive for the target, the P3bs were greater for the current trial. The pop-out target trials did not produce any sequential P3b effects. Set-size effects were not evaluated within sequential P3b effects. Considering that priming of pop-out is the result of previous trials with the same primary feature (e.g., color) and following the rationale of Luck and Hillyard, P3b amplitudes should be sensitive to the subjective probabilities induced by previous trials, at least in cases where short-term memory representations are driving visual search performance.

Present Work

To summarize, in this series of experiments my primary aim is to show the contributions of perceptual, working and long-term memory systems in priming of pop-

out in visual search. My primary argument regarding the role of these memory systems in priming of pop-out is that they are sufficient to explain the main findings from priming of pop-out studies and that a separate, special memory system (i.e., visual implicit memory; Maljkovic & Nakayama, 1994, 1996, 2000) is not necessary. I used well-established ERP measures of working and long-term memory (i.e., P3b and P170, respectively) to examine how these measures are influenced by factors such as the number of repetitions and the type of repetitions (i.e., target feature, response feature, and position). The first experiment in my study considered the role of perceptual memory representations to explain why more distractors led to faster reaction times with target feature repetitions. The second experiment evaluated the handing out of working memory representations to long-term memory representations in priming of pop-out with increasing number of repetitions. The work from our laboratory (Carlisle et al., 2011; Reinhart & Woodman, 2013) showed that such an interplay between working and long-term memory representations indeed occur in simple visual search, but it remains to be seen whether this is the case in priming of pop-out. In the third experiment, I examined the effect of repeating the target in the same position across many trials. Visual search is argued to be employing spatial working memory representations (Woodman & Luck, 2004), but it is not known through which means repetitions of locations of the target facilitate visual search. Maljkovic and Nakayama (1994, 1996) proposed that the special memory system also included location information, however both working and long-term memory representations involve location information and thus could account for intertrial priming of location in visual search.

CHAPTER 2

EXPERIMENT 1

Rationale

Different memory systems might play specific roles during visual search. Working memory representations could facilitate finding the target by allowing for comparisons of the stimuli in the search array with the working memory representation of the target (i.e., attentional template; Duncan & Humphreys, 1989). Additionally, long-term memory representations of the targets might be at work when the same target is repeatedly searched for over several trials (Carlisle et al., 2011; Reinhart & Woodman, 2013). These memory systems might be working in harmony in cases where working and/or long-term memory representations could inform visual search. This experiment evaluates specifically the contribution of working memory representations in priming of pop-out. In this experiment, target and response features were allowed to repeat or switch, each with a probability of 0.5. In addition to feature repetitions, the number of distractors varied to evaluate the role of perceptual memory representations and attention in priming of pop-out. Because repetition sequences were unlikely and target and distractor colors might have swapped in any trial (i.e., variable mapping, VM),

working memory, rather than long-term memory, representations should have been employed. However, Experiment 1 also included experimental blocks where target would stay the same throughout (i.e., consistent mapping). When this was the case, long-term memory representations should have guided visual search.

Bravo and Nakayama (1992) found that reaction times in responding to the target were reduced with more distractors (i.e., set size effect), only in the VM condition of the compound-search task. One explanation for this effect was that because a secondary feature (i.e., the gap at either top or bottom of the target) determined the correct response, the task required focal attention. With the help of focal attention on the quality of information gathered bottom-up, the visual system might be able to identify the “odd” item more easily (Julesz, 1986; Koch & Ullman, 1985; Nakayama, 1990), especially when there are more “regular” stimuli in display (Bravo & Nakayama, 1992). However, although this basic finding led Maljkovic and Nakayama (1994, 1996, 2000) to examine priming of pop-out, any possible interactions of repetition of primary or secondary feature with this set size effect was not examined hitherto. In Maljkovic and Nakayama’s first experiment, the basic finding was that the VM condition produced faster reaction times with more distractors, whereas reactions for CM did not show a set size effect. One of my aims in Experiment 1 was to reveal whether repetition of color, response, or neither drives the set size effect in the VM condition. Repetition of color could provide more bottom-up information to the visual system (Maljkovic & Nakayama, 1994) and this might have led to facilitation of the detection of the “odd” item in an otherwise uniform display (Julesz, 1986; Koch & Ullman, 1985). The contribution of color repetition might have declined with greater set sizes because the bottom-up information from a crowded

“uniform” scene might provide maximal benefit, thus rendering priming of pop-out futile. Additionally, repetitions of response occurring with color repetitions might have sped-up reaction times through forming of more robust stimulus-response mappings (Schacter, Dobbins, & Schnyer, 2004).

If these behavioral effects were based on working memory representation of the target feature from the previous trial, the P3b amplitude, as the index of working memory, should have decreased with target feature repetitions in VM. This activity should have been related to the set size effect if working-memory representations contributed to the bottom-up processing necessary for responding to the “odd” target. However, long-term memory representations can be observed as well, even with single repetitions of color or responses (Carlisle et al., 2011; Reinhart & Woodman, 2013). On the other hand, in CM, long-term memory representations might have governed performance, which should be related to ERP correlates of long-term memory (e.g., P170 or Late Positive Complex, LPC).

A schematic of the stimuli and an example of a sequence of trials are presented in Figure 1.

Method

Participants

Fifteen volunteers participated in the study. All had normal or corrected-to-normal visual acuity, normal color vision, and no history of neurological problems. The Vanderbilt Institutional Review Board approved all experimental procedures. Participants were monetarily compensated for their participation.

Stimuli

The viewing distance between the screen and participants was kept at 114 cm. All stimuli were presented on a black background ($< 0.01 \text{ cd/m}^2$). The stimuli were 45° rotated squares ($0.8^\circ \times 0.8^\circ$ of visual angle) that missed half of their diagonal (gap thickness = 0.28°) either from the top or bottom to the center. The color of the stimuli was red ($x = 0.612, y = 0.333, 15.1 \text{ cd/m}^2$), green ($x = 0.281, y = 0.593, 45.3 \text{ cd/m}^2$), or blue ($x = 0.146, y = 0.720, 6.41 \text{ cd/m}^2$). The search array included 4, 6, or 12, depending on the type of the experimental block. Stimuli were presented on an invisible circle with a radius of 2.82° . The locations of stimuli were arranged in clock face positions (4 stimuli: 1, 5, 7, and 11 o'clock positions; 6 stimuli: 1, 3, 5, 7, 9, and 11 o'clock positions; 12 stimuli: all clock face positions). A white fixation cross ($< 120 \text{ cd/m}^2, 0.4^\circ \times 0.4^\circ$ of visual angle) was presented throughout trials. Stimuli were prepared and presented with Psychtoolbox (Brainard, 1997) for MATLAB (The Mathworks Inc., Natick, MA). A schema of the stimuli is presented in Figure 1.

Procedure

The number of stimuli in the search array (i.e., set size: 4, 6, or 12) remained the same throughout an experimental block and this information was presented at the start of each experimental block. Trials started with the presentation of the search array. Participants were instructed to identify the target color and detect the direction of the gap (i.e., top or bottom) in the target item. The search array stayed on the screen for three seconds or until response. One of three stimuli colors (i.e., red, green, or blue) was randomly designated as the irrelevant distractor item in all trials for a participant to rule out low-level sensory confounds which are especially problematic for lateralized ERP components (S. J. Luck, 2005; G.F. Woodman, 2010). The irrelevant distractor was always presented in the opposite visual field to the target item. Participants were informed about the color of the irrelevant distractor before the experiment.

The target stimulus was defined as the odd-colored stimulus from the set of remaining two colors. Participants responded to the direction of the gap in the target item using a hand held gamepad. Participants pressed the top left or right buttons on the gamepad to indicate that the gap was upwards or downwards, respectively. The time interval between trials was picked from a rectangular distribution with a minimum and a maximum of 1.8 and 2.2 seconds, respectively. All experimental blocks consisted of 150 trials. Each set size had 4 variable mapping blocks where the target color was allowed to switch from trial to trial between the two relevant colors (4 X 3 set size = 12 variable mapping blocks in total). Color (i.e., target feature) and responses were allowed to repeat independently from each other with a probability of 0.5. This produced four possible types of repetition for consistent mapping trials: i) color repetition: in which

target color from the previous trial repeated ii) response repetition: where the required response for the target item was the same with the previous trial iii) both repetitions: if both color and response repeated from the previous trial iv) no repetition: neither of the features repeated.

The remaining three were consistent mapping blocks in which one of the two relevant colors was randomly designated as the target through the block. All set sizes had one of these consistent mapping blocks. An example of a Set Size 12 variable mapping trial is presented in Figure 1.

Participants completed 24 practice trials before the experiment. They were instructed to respond as fast as they could while keeping the accuracy high throughout the experiment. Participants were also required to fixate at the fixation cross in the center of the screen throughout the trials and to time their blinks to intertrial intervals to produce the least amount of eye artifacts. Accuracy feedback was provided after all experimental blocks.

EEG Recording and ERP Analyses

Electroencephalogram (EEG) signals from the scalp were measured with an elastic cap (Electrocap International, Eaton, OH) equipped with 19 tin (Sn) electrodes configured for the International 10/20 System. The 19 electrodes used in the experiment consisted of 3 midline electrode (Fz, Cz, Pz) and 7 lateral electrode pairs (F3, F4, C3, C4, P3, P4, PO3, PO4, T3, T4, T5, T6, O1, and O2). Additionally, one non-standard pair of sites was used: OL (placed halfway between O1 and O5) and OR (placed halfway

between O2 and T6). An electrode placed on the right mastoid was employed as the online reference site during recording. Signals were re-referenced offline to the average of left and right mastoid electrodes (Nunez, 1981). EEG signals were amplified by a SA Instrumentation amplifier with a gain and a band-pass filter of 20,000 decibels (dB) and 0.01-100 Hz, respectively, at 250 Hz sampling rate.

For Electrooculogram (EOG) measurements, two tin electrodes were placed 1 cm lateral to the external canthi to measure horizontal eye movements and signals from these channels were averaged online. Another electrode below the left eye measured vertical eye movements and blinks. EOG electrodes were also referenced to the right mastoid electrode. Ocular artifact rejection involved a two-step procedure as described in Woodman and Luck (2003). Briefly, first, trials were discarded when the covariance between a 100 ms step function and the EOG waveforms exceeded a threshold value of 20 and 100 μV for HEM and VEM, respectively. Second, trials with residual EOG activity above 3 μV were discarded. At this second stage, participants with a propagated voltage of more than 0.1 μV at the posterior scalp sites (Lins, Picton, Berg, & Scherg, 1993) were excluded from further data analyses. Four participants were replaced because of excessive eye movement artifacts (30% or more of individual trials rejected or the residual HEOG activity remained above 3 μV , which, in our laboratory set-up, corresponds to $\pm 0.1^\circ$ eye movements). The average single trial rejection rate for the final 15 participants was 16%.

Only correct trials slower than 300 ms were used for ERPs. Before extracting ERPs, grand average ERP waveforms were plotted and the time window for maximal ERP activity was visually detected. Next, ERPs from each participant was plotted

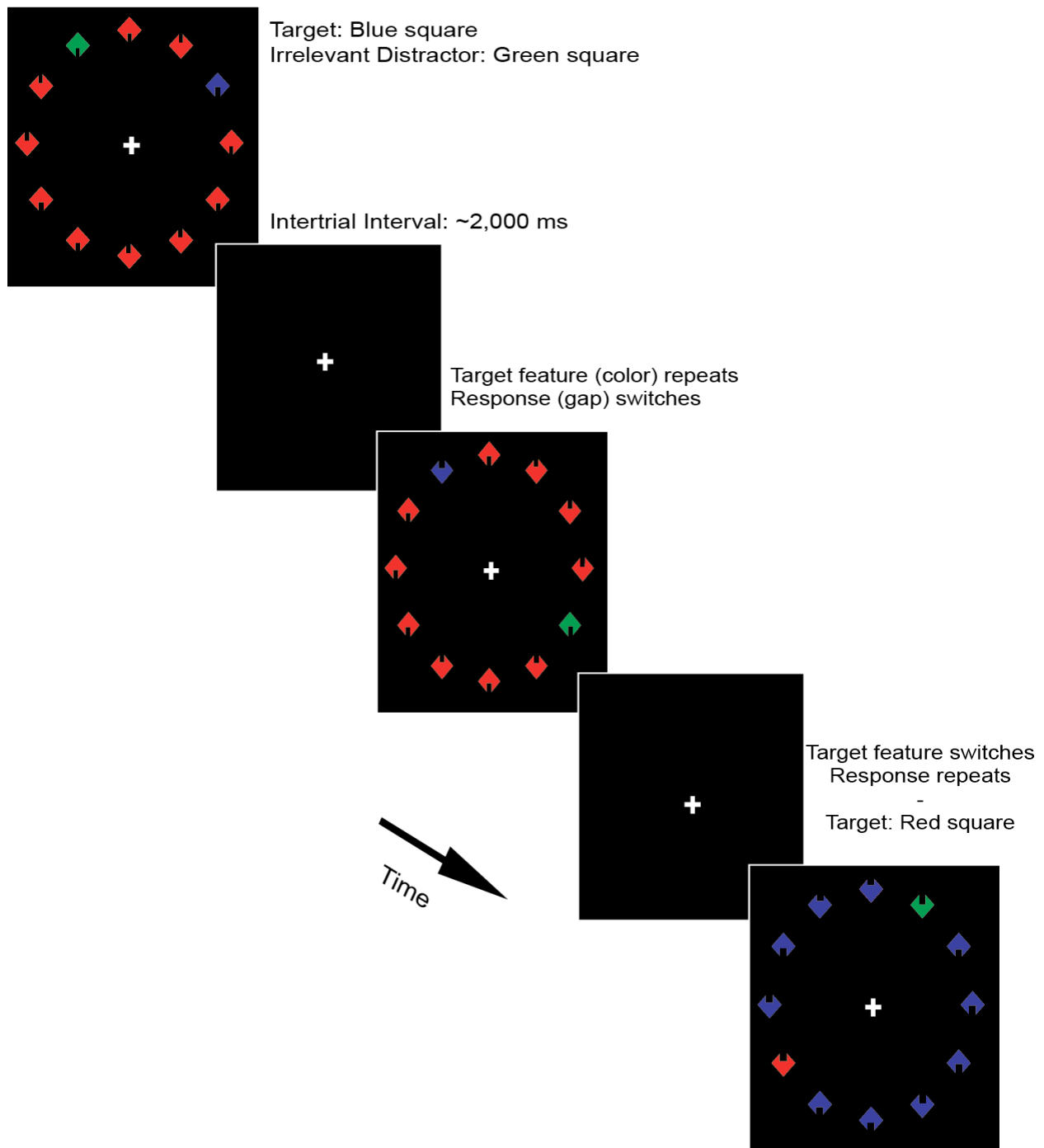


Figure 1. A schematic of a run of three trials in Experiment 1. In this example, targets are either red or blue and the irrelevant distractor color is always green. The task of the participants is to find the color singleton among red and blue stimuli and to respond to the direction of the gap in that target item. Target colors were allowed to switch in variable mapping (VM) trials as illustrated in this figure whereas target color remained the same throughout an experimental block in consistent mapping (CM) trials.

separately and the time windows to extract ERPs were assessed on an individual basis. -200 to 0 ms relative to the search array onset was used for baseline correction. All ERP analyses were run on Custom written MATLAB (The Mathworks Inc., Natick, MA) scripts, based on the EEGLAB analyses package (Delorme & Makeig, 2004).

Based on previous studies (e.g., Duarte, Ranganath, Winward, Hayward, & Knight, 2004; Reinhart & Woodman, 2013; Voss, Schendan, & Paller, 2010) P170 was extracted from the average of the signals at the frontal midline and lateral electrodes (Fz, F3, F4), 170-200 ms after the presentation of the search array. Based on previous work (Duncan-Johnson & Donchin, 1982; Isreal et al., 1980; Arthur F. Kramer & Strayer, 1988; Kutas et al., 1977; Steven J. Luck & Hillyard, 1994) P3b was extracted from Fz, Cz, and Pz, from the 400-500 ms time interval. For lateralized ERPs (i.e., CDA), voltage at the contralateral side to the target item (e.g., right electrode if target was on the left visual field) was subtracted from the ipsilateral side activity (i.e., lateralized difference waves). The difference waves from the posterior-occipital electrode pairs (i.e., P3/P4, PO3/PO4, O1/O2) were used to measure CDA (400-650 ms; Vogel & Machizawa, 2004). Especially for late ERPs, reaction time of each individual was taken into account when extracting individual ERPs to avoid the possible effects of response on the waveforms. For example, if the mean RT of a participant for Set Size 4 was 600 ms, the time window of ERPs were adjusted to exclude the 600 ms window for that participant.

Repeated-measures Analyses of Variance (ANOVAs) were employed to test the statistical significance of effects at an alpha level of 0.05. Degrees of freedom and *p*-values were corrected to Greenhouse-Geisser criteria when the assumption of sphericity was violated (Jennings & Wood, 1976). For pairwise-comparisons, Tukey's

post-hoc comparison correction (Tukey, 1949) was applied. To preserve statistical power, blocked repetition trials were excluded from the post-hoc comparisons when differences between repetition types in the variable mapping condition were analyzed (Tukey, 1949).

Results

Behavioral

RT

RT results are illustrated in Figure 2a. A repeated-measures ANOVA with factors Set Size (three levels: 4, 6, and 12) and Type of Mapping (two levels: consistent vs. variable) showed that RTs became faster as set size increased ($F(1.193, 16.695) = 22.49, p < 0.001$). Consistent mapping produced faster RTs overall than variable mapping ($F(1, 14) = 56.33, p < 0.001$). However, more importantly, the Set Size X Mapping interaction was also significant, $F(2, 28) = 8.231, p < 0.003$, indicating that the effect of Mapping differed with Set Size.

In order to assess the effect of mapping on RTs in detail, variable mapping trials were divided into four categories of feature repetition. In color repetition condition, only the color of the target item repeated from the previous trial, whereas the response feature (i.e., gap up vs. gap down) did not repeat. In response repetition condition, the

response feature from the previous trial was repeated while the target's color changed. In the no repetition condition, none of the features repeated. Lastly, in the both repetitions condition, both target and response features repeated from the previous trial. Separate ANOVAs for each set size were run to analyze the effect of repetition type in variable mapping condition on RTs.

In Set Size 4, the effect of Repetition Type (four levels: Both repetitions, Color repetition, Response repetition, and no repetition) was significant, $F(3, 42) = 35.7$, $p < 0.001$. Tukey-corrected pair-wise comparisons showed that both repetitions and color repetition conditions did not differ from each other ($p = 0.705$); however, both of these repetition types led to faster RTs than response only and no repetition conditions ($ps < 0.001$). RTs for no repetition condition did not differ from response repetition ($p = 0.668$).

The effect of repetition type on RTs also worked in a similar fashion for set sizes 6 and 12 ($F(2, 116), 29.620 = 34.41$, $F(3, 42) = 15.04$, $ps < 0.001$, respectively, for set sizes 6 and 12). Both repetitions and color repetition were consistently faster than no repetition and response repetition ($ps < 0.006$), but were not different from each other ($ps > 0.544$) in both Set Size 6 and 12. No repetition and response repetition RTs also produced similar RTs ($ps > 0.643$).

The RTs for consistent mapping trials were analyzed in a similar fashion. However, because target color repeated throughout the consistent mapping blocks, the effect of only response repetition could be analyzed. An ANOVA with factors Set Size and Repetition Type showed that RTs did not differ with set size or response repetitions; $F(1, 168), 16.346 = 2.106$, $p = 0.165$, and $F(1, 14) = 4.039$, $p = 0.064$, respectively. The

Set Size X Repetition Type interaction was also not significant: $F(1.453, 20.335) = 0.676, p = 0.474$.

Accuracy

Accuracy results are illustrated in Figure 2b. The same set of analyses was run for accuracy scores. An ANOVA with factors of Set Size and Type of Mapping showed that accuracy did not change with set size ($F(2, 28) = 0.162, p = 0.851$). However, consistent mapping trials had higher correct responses than variable mapping trials, $F(1, 14) = 8.987, p < 0.02$. The effect of type of mapping was similar across set sizes because the Type of Mapping X Set Size interaction did not reach significance: $F(2, 28) = 0.474, p = 0.627$.

The effects of different repetition types (both repetitions, color repetition, response repetition, no repetition) within variable mapping blocks on accuracy were analyzed for each set size separately. In Set Size 4, the effect of repetition type was significant: $F(3, 42) = 3.073, p < 0.039$. Post-hoc tests exhibited that this effect was driven by the fact that no repetition trials produced higher accuracy than response repetition trials ($p < 0.032$). No other comparisons reached significance. In Set Size 6, repetition type also exerted an effect on accuracy, $F(3, 42) = 2.949, p < 0.044$. However, in Set Size 6, both repetitions trials were more accurate than response repetition trials ($p < 0.030$). No other comparisons were significant. The repetition type effect disappeared in Set Size 12 ($F(3, 42) = 1.598, p = 0.204$).

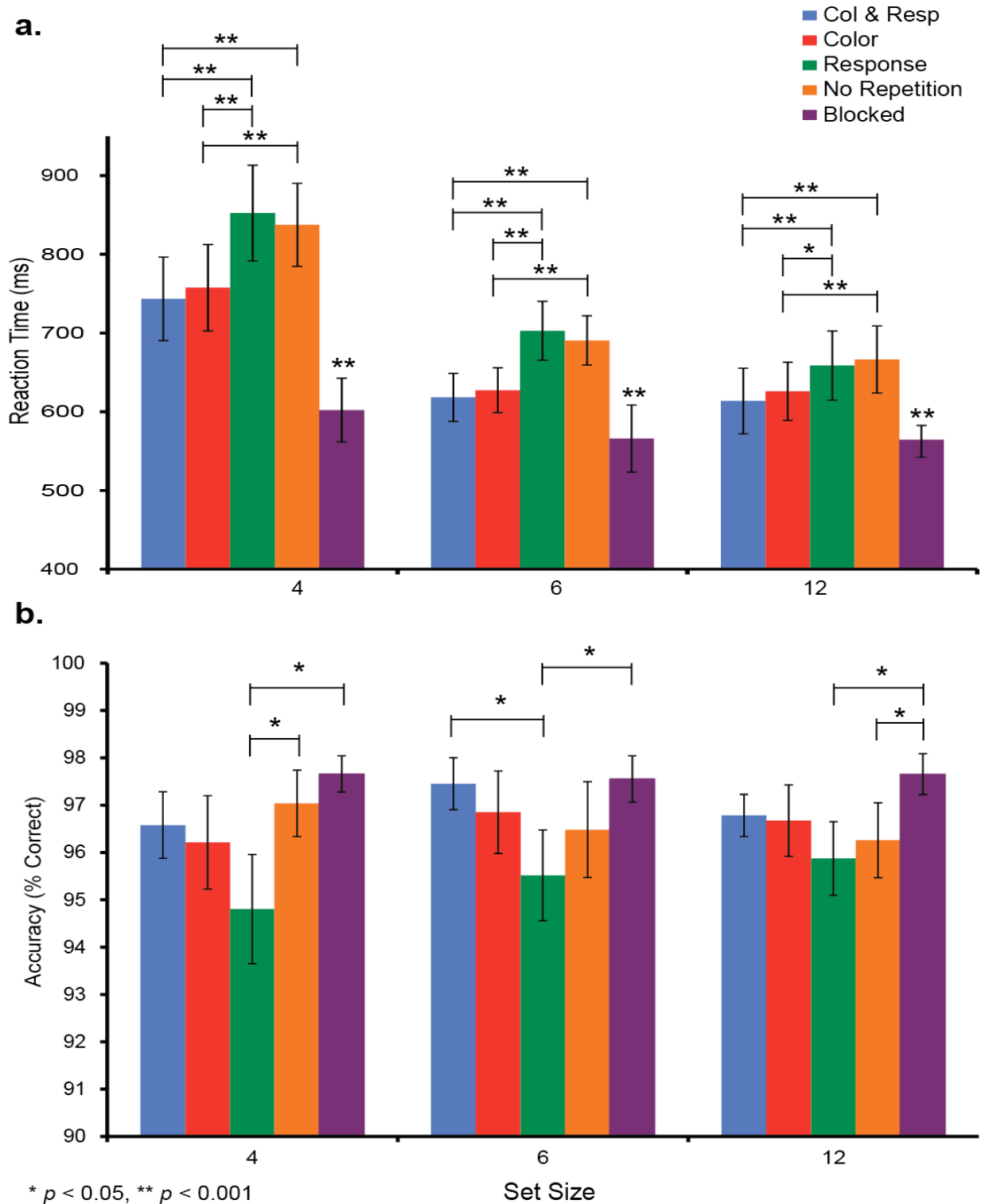


Figure 2. Behavioral results from Experiment 1: a) Reaction Time, b) Accuracy. Error bars represent the standard error of the mean in this and all following figures when they are present.

In consistent mapping trials, color remained constant throughout the experimental block while responses were allowed to repeat randomly with a probability of 0.5. I tested the effect of response repetition and set size on accuracy in consistent mapping trials with an ANOVA with the corresponding factors. None of the effects exhibited significant effects, indicating that accuracy was similar across set sizes regardless of response repetition (Set Size: $F(2, 28) = 0.069$, $p = 0.933$; Response Repetition: $F(1, 14) = 2.351$, $p = 0.147$, Set Size X Response Repetition: $F(2, 28) = 0.032$, $p = 0.969$).

P170

For the analysis of P170 and other ERP components, repetition types within variable mapping blocks (i.e., color, response, no, and both repetitions) and the only repetition type in the consistent mapping trials (i.e., blocked color repetition) were compared separately for each set size.

In Set Size 4, an ANOVA with the factor of Repetition Type (5 levels: color, response, both, no, and blocked repetition) was significant: $F(4, 56) = 2.817$, $p < 0.035$. Post-hoc tests showed that both repetitions trials led to significantly less P170 amplitude (i.e., higher LTM activity) than blocked repetition trials ($p < 0.027$). No other comparisons resulted in significant differences ($ps > 0.093$) (see Figure 3a).

However, this P170 effect disappeared in set sizes 6 and 12. ANOVAs evaluating the effect of repetition type on P170 failed to reach significance for both set sizes: $F(4, 56) = 0.701$, $p = 0.595$; $F(4, 56) = 0.619$, $p = 0.651$, respectively, for Set Size 6 and 12.

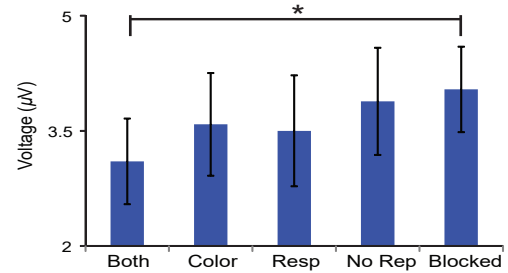
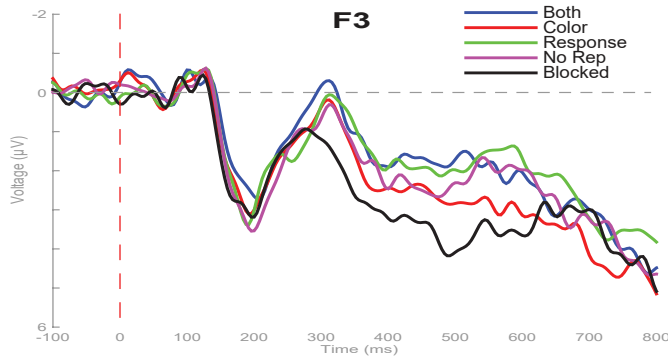
P3b

Repetition type exerted a significant effect on P3b amplitude in all set sizes. Blocked repetition trials consistently resulted in the highest P3b amplitudes compared to other repetition types. In Set Size 4, this effect was confirmed with an ANOVA with the factor Repetition Type: $F(2.233, 31.267) = 14.73, p < .001$ (see Figure 3b). Post-hoc comparisons showed that Blocked repetition had significantly higher P3b amplitude than all other repetition types ($ps < 0.001$). Color repetition trials also had higher P3b amplitudes than response repetition trials ($p < 0.046$). No other comparisons were significant.

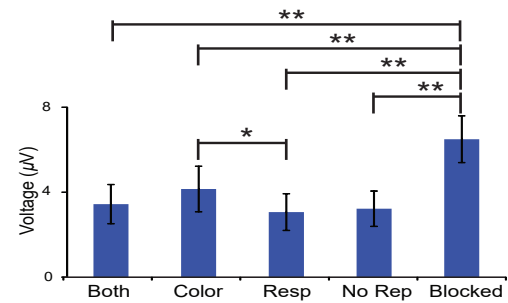
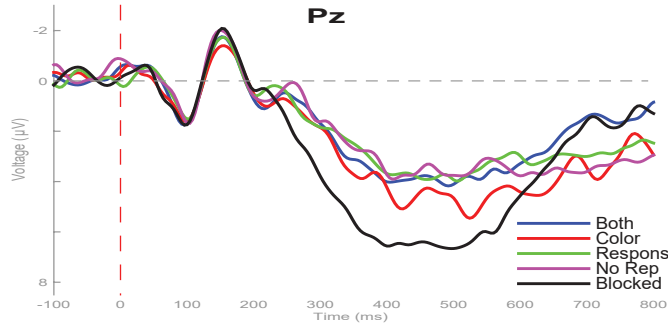
In Set Size 6, the effect of repetition type on P3b amplitude was also significant: $F(2.134, 29.881) = 6.199, p < 0.006$ (see Figure 3c). However, in contrast to Set Size 4, blocked trials significantly differed from only response and no repetition trials ($ps < 0.004$; $ps > 0.136$ for other comparisons). Color and both repetitions trials differed significantly from response repetition trials ($p > 0.022$ and $p > 0.017$, respectively, for color vs. response and both vs. response repetition trials). The rest of the comparisons did not lead to significance ($ps > 0.179$).

The P3b repetition type effect remained in Set Size 12; $F(2.552, 35.725) = 4.66, p < 0.011$ (see Figure 3d). Similar to Set Size 6, post-hoc tests demonstrated that P3b amplitude for blocked trials were higher than P3b amplitudes for response and no repetition trials, $ps < 0.005$. However, in contrast to Set Size 4 and 6, both feature repetitions and color repetition did not differ from response and no repetition trials in P3b amplitude in Set Size 12 (all $ps > 0.238$).

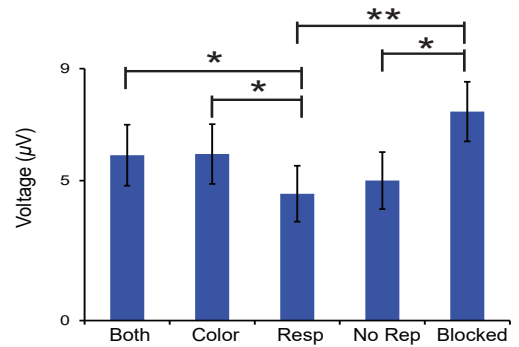
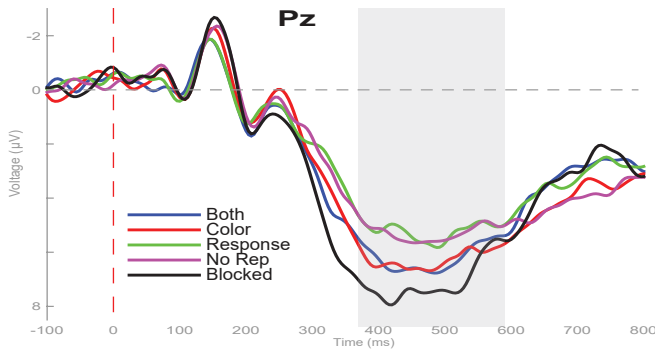
a. Set Size 4 P170



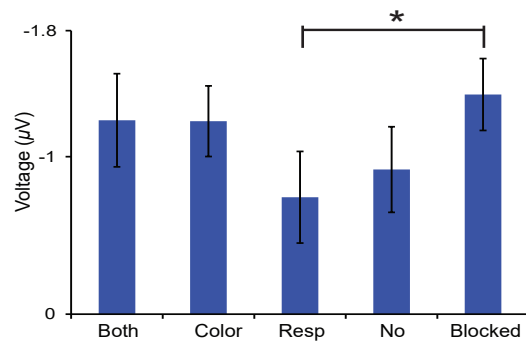
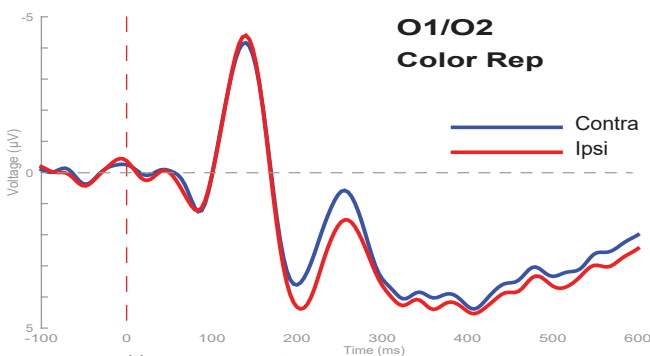
b. Set Size 4 P3b



c. Set Size 6 P3b



d. Set Size 12 P3b



* $p < 0.05$, ** $p < 0.001$

Figure 3. ERP results from Experiment 1 across all set sizes: a) P170 for Set Size 4, b) P3b for Set Size 4, c) P3b for Set Size 6, and d) P3b for Set Size 12. The red dashed line in the waveform graphs represents the onset of the search array. The shaded gray area is the approximate measurement time window of the ERPs.

Although the topography of P3b was not different in blocked trials compared to mixed (i.e., variable mapping) trials, (see Figure 4), I still assessed the possible effect of set size on P3b for blocked trials with an ANOVA. The results demonstrated that set size did not exert any effect on P3b amplitude in blocked trials; $F(2, 28) = 1.367, p > 0.270$, meaning that the number of stimuli on the search array was not represented in working memory, as indexed by P3b.

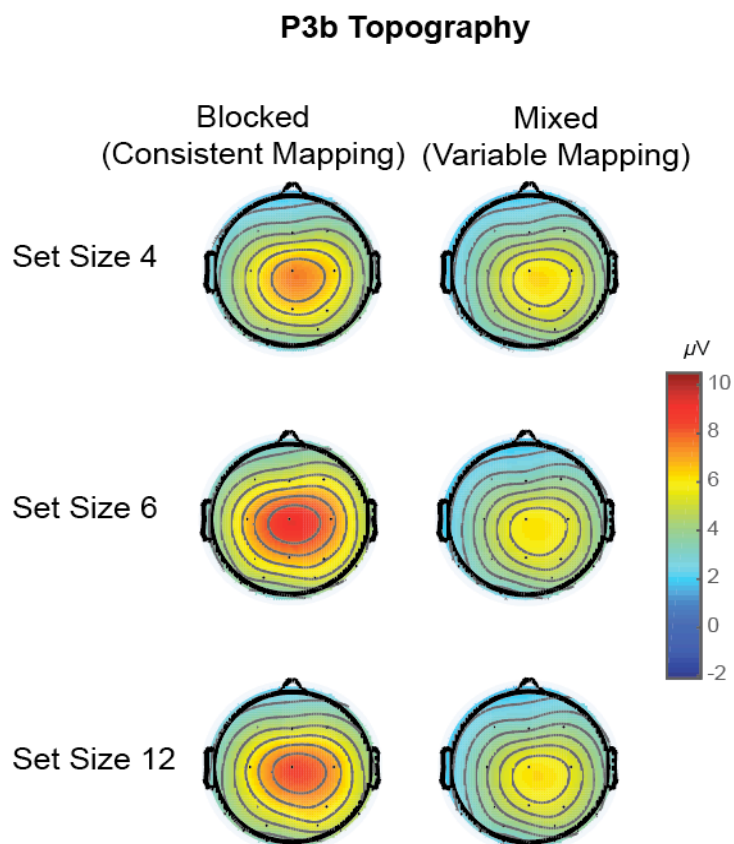


Figure 4. Comparisons of topography of the P3b between blocked and mixed repetition trials for all set sizes in Experiment 1. The time window of measurement was between 400-600 ms after search array onset.

CDA

Repetition type did not exert any significant effect on CDA amplitude in any of the set sizes ($F(4, 56) = 0.580, p = 0.678$, for Set Size 4; $F(4, 56) = 0.814, p = 0.522$, for Set Size 6; $F(4, 56) = 1.776, p = 0.147$, for Set Size 12).

Additionally, an ANOVA comparing CDA amplitude across set sizes in blocked repetition trials showed that CDA for blocked repetition trials was comparable in all set sizes, $F(1.358, 19.009) = 0.277, p = 0.675$.

Discussion

Behavioral results from Experiment 1 can be summarized as following: First, Set Size had an effect on RTs only in variable mapping trials. Reaction times were faster with increasing set sizes for variable mapping trials. This finding is in line with previous studies of priming of pop-out (Bravo & Nakayama, 1992; Maljkovic & Nakayama, 1994). Additionally, in this experiment I found that within variable mapping trials, there were sharp RT differences between trials in which only color or both features repeated and trials in which response alone or neither features repeated. However, the differences in RTs became smaller with increasing set sizes. It is possible that RT differences between repetition types disappear with larger set sizes. I also observed these effects in accuracy scores to a smaller extent, probably because of very high accuracy throughout all set sizes. Behavioral results alone suggests that the mechanisms at work in priming of pop-out becomes highly efficient with increasing set sizes and the role of target

feature repetition starts to diminish with this efficiency. ERP results shed more light on this point.

In contrast to the P3b prediction that color repetition would lead to decreases in P3b amplitude, I observed increases in P3b when the color repeated from the previous trial. Previous research (e.g., Squires et al., 1977; Sutton et al., 1965) demonstrated that repeated presentations of a stimulus lead to decreases in P3b. However, these studies explored the effect of the oddball stimulus and thus used long stimulus presentation sequences with oddball stimulus interleaved between these sequences. However, the presentation pattern in this experiment allowed for rapid changes in the stimulus (i.e., 50% chance of target color or gap repetition), therefore the participant needed to monitor the features all the time and working memory was probably updated accordingly. Regardless of the direction of the changes in P3b, the responsiveness of P3b to repetition of color suggests that working memory keeps track of the primary feature and this activity is very likely to be related to the speeding-up of RTs with color repetitions.

Nevertheless, the main P3b effect across set sizes was between variables (i.e., mixed repetition blocks) and consistent mapping trials (i.e., blocked repetition blocks). P3b was consistently larger in consistent mapping trials, although this effect diminished with set size increases. There were no discernible topographical differences between the P3bs observed for consistent and variable mapping trials, thus it is safe to conclude that the processes indexed by P3bs were similar between these conditions. These results suggest that working memory still needs to be updated when the target color repeats throughout the experimental block (i.e., consistent mapping). Consistent

mapping tasks employ mainly long-term memory representations (Logan, 1988a, 1988b; Logan, 1990), thus, when first examined, it is surprising to see that consistent mapping trials led to the greatest P3b amplitudes in the current experiment. However, participants were not aware of the fact that some of the experimental blocks were consistent mapping blocks in this study, thus it is possible that they thought the target could change any time throughout any block. The fact that there were only 3 consistent mapping blocks (one for each set size) compared to 12 (four for each set size) for variable mapping supports this possibility. Nevertheless, P3b as the measure of working memory updating keeps track of performance in priming of pop-out for both consistent and variable mapping.

The ERP measure of long-term memory in the current study, P170, differed between consistent mapping (i.e., blocked repetition) and variable mapping trials with color and response both repeating from the previous trial. In contrast to previous studies reporting lower P170 amplitudes with more target repetitions (Reinhart & Woodman, 2013; Voss et al., 2010), blocked repetition trials led to higher P170 amplitudes in this experiment. This effect was significant only in Set Size 4. One potential explanation of this finding is the idea that P170 indexes long-term memory retrieval attempts (Duarte et al., 2004). In blocked repetitions, because the target remains the same, participants do not need to retrieve from long-term memory. However, change is expected in each trial in variable mapping trials and there might be attempts at long-term memory retrieval. These long-term memory retrieval attempts are even more probable with smaller set sizes in the current task as the performance diminishes and attention benefits from target feature repetitions.

To sum up, findings from Experiment 1 suggest that working memory is constantly updated during priming of pop-out tasks and the amount of the updating decreases with set size increases, similar to the RT effect. Long-term memory might also be employed, especially when the “pop-out” target cannot be determined with ease (i.e., Set Size 4).

CHAPTER 3

EXPERIMENT 2

Rationale

Maljkovic and Nakayama (1994) showed that when a target feature repeated over several trials, the reaction times in responding to the secondary feature became faster. This reaction time benefit was cumulative but stopped at approximately the seventh repetition. Based on this finding, Maljkovic and Nakayama argued that the special memory system they proposed to explain priming of pop-out (i.e., visual implicit memory) had a temporal capacity limitation of approximately seven trials. However, previous research on the effect of repeatedly searching for the same target over sequences showed that with longer repetition sequences long-term memory representations guided visual search over working-memory representations that guided visual search with fewer target repetitions (Carlisle et al., 2011; Reinhart & Woodman, 2013). That is, long-term memory representations can drive priming of pop-out in relatively long color repetition sequences.

Carlisle et al. and Reinhart and Woodman monitored how working and long-term memory representations change through sequences of repetitions by ERP components

CDA and P170, respectively. In this experiment, I adapted the rationale of Carlisle et al. (2011) and Reinhart and Woodman (2013) in using ERPs as indices of working and long-term memory representations to priming of pop-out. First, I expected that the shape of the speeding-up of RTs with sequential color repetitions would fit very well to a power function, indicating that automaticity, driven by long-term memory representations (Logan, 1988b, 1990), had developed in priming of pop-out. Next, I investigated the ERP measures of long-term and working memory representations to explore which of these memory systems guides attention in priming of pop-out, thus relates to behavior (i.e., RT).

In line with the results from the studies of Carlisle et al. (2011) and Reinhart and Woodman (2013), if long-term memory representations underlie priming of pop-out with color repetitions, the P170s (i.e., ERP long-term memory measure in the current experiment) would become more negative with longer target-feature repetition sequences. Because updating into working memory resulted in increase in P3b amplitude in Experiment 1, I expected that working memory would be recruited in the first few repetitions, resulting in increases in P3b. However, I also expected them to gradually diminish with longer repetitions, because long-term memory representations would drive performance later in a color repetition sequence. Therefore, P3b amplitude, as the measure of updating working memory, would diminish quickly after a few target-feature representations.

In addition to the P3b as the working memory updating measure, I also utilized an additional ERP measure of working memory, the CDA (Vogel & Machizawa, 2004), to track working-memory modulations in priming of pop-out although the time window in

which information was to be maintained in working memory was very short (i.e., less than 400 ms) in this experiment. I also explored whether encoding into working memory, as measured by suppression of the power in the alpha frequency band of the EEG in parietal/occipital sites (Fukuda & Woodman, 2015; Hanslmayr, Spitzer, & Bauml, 2009; Klimesch et al., 1996), would be modulated by color. The alpha power suppression effect could be sensitive to the length of color repetition such that it decreases with more repetitions, meaning that less color information needs to be encoded into working memory.

The design and an example of a sequence of trials in Experiment 2 are illustrated in Figure 5.

Method

Participants

Another set of 15 volunteers participated in the study. All had normal or corrected-to-normal color vision. None of them reported any history of neurological conditions. Vanderbilt University IRB approved all experimental procedures.

Stimuli

The stimuli used in this experiment were the same as Experiment 1.

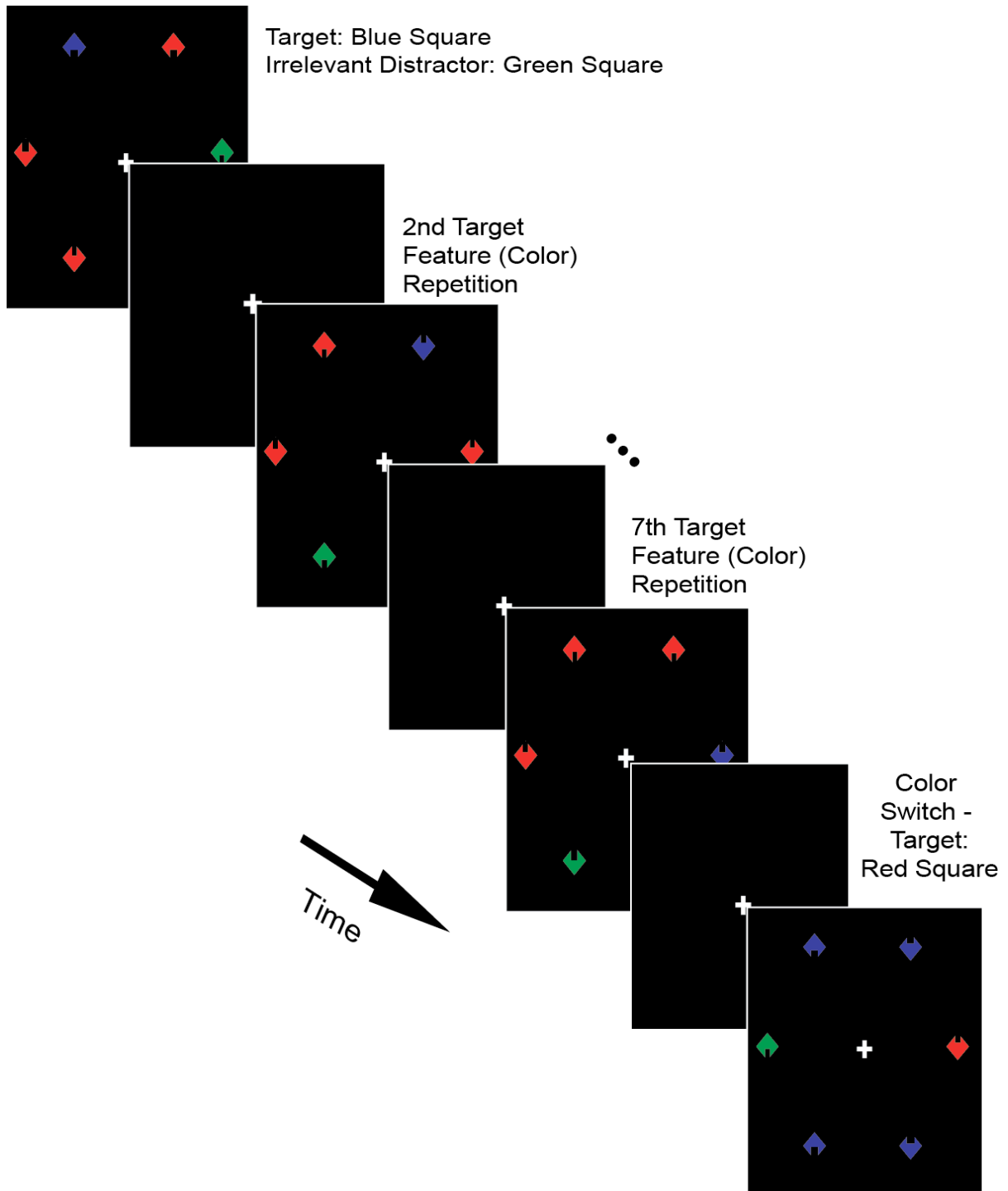


Figure 5. A schematic of a sequence of color repetition in Experiment 2. In this example, the target color (blue) sequentially repeats 7 times. At the 8th trial, target color switches to red and a new color repetition sequence begins. Green is always the irrelevant color in this example. Direction of the gap in the target is allowed to repeat with a probability of 50%.

Procedure

The experimental procedures were the same as Experiment 1, except for the following. Firstly, the set size was constant at 6 (one target, four relevant distractors, and one irrelevant distractor). Secondly and most importantly, color (i.e., target feature) repeated in sequences of 3, 5, or 7. Each of these sequences was presented 10 times in each experimental block, thus, as in Experiment 1 blocks were 150 trials long. Response feature (i.e., direction of the gap of the target item) was allowed to repeat regardless of color repetition sequences, with a probability of 0.5. Participants received no information about the length of the repetition sequences within blocks.

EEG Recording & ERP Analyses

All EEG recording and ERP analyses procedures were the same as Experiment 1.

Three participants were replaced because of excessive eye movement artifacts (30% or more of individual trials rejected or the residual HEOG activity remained above $3 \mu V$, which, in our laboratory set-up, corresponds to $\pm 0.1^\circ$ eye movements). The average single trial rejection rate for the final 15 participants was 16%.

Time-Frequency Decomposition

To perform time-frequency decomposition, EEG data were convolved with a Morlet wavelet, which is the product of a Gaussian window with a complex-valued sine

wave. Peaks of the complex-valued sine wave varied with frequencies (min: 2 Hz, max: 30 Hz, 29 linear steps). Standard deviation of the Gaussian window was determined by the number of cycles for each frequency. In this analysis, I used variable number of cycles, which increased from 3 to 10 with increases in frequency, for an optimal balance between temporal and spatial (i.e., frequency band) resolution (Cohen, 2014). The Morlet wavelet was convoluted with the EEG signal in all time points with the following formula:

$$\frac{e^{i2\pi ft + \frac{-t^2}{2s^2}}}{(s\sqrt{\pi})^{1/2}}$$

where t is the time points in the EEG data, s is the standard deviation of the Gaussian window, and f is the frequency of interest. The Morlet-wavelet convolution resulted in complex-values for each time point in each frequency of interest. The conjugate of the complex values was taken to compute frequency power. Lastly, -200 to 0 ms window, relative to the search array onset, was used for the baseline correction and the conversion of power to relative dB units.

I employed custom written MATLAB scripts, modified from Cohen's (2014) scripts, to carry out time-frequency decomposition. Based on the literature (e.g., Klimesch, 1999) the alpha frequency band was measured between 8 and 12 Hz to assess alpha suppression in the parietal electrodes. Alpha power related to memory

encoding was extracted from Pz (Klimesch et al., 1996), between 250-400 ms after stimulus array onset.

Fitting Power Function to RT and P3b

The power function was fit to RTs and P3b amplitudes over the number of repetitions with the following formula:

$$y = a + bN^{-c}$$

where Y is the predicted RT or P3b amplitude. As explained by Logan (1990), a is the asymptote of learning or updating, b is multiplicative constant indicating how much there is to be learned or updated between the initial condition and the learning asymptote, N is the number of target feature repetitions, and c is the learning or updating rate. The method for fitting the function was non-linear least squares.

Results

Behavioral

RT

RTs became faster with repetitions of the target feature (i.e., color) ($F(1.361, 19.049) = 86.62, p < 0.001$). The RT speeding function fit very well to a power function, (see Figure 6a) with a mean adjusted goodness-of-fit value of 97.5% across participants (individual and grand-average fit parameters are reported in Appendix A), suggesting that most of speeding up happens in the first few repetitions and RT benefits start to diminish with more repetitions. The power function fit to RTs is an indicator that long-term memory representations guide performance (Logan, 1988b; Logan, 1990; Newell & Rosenbloom, 1981).

Does the length of a repetition sequence have a cost on RT? This possibility was explored by comparing the RTs for the first trials after sequence ends (sequence lengths: 3, 5, and 7). The effect of sequence length was significant, $F(2, 28) = 54.74, p < 0.001$, such that RTs were the slowest after a repetition sequence of 7 and the fastest after a repetition sequence of 3 ($ps < 0.001$) (see Figure 6b).

Although colors were repeated in sequences, responses were free to repeat anywhere in a repetition sequence, with a probability of 0.5. However, RTs for trials with

the same response as the previous trials were not faster than trials without response repetition ($t(14) = -1.994, p > 0.065$).

Accuracy

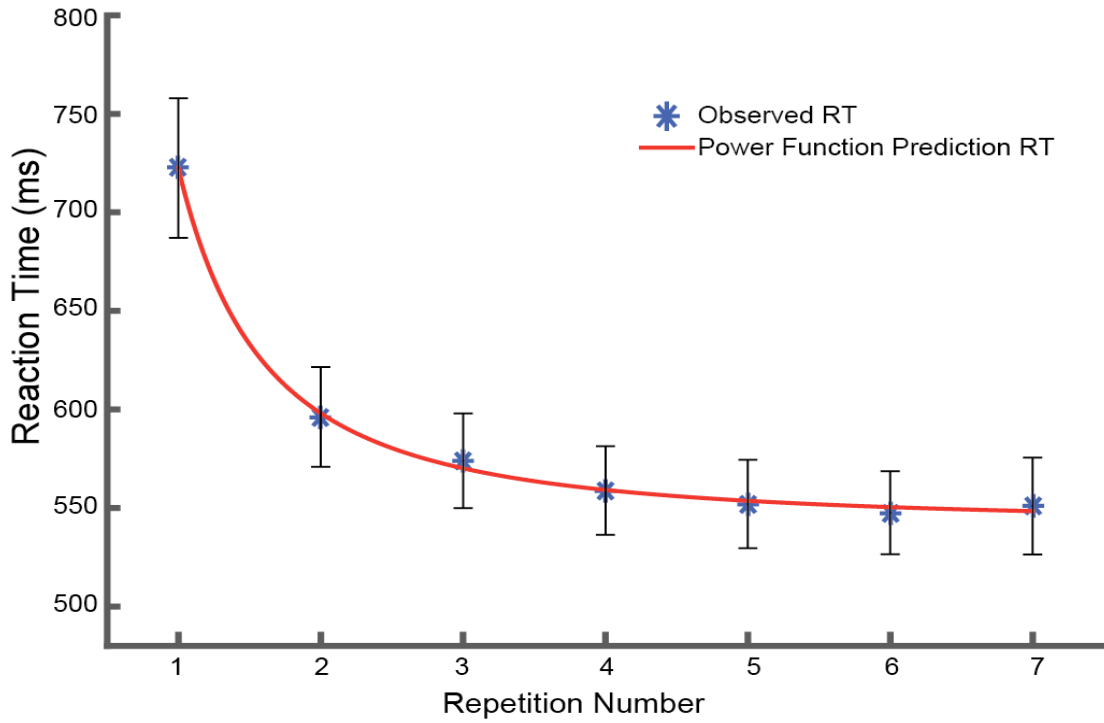
More target feature repetitions also led to increases in accuracy, $F(1.977, 27.863) = 4.992, p < 0.015$ (see Figure 6c). Most of the benefit of repetition was observed for the second repetition: accuracy for first repetition significantly differed from all other repetitions ($ps < 0.048$); however, accuracy did not differ between repetitions after the first repetition ($ps > 0.594$).

The sequence length effect disappeared for accuracy, $F(1.426, 19.963) = 1.313, p = 0.281$. Also, response repetitions did not lead to changes in accuracy, $t(14) = -0.244, p = 0.811$.

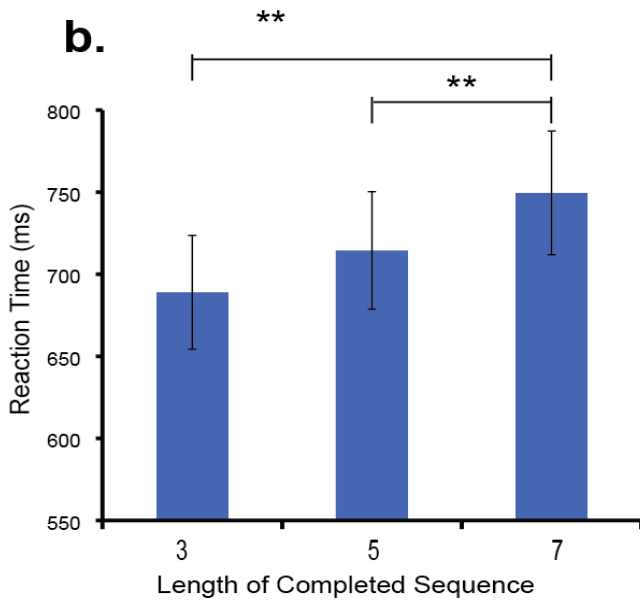
P170

Does the measure of long-term memory in this study, P170, track the speeding-up of RTs? Although the effect of repetition was significant on the P170 amplitude ($F(6, 84) = 2.589, p < 0.025$), the shape of the repetition function was different for P170 (see Figure 7a). From Repetition 1 to 6, P170 decreased linearly (linear contrast, $p < 0.001$; all other polynomial contrasts, $ps > 0.448$), indicating an increase in activation of long-term memory representations (Duarte et al., 2004; Reinhart & Woodman, 2013; Voss et al., 2010). However, the P170 amplitude increased in Repetition 7 and rebounded back

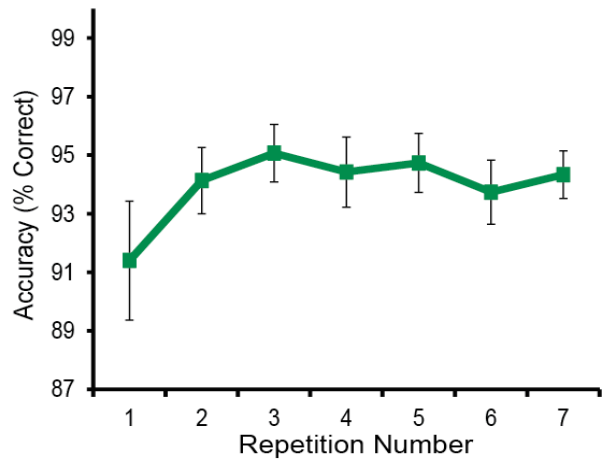
a.



b.



c.



* $p < 0.05$, ** $p < 0.001$

Figure 6. Behavioral results from Experiment 2: a) RTs across color repetitions and their fit to the power function, b) RTs observed in the first trial after a color repetition sequence is completed, as a function of the length of the previous repetition sequence, and c) Accuracy scores across color repetitions.

to the P170 for Repetition 1 (Rep 1 P170 vs. Rep 7 P170 did not differ from each other, $p = 0.999$).

Are changes in P170 with repetition correlated with RTs? Table 1 shows that P170s are positively correlated with RTs after Repetition 5. Participants with higher P170 amplitudes in Repetitions 6 and 7 also demonstrated faster RTs, suggesting that employing long-term memory representations through the end of the repetition sequence is beneficial for performance (see Figure 8).

RTs were slower for the first trial of a repetition sequence when the previous sequence was longer. However, P170 was not sensitive to the length of the previous sequence; P170 did not differ in trials after repetition sequences of 3, 5, and 7 ($F(2, 28) = 0.161, p = 0.852$). This finding suggests that long-term memory representations were reset at the start of a new sequence.

Table 1.

Correlations between RTs and ERP Components in Experiment 2 (Pearson Correlation Coefficient, p value)

<u>Repetition</u>	<u>P170</u>	<u>P3b</u>	<u>CDA</u>	<u>Alpha Power</u>
1	0.205 (0.465)	-0.194 (0.488)	0.233 (0.404)	-0.500 (0.057)
2	0.339 (0.217)	-0.406 (0.133)	0.084 (0.766)	-0.388 (0.153)
3	0.392 (0.149)	-0.489 (0.064)	0.033 (0.906)	-0.358 (0.191)
4	0.370 (0.175)	-0.574 (0.025)*	-0.252 (0.364)	-0.458 (0.086)
5	0.408 (0.131)	-0.619 (0.014)*	0.009 (0.976)	-0.504 (0.056)
6	0.618 (0.014)*	-0.652 (0.008)**	-0.120 (0.670)	-0.449 (0.093)
7	0.656 (0.008)**	-0.603 (0.017)*	-0.343 (0.211)	-0.469 (0.078)

Note. * $p < 0.05$, ** $p < 0.01$. Correlation coefficients were computed between the RTs and ERP components for the corresponding repetition order (e.g., RT and P170 for Repetition 1).

P3b

P3b amplitude, the measure of working memory updating, increased overall with target-feature repetitions ($F(2.441, 34.168) = 16.500, p < 0.001$) (see Figure 7b). However, the shape of the function did not mirror the power law speeding-up of RT: although the power function fit the grand mean adequately (adjusted goodness-of-fit for grand average = 98.49%), fit across participants was poor (average adjusted goodness-of-fit across participants = 61.85%). Individual and grand-average fit parameters are reported in Appendix B. The sharp P3b increase between Repetition 1 and 2 (Tukey's post-hoc test, $p < 0.001$) was followed by a linear, but smaller increase between repetitions 2 and 7 (linear contrast, $p < 0.001$; all other polynomial contrasts, $ps > 0.417$).

What is the relationship between increases in P3b with repetition and RTs? Table 1 shows that after Repetition 4, P3b is negatively correlated with RTs. That is, participants with higher P3b amplitudes in Repetition 5, 6, and 7 were faster in responding to the gap of the target (see Figure 9). These results indicate that the amount of the updated information in working memory might be related to faster RTs, in similar to the P170 results.

Similar to the case of P170, P3b amplitude for the first repetition trials also did not differ with the length of the previous repetition sequence ($F(2, 28) = 1.142, p = 0.334$).

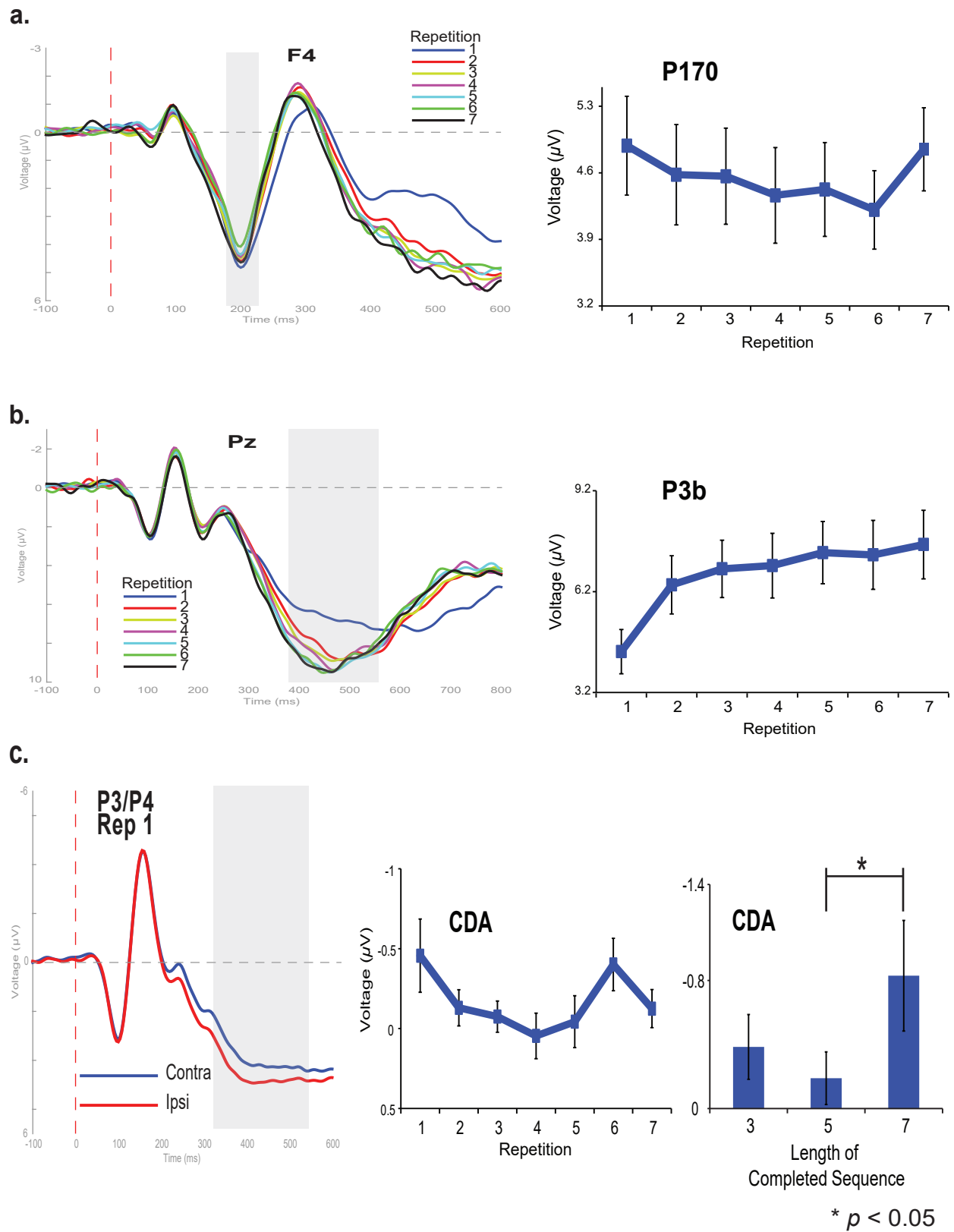


Figure 7. ERP results from Experiment 2: a) P170, b) P3b, and c) CDA. Difference waves for CDA are illustrated in Appendix E.

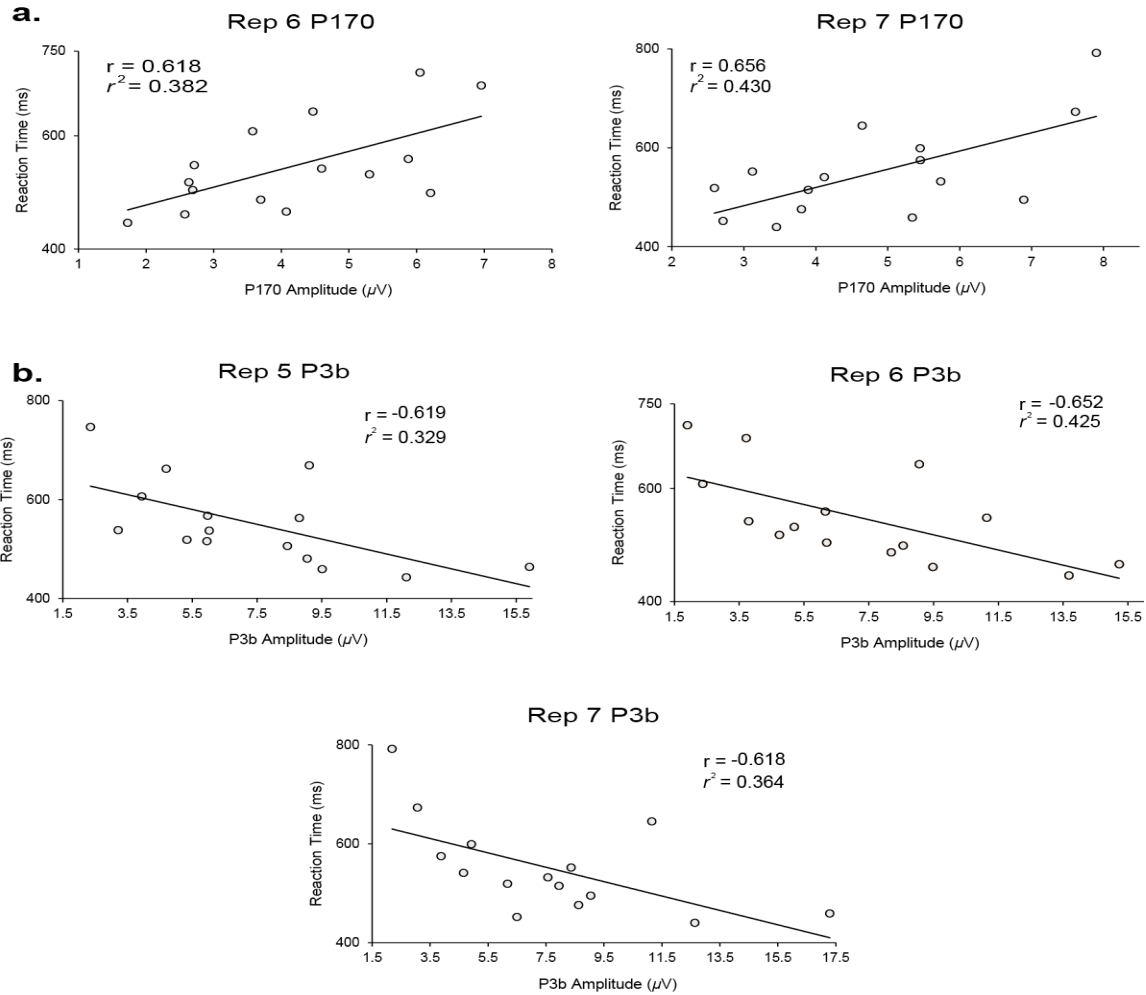


Figure 8. Correlations between RTs and a) P170 amplitudes in Repetitions 6 and 7, and b) P3b amplitudes in Repetitions 5, 6, and 7 in Experiment 2. All of the illustrated correlations were significant at $\alpha = 0.05$.

CDA

CDA, the index of working-memory maintenance, changed with color repetitions ($F(6, 84) = 3.624, p < 0.004$) (see Figure 7c). Specifically, the first 5 repetitions did not produce significant CDAs (one sample t-tests for comparisons with 0, $ps > 0.066$), whereas the CDA was different than 0 in Repetition 6 (one sample t-test, $t(14) = -2.447, p < 0.029$). The CDA diminished again in the last repetition ($t(14) = -1.056, p = 0.309$).

This result might have stemmed from the possibility that when the target color repeated the sixth time, participants realized that they needed to maintain the color information in working memory because it was certain that the sequence would extend to the seventh repetition. At the seventh repetition, however, knowing that colors repeated at most 7 times, participants might have decided not to maintain color information, as reflected by the absence of CDA in the 7th repetition.

The CDA did not significantly correlate with RTs in any of the repetitions (see Table 1, $ps > 0.210$)

The sequence completion effect was observed in CDA ($F(2, 28) = 4.542, p < 0.021$) (see Figure 7c). The CDA observed in the first trial after a sequence of 7 repetitions was greater in amplitude than sequences of both 5 repetitions ($p = 0.017$). No other comparisons were significant ($ps > 0.119$).

Parietal Alpha Power

Parietal alpha power changed with the number of repetitions ($F(6, 84) = 2.752, p < 0.018$) (see Figure 9). Importantly, similar to the CDA results, alpha power systematically increased until the 6th repetition, indicating less memory encoding (Fukuda & Woodman, 2015) with more repetitions (linear contrast, $p < 0.001$; all other polynomial contrasts, $ps > 0.151$). However, at the 6th repetition, alpha power suppression increased significantly (Tukey's post-hoc test between Repetition 5 and 6, $p < 0.047$). This finding suggests that color information was encoded strongly in Repetition 6, probably because it was certain at Repetition 6 that the sequence would

Parietal Alpha Repetition Effect

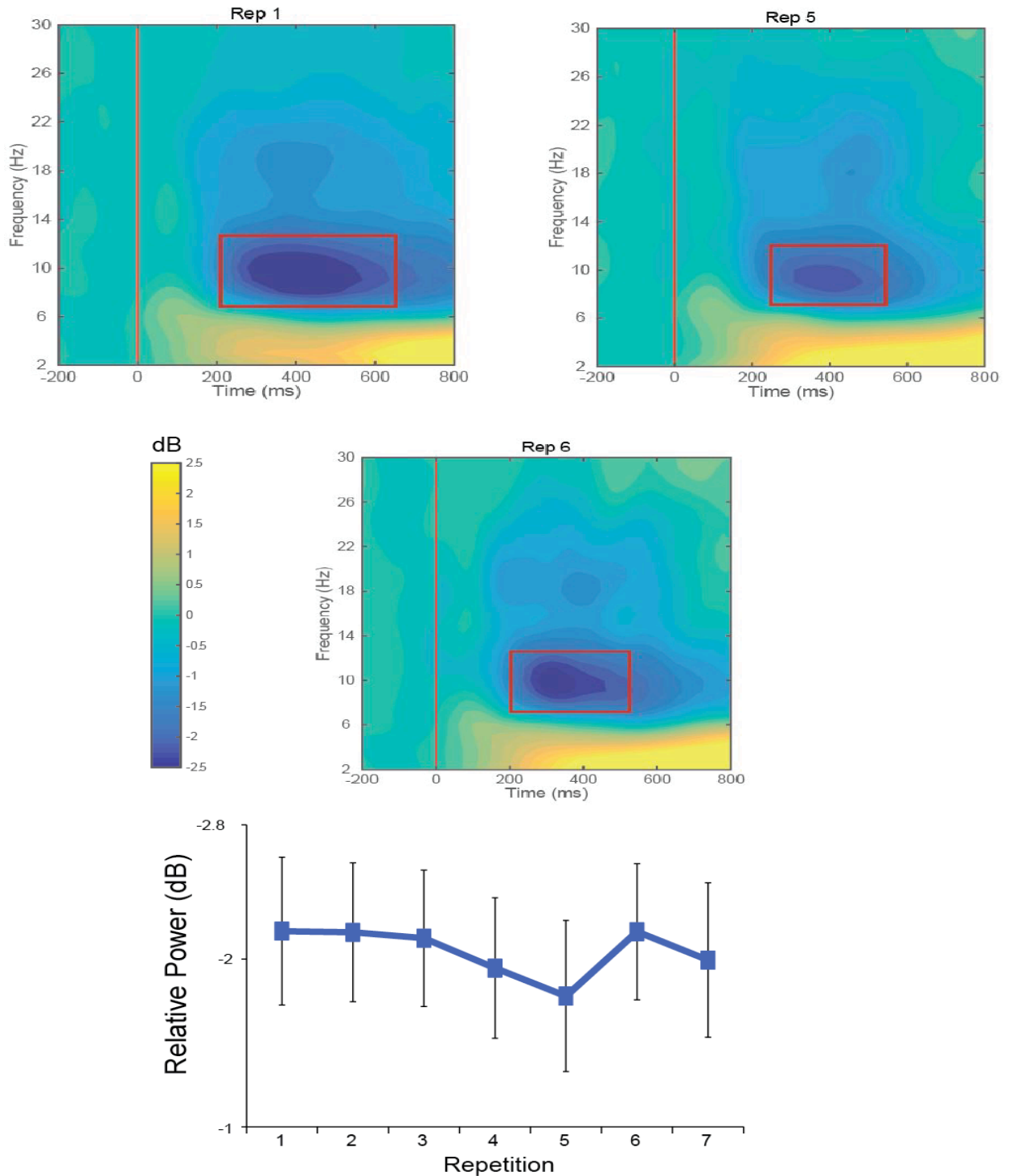


Figure 9. Parietal alpha suppression across color repetitions in Experiment 2. The red square in the time-frequency decomposition graphs represents the approximate time window of the alpha measurements.

continue until Repetition 7 but not more. In this case, getting working memory online and preparing to reset long-term memory for the upcoming sequence can be considered as an optimal approach, as supported by P170, CDA, and parietal alpha suppression findings.

The correlation between the extent of parietal alpha suppression and RTs were negative throughout all repetitions, indicating stronger alpha suppression (i.e., better encoding into working memory) is related to slower reaction times, although this correlation was only marginally significant (see Table 1, $ps > 0.055$).

Discussion

In this experiment, I tracked the question of how repeated presentations of a target feature in priming of pop-out affect search efficiency, attentional selection, and long-term and working memory mechanisms. RTs benefited from repetitions of color (i.e., target feature): most of this benefit was observed for the first few repetitions and the benefit became smaller with increasing repetitions. The power function fit for RTs over repetitions explained the data adequately (adjusted goodness-of-fit across participants = 97.51%). The power function fit has been observed in tasks where automaticity is developed after a few task repetitions (Logan, 1988b; Logan, 1990; Newell & Rosenbloom, 1981). Logan (1988b) argued that long-term memory representations govern performance once automaticity is developed, whereas the effect of short-term memory representations (i.e., the algorithmic component working online

solutions to the problem) on performance starts diminishing. Logan (1988b) explained the relationship of long-term memory representations with the power function of performance speed-up with a race model between working and long-term memory. In this model, each presentation of the target item forms new long-term memory representations (i.e., instances). The number of long-term memory representations increases with repetitions and so does the probability of them winning the race against working memory. The shape of the RT speed-up function in this experiment and the good fit of the power function to RTs suggest that long-term memory representations are driving RTs in this task.

The ERP measure of long-term memory, P170 amplitude, also supports the idea that long-term memory representations are utilized in priming of pop-out. I found that P170s decreased linearly with repetition of color up to the 6th repetition, indicating that long-term memory representations were accumulating over repetitions. However, P170 rebounded to its initial levels at the 7th repetition, which was the maximum number of repetitions in this experiment. It seems likely that regularities in the presentation of the stimuli, such that it is aware that target color will not repeat more than 7, are determined in priming of pop-out. Thus, this rebound of P170 amplitude at the 6th repetition might imply that long-term memory representations are reset (Grossberg, 1978) as they will no longer be recruited afterwards.

The index of maintenance in working memory, CDA, also reacts differently to the 6th repetition of color. I found that CDA decreased until the 6th repetition of the target, suggesting that the amount of information maintained in working memory decreased with repetitions. However, CDA increased sharply for the 6th repetition. It might be the

case that the system keeping track of the presentation regularities led to the recruitment of working memory representations at the 6th repetition, at which point it is certain that there can only be one more repetition. Therefore, the interplay between working and long-term memory can be observed through the end of the series of the repetition sequence: long-term memory is increasingly influential until the end of the series whereas working memory takes control at the end of the series.

The finding that parietal alpha suppression decreased until the 6th repetition and made a sharp increase at the 7th repetition further supported the above possibility. Previous research on parietal alpha suppression suggested that the more suppression of alpha band activity in the parietal/occipital electrodes is indicative of better encoding of to-be-memorized items (Fukuda & Woodman, 2015; Hanslmayr et al., 2009; Klimesch et al., 1996). In this experiment, the linear decrease in alpha suppression until the 6th repetition indicates that color information was encoded less and less. However, at the 6th repetition, encoding of the target feature, as indexed by parietal alpha suppression, was enhanced. It is likely that length of the repetition sequence was tracked by a system that informed the memory encoding mechanisms indexed by the parietal alpha suppression to get online, as a preparation for the ending of the sequence. It should be noted that the sequence end effects are not observed with 3 and 5 color repetition sequences because it cannot be known beforehand whether the sequence would end or not after Repetitions 3 and 5. When the CDA and parietal alpha suppression findings are taken together, it seems likely that working memory is recruited when the finish of the repetition sequence is anticipated. Otherwise, long-term memory, indexed by changes in P170, is associated more with priming of pop-out.

Results from the analyses of repetition effects in P3b demonstrated that repetition of color leads to updating of contextual information in working memory. Also, the increase between the first and the second repetitions is sharper compared to the rest of the sequence. RT benefits are also maximal in the second repetition. The system keeping track of the length of the repetition sequence and possibly informing working and long-term memory systems might be related to the working memory update processes indexed by the P3b (Donchin & Coles, 1988). However, this system alone does not seem to determine RTs because the power function that was an appropriate fit for RTs was not a good fit for P3b (average adjusted goodness-of-fit across participants for the P3b power function fit = 61.85%). Rather, P3b might have been indexing the process of keeping track of the presentation context (e.g., repetition sequence length), which could inform an executive control system to hand out of long-term memory representations to working memory representations, which was apparent at the 6th repetition. However, the employment of either working or long-term memory representations to guide attention produced similar RTs: higher P3b amplitude, indicative of more pronounced context updating into working memory and lower P170 amplitudes, indicative of higher long-term memory activation, were correlated with faster RTs.

Overall, the results of this experiment suggest that priming of pop-out is shaped by a complex interplay between working and long-term memory systems. Long-term memory representations control priming of pop-out until the end of a color repetition sequence. A system keeping track of the number of color repetitions throughout the sequence informs the memory systems whether or not the sequence will finish soon

When it is certain that the sequence will end, working memory is recruited more as a preparation for the upcoming sequence change. Thus, priming of pop-out cannot be accounted for by a single memory system that controls attention throughout the repetition sequence (Maljkovic & Nakayama, 1994, 1996, 2000), regardless of the length of the sequence. Rather, it is a dynamic phenomenon informed by several, canonical memory systems.

CHAPTER 4

EXPERIMENT 3

Rationale

Maljkovic and Nakayama (1996) showed that repeating locations of the target in priming of pop-out led to faster reaction times in responding to the secondary feature of the target. From this result, Maljkovic and Nakayama (1996) argued that the visual implicit memory also involved spatial information about targets. However, canonical interpretations of working memory and long-term memory propose that both memory stores include spatial information (Logan, 1998; Phillips, 1974), thus either of them could explain the priming of position in priming of pop-out. I used the same ERP and EEG measures of long-term and working memory representations as Experiment 2 to elucidate the question of which memory representations could track priming of location.

To investigate this question, I presented the target item at the same location for 3, 5, or 7 times. Importantly, I allowed color (i.e., target feature) and responses to vary independently of each other with a probability of 0.5 in target location repetition sequences. As with Experiment 2, I explored the shape of the RT speeding-up function with target location repetitions. I expected the shape of the function to fit a power

function, indicating that responding to the target in the same location became an automatic task driven by long-term memory representations. Next, I looked at the ERP and EEG measures of long-term and working memory measures to evaluate which memory system might have driven behavior (i.e., RT) in priming of location. I used the same ERP and EEG measures as Experiment 2. If long-term memory representations guide attention in sequential target location repetitions, then P170 amplitude should decrease (i.e., greater long-term memory activation) with the number of repetitions. However, if working memory drives RT speeding-up in this task, any ERP and EEG measure of working memory (i.e., P3b, CDA, and parietal alpha suppression) would be modulated with location repetitions. Lastly, If the memory systems guiding attention had switched from working memory to long-term memory in the course of a repetition sequence (e.g., Logan, 1988b), this would have been implied by a quick diminish in working memory measures in the first few repetitions and a stable increase in long-term memory measures.

In this experiment, repeating the target at the same location in sequences might have rendered the target location an attentional cue (Posner, 1980). After a few location repetitions, the visual system might have already developed expectations about where the target would be presented in the next trial. However, after completion of a target location repetition sequence, the new location would capture attention. The cost of moving the target to a new location after a repetition sequence would be related to a) length of the completed sequence, and b) the proximity of the new target location to the target location from the recently completed sequence. Therefore, RTs would slow down

according to the proximity of the new location and this slowing down effect should be reflected in the ERP measures of working and long-term memory (i.e., P3b and P170).

An example of a sequence of trials from Experiment 3 is illustrated in Figure 10.

Method

Participants

A different group of 15 volunteers participated in Experiment 3. All participants had normal or corrected-to-normal color vision. None reported any history of neurological conditions. Vanderbilt University IRB approved all experimental procedures.

Stimuli

Stimuli were the same as Experiment 1 and 2.

Procedure

The experimental procedure was the same as Experiment 2, except for the following. The set size was still constant at 6 (one target, four relevant distractors, and one irrelevant distractor). However, in this experiment, location of the target item was repeated 3, 5, or 7 times. The target feature (i.e., color) and responses were allowed to

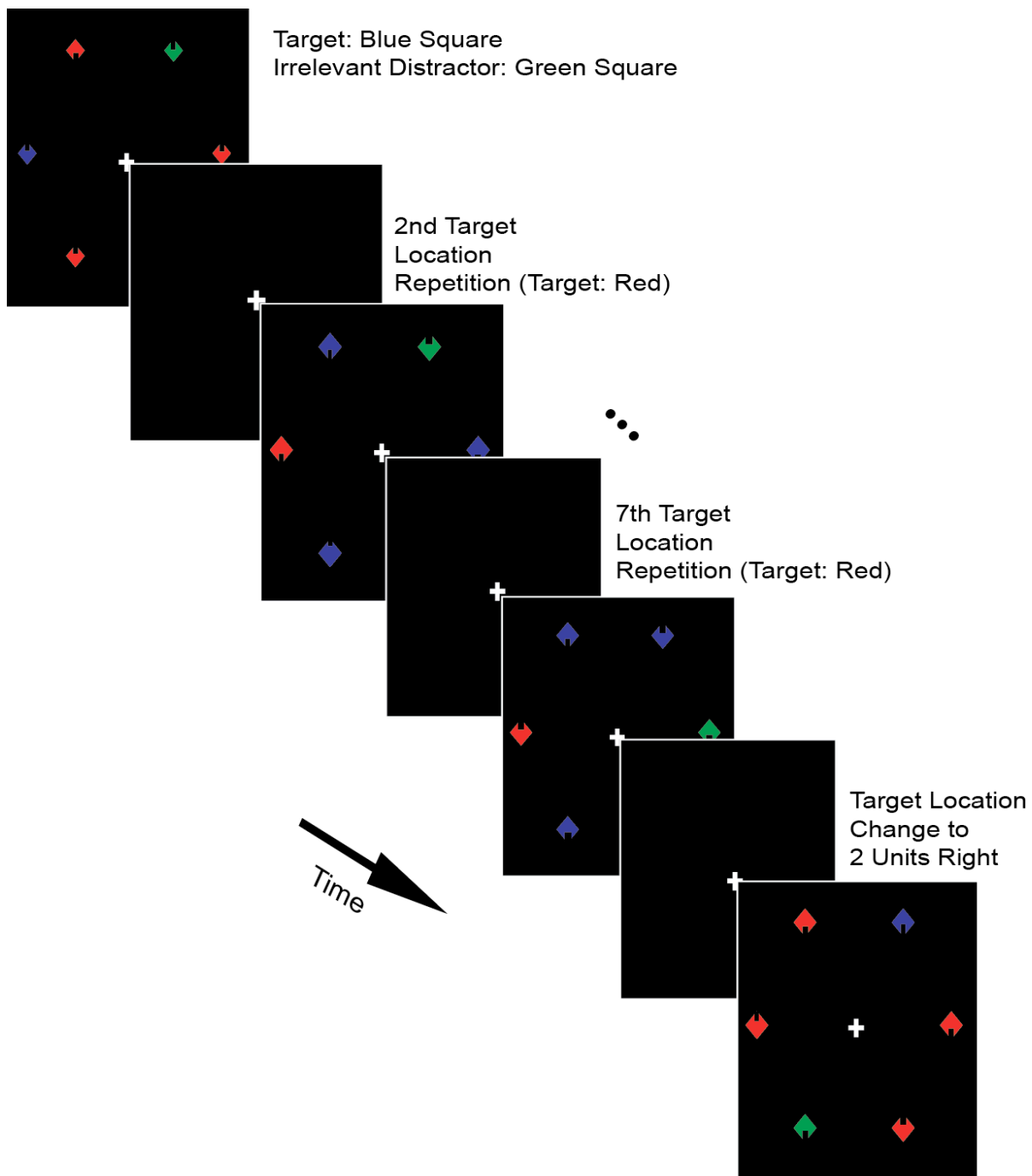


Figure 10. A schematic of a sequence of target location repetition in Experiment 3. In this example, the target location (9 o'clock position) sequentially repeats 7 times. At the 8th trial, target location switches to 1 o'clock position and a new location repetition sequence begins. Green is always the irrelevant color in this example. In Experiment 3, target color and responses were allowed to repeat independently of each other with a probability of 50%.

repeat with a probability of 0.5, however these changes were independent of each other and of location repetitions. The new location of the target after a location repetition sequence was randomized, resulting in approximately the same number of repetitions at each of the 6 locations on the invisible presentation circle.

EEG Recording & ERP Analyses

All EEG recording and ERP analysis procedures were the same as Experiment 1 and 2.

As in Experiment 2, three participants were replaced because of excessive eye movement artifacts (30% or more of individual trials rejected or the residual HEOG activity remained above $3 \mu V$, which, in our laboratory set-up, corresponds to $\pm 0.1^\circ$ eye movements). The average single trial rejection rate for the final 15 participants was 17%.

Time-Frequency Decomposition & Fitting Power Function to RT and P3b

The same analyses and procedures as Experiment 2 were used in Experiment 3.

Results

Behavioral

RT

RTs became faster with location repetitions ($F(1.745, 24.428) = 84.390, p < 0.001$). Power function was a good fit for the shape of the RT speed-up function (see Figure 11a) as demonstrated by appropriate adjusted goodness-of-fit values for both across participant RTs (mean goodness-of-fit = 91.72%) and grand-average RTs (goodness-of-fit = 99.12%). Based on the appropriate fit of power function to RTs, it seems that automatization is established in sequential repetition of locations, just like it was the case in target-feature repetitions (Experiment 2). Individual and grand-average fit parameters for RTs are reported in Appendix C.

In the current experiment, color (i.e., target feature) and response were allowed to repeat independently, therefore there were four possible repetition types at each step of the location repetition sequence: a) color repetition b) response repetition c) both repetitions, and d) no repetition. The question of whether response type exerts an effect on RTs throughout a location repetition sequence was evaluated with an ANOVA with factors of Repetition Type (4 levels: color, response, both, and no repetitions) and Number of Location Repetitions (7 levels: 1 through 7). As expected from the results of Experiment 1, the effect of Repetition Type was significant ($F(3, 42) = 42.505, p < 0.001$), such that response and no repetition trials were the slowest ($ps < 0.001$) and did

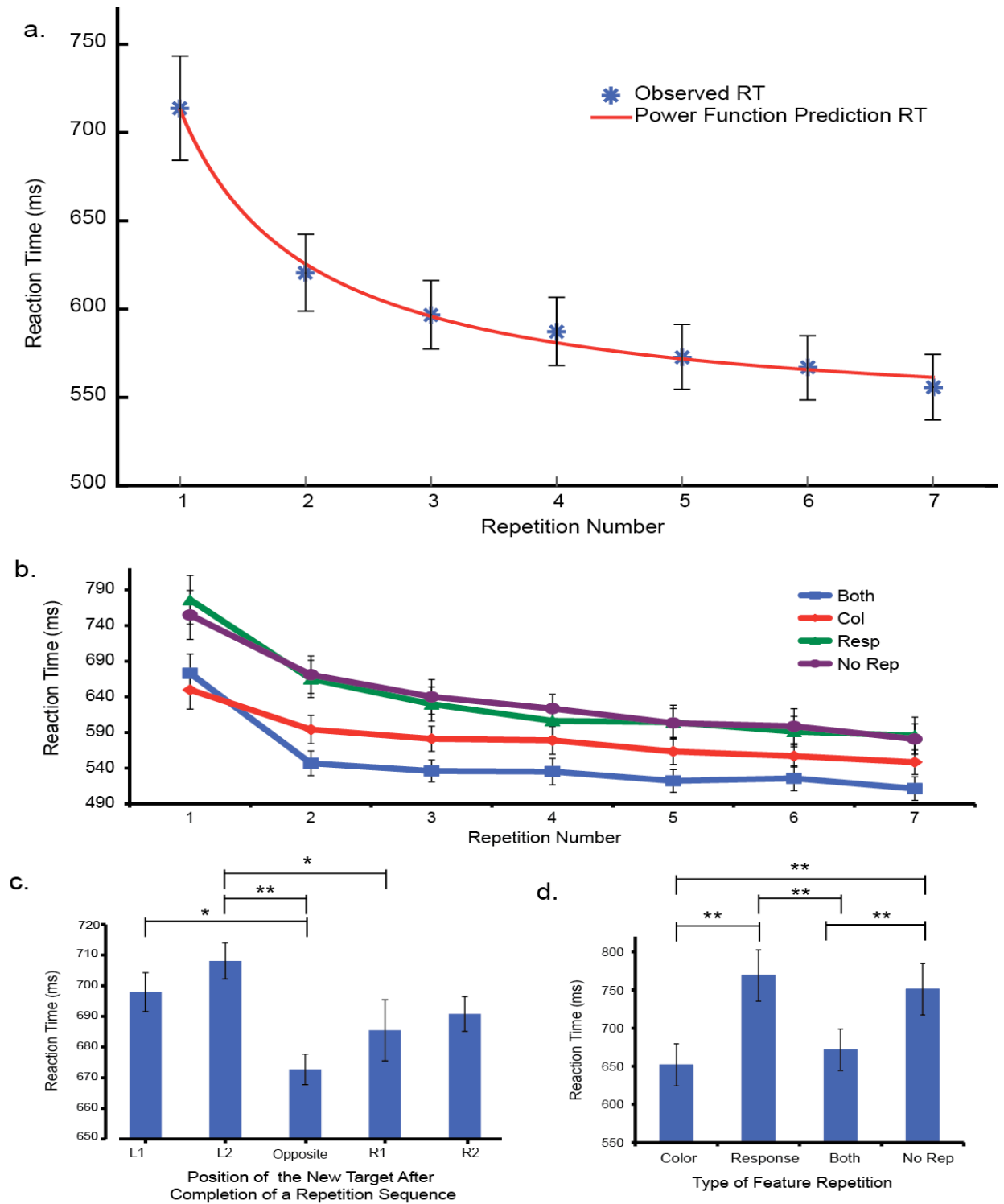
not differ from each other ($p = 0.997$) (see Figure 11b). Both repetitions were the fastest overall (Both vs. Color Repetition: $p < 0.009$). The effect of Number of Location Representations was also significant ($F(6, 84) = 84.45, p < 0.001$), and as described above, this effect was very well captured by a power function. Importantly, the effect of Repetition Type changed with the Number of Location Repetitions because the Repetition Type X Number of Repetitions interaction was significant ($F(18, 252) = 6.805, p < 0.001$).

A visual inspection of the graph illustrating the relationship between Repetition Type and Number of Repetitions (see Figure 11b) suggested that this interaction might have been driven by differences across Repetition Types in the first and second location repetitions. To test this possibility, the first two repetitions were excluded from the ANOVA with factors Repetition Type and Number of Location Repetitions. Although effects of repetition type and number of repetitions remained significant ($F(4, 56) = 20.676, p < 0.001$, for Number of Repetitions; $F(1.916, 26.818) = 35.149, p < 0.001$, for Repetition Type), the Repetition Type X Number of Repetitions interaction disappeared ($F(5.285, 73.996) = 1.919, p = 0.293$). These results suggest that differences between repetition types were preserved through Repetition 3 and Repetition 7. The direction of the repetition type effect is similar throughout the repetition trial; however, its magnitude differs between Repetitions 1 and 2 and the rest of the sequence (see Figure 11b).

The first presentation of the target in a repetition sequence (i.e., Repetition 1) could have occurred after a location repetition sequence of 3, 5, or 7. It was apparent from the significant interaction between Repetition Type and Number of Repetitions described above that the first trials in each sequence behave differently overall

compared to the rest of the repetition sequence. To evaluate whether the length of the recently completed sequence might have influenced RTs in the first trial of the current repetition sequence, I ran an ANOVA with the factor of Completed Sequence Length (3 levels: sequence length 3, 5, or 7) and Repetition Type. The length of the completed sequence did not influence RTs ($F(2, 28) = 1.554, p = 0.229$), indicating that location repetition sequenced did not bring any residual cost when they ended and a new sequence began. Repetition type influenced RTs after a sequence completion ($F(3, 42) = 31.489, p < 0.001$), such that when color alone or color and response both repeated from the last trial of the completed sequence, the RTs were faster compared to when only response or neither features repeated ($ps < 0.001$).

New target locations after the completion of a location repetition sequence could be 1 step right (1R), 2 steps right (2R), 1 step left (1L), 2 steps left (2L), or the opposite location in the invisible presentation circle (see Figure 10). The distance from the new location of the target to its old location from the previous sequence influenced RTs ($F(1.599, 22.390) = 7.713, p < 0.006$) (see Figure 11c). Overall, when the target item moved to the opposite location in the new target sequence, the RTs in the first trial of the new sequence were faster, compared to when it moved to one unit left (1L) or two units left (2L) ($ps < 0.005$) (see Figure 11 for a visual demonstration of location shifts with new repetition sequences). Also, trials in which the new target was one unit right to the location of the previous target location (1R) were faster than trials in which the new location was two steps right (2L) ($p < 0.013$). No other comparisons were significant. The results indicate that the scope of attention captures both the present and opposite



* $p < 0.05$, ** $p < 0.001$

Figure 11. RT results from Experiment 3: a) RTs across color repetitions and their fit to the power function, b) RTs across color repetitions as a function of the type of feature repetition, c) RTs as a function of the proximity of the new target location to the old target location after the completion of a location repetition sequence, and d) RTs as a function of the type of feature repetition combined across repetitions.

locations. There is also a benefit of moving targets to the right of the old target location rather than to the left.

Accuracy

These behavioral effects were also observed for accuracy although some of the effects vanished possibly because of ceiling-effects. Accuracy was better with increasing number of location repetitions ($F(2.466, 34.517) = 16.960, p < 0.001$) (see Figure 12a). The Repetition Type X Number of Repetitions interaction remained significant ($F(18, 252) = 4.510, p < 0.001$) as well as the main effect of Repetition Type ($F(3, 42) = 4.102, p < 0.013$) (see Figure 12b). However, this interaction vanished when the first target presentation trials (i.e., Repetition 1) were omitted from the ANOVA ($F(15, 210) = 0.864, p = 0.605$), suggesting that Repetition 1 behaved differently than the rest of the repetition sequence in terms of the Repetition Type effect.

However, in contrast to RTs, when a repetition sequence ended and a new one began, color repetition trials were significantly more accurate than trials with either response alone or both repetitions trials ($ps < 0.003$) (see Figure 12c). Within the first trials of a new sequence, accuracy for response repetition trials was worse than no repetition ($p < 0.013$) trials. The last finding suggests that when only response repeats from the last trial of a completed sequence, accuracy for the first trial of the new sequence is taxed.

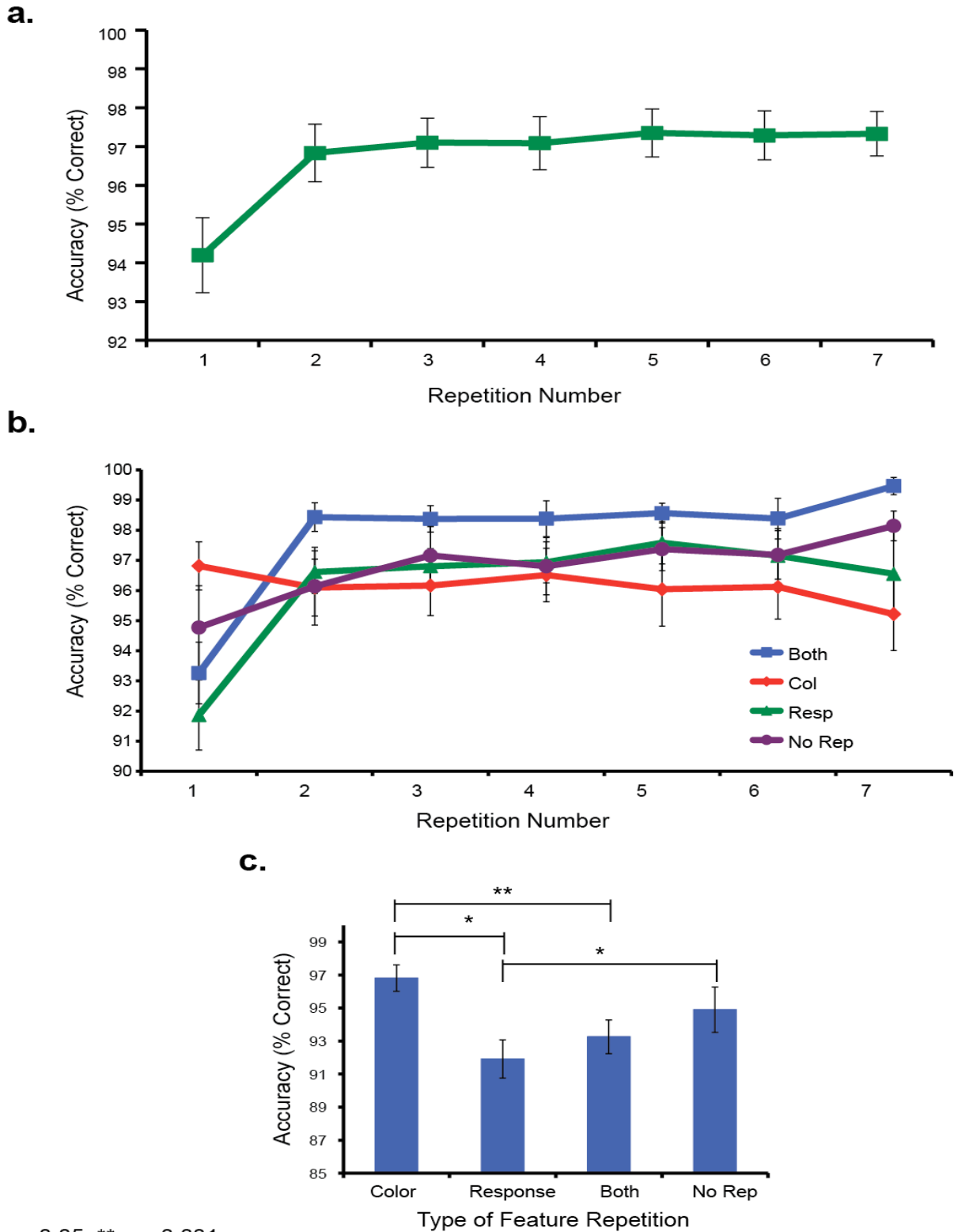


Figure 12. Accuracy results from Experiment 3: a) Accuracy across target location repetitions, b) Accuracy across color repetitions as a function of type of repeated feature, and c) Accuracy as a function of the type of repeated feature combined across repetitions.

The effect of the length of the completed repetition sequence (i.e., 3, 5, or 7) failed to reach significance ($F(2, 28) = 1.156, p = 0.329$). The new location of the target (i.e., 1L, 2L, Opposite, 2R, 1R) after sequence completions also did not exert any effects on accuracy ($F(4, 56) = 0.529, p = 0.715$).

P170

Overall, none of the behavioral effects were observed with P170. In contrast to repetition of target feature (i.e., color, Experiment 2), repetition of location did not alter P170 amplitude ($F(6, 84) = 1.553, p = 0.171$). This finding suggests that location information was not included in long-term memory representations indexed by P170. The type of repetition (i.e., color, response, both, and no repetition), combined at all steps in location repetition sequences, also did not exert an effect on P170.

P170 did not change with the distance from the new location in a new repetition sequence to the repeated location in the previous sequence ($F(2, 28) = 0.253, p = 0.778$). However, it should be noted that less than 30 trials were observed per each location shift (i.e., 1L, 2L, Opposite, 1R, 2R), which results in less than ideal signal-to-noise ratios for ERPs, possibly causing any true ERP effects to be missed.

P3b

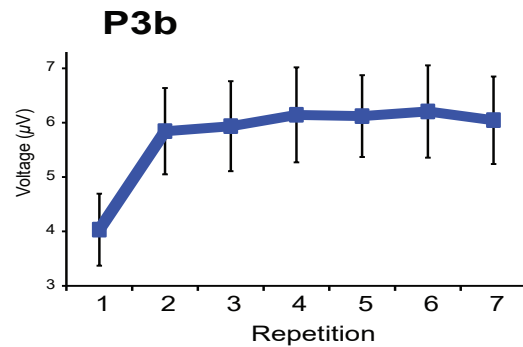
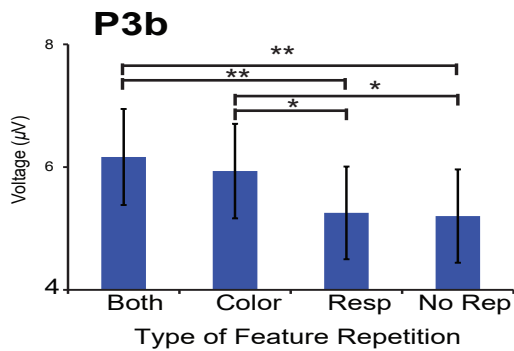
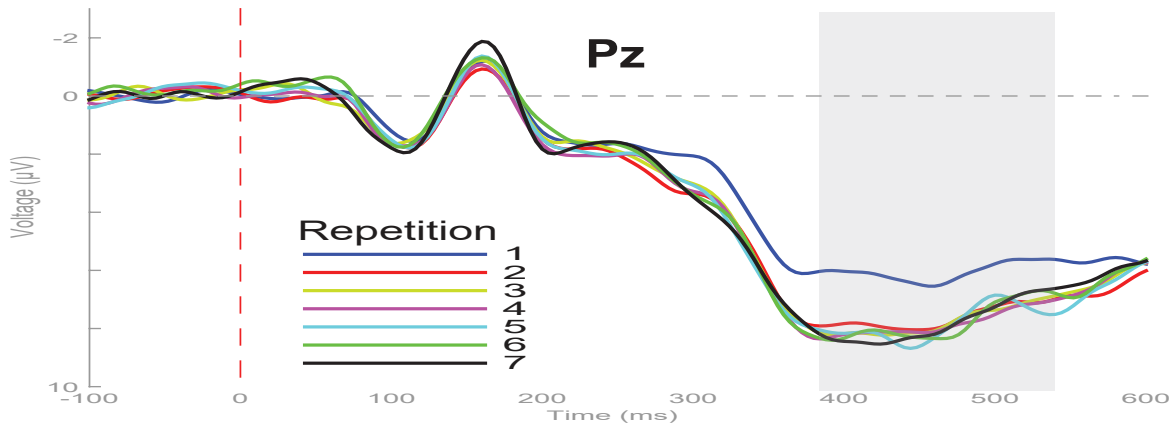
The effect of repetition was reflected in P3b amplitude ($F(3.363, 47804) = 9.804, p < 0.001$). Most of the increase in P3b amplitude occurred between Repetitions 1 and 2

(see Figure 13). To assess this statement statistically, I omitted Representation 1 from the ANOVA assessing the location repetition effect. This ANOVA resulted in the disappearance of the repetition effect ($F(5, 70) = 0.438, p = 0.821$), suggesting that P3b amplitude stayed the same between Repetition 2 and Repetition 7. The repetition power function fit to P3b amplitude was also poor in general (adjusted goodness-of-fit across participants = 61.02%), although the grand average P3b function fit better (adjusted goodness-of-fit for P3b grand mean = 98.87% - individual and grand-average fit parameters for RTs are reported in Appendix D). In sum, P3b was only responsive to the second repetition of target location and repetition beyond two did not lead to updating in working memory.

P3b amplitude changed with repetition type ($F(3,42) = 12.64, p < 0.001$) (see Figure 13). Greater P3b amplitudes were observed when color alone or both response and color repeated from the previous trial compared to response alone or no response repetition trials ($ps < 0.006$). Color alone and both feature repetitions did not differ significantly from each other ($p = 0.636$), indicating that specifically color information was updated in working memory.

In order to assess whether P3b amplitude changed with RTs, I ran correlational analyses between RTs and P3b amplitudes separately for each repetition. None of the correlations reached significance ($ps > 0.403$).

As with P170, P3b amplitude also did not change with the distance of the old target to the new target after a repetition sequence change ($F(4, 56) = 0.778, p = 0.544$).



* $p < 0.05$, ** $p < 0.001$

Figure 13. P3b results from Experiment 3.

CDA

In contrast to target feature repetitions (Experiment 2), target location repetitions did not lead to any changes in the maintenance of working memory representations, as indexed by the CDA amplitude ($F(6, 84) = 0.747, p = 0.613$). Also, none of the repetitions led to CDAs significantly different from zero as tested by one-sample t-tests ($p_s > 0.053$), except Repetition 7 ($p < 0.017$). These findings indicate that the last repetition led to significant working-memory maintenance, whereas the rest of the

repetition sequence was not maintained in working memory in contrast to the case observed for target feature repetitions (Experiment 2).

Repetition types did not lead to any changes in the CDA amplitude ($F(3, 42) = 1.410, p = 0.253$), suggesting that feature repetitions were not maintained differently in working memory.

Parietal Alpha Power

Parietal alpha power did not change throughout target location repetition sequences ($F(3.359, 47.023) = 0.598, p = 0.638$), again in contrast to the parietal alpha effect for target feature repetitions in Experiment 2. However, one-sample t-tests indicated that alpha power relative to the baseline was significantly different from zero in all repetition steps ($ps < 0.001$). Therefore, this activity was not responsive to sequential location repetitions although the location information was encoded in working memory.

Discussion

In Experiment 3, I explored whether the mechanisms responsible for priming of pop-out also is also responsible for priming of target location. Maljkovic and Nakayama (1996) argued that the same memory system (i.e., visual implicit memory) led to those two phenomena because visual implicit memory consisted of two types of information about the target: a) target feature (i.e., color), and b) location of the item. In this experiment, I compared whether the shape of the RT-repetition function and ERP

components keeping track of this function are similar between sequential color and location repetitions.

The RT findings from Experiment 3 showed that RTs sped-up quickly after the first presentation of the target and this speeding-up decreased after the first few repetitions. The power function described the shape of the function quite adequately (mean adjusted goodness-of-fit across participants = 91.72%). The shape of the RT-repetition function and its good fit to the power function indicate that repetition of location led to automaticity in which long-term memory representations underlie performance (Logan, 1988b, 2002). Accuracy showed a similar trend, however, accuracy scores hit ceiling level performance, and thus accuracy did not show increases after the 2nd repetition.

I evaluated whether ERP measures of different memory systems keep track of the location repetition RT effect. Unlike Experiment 2, P170 did not change with location repetitions. This finding suggests that P170, one of the long-term memory measures in this study, is selectively responsive to identity-defining features of the target item (e.g., color in Experiment 2), but does not track its location.

The measure of working memory updating, P3b amplitude, was only modulated at the 2nd location repetition. P3b amplitude did not change for the rest of the location repetition sequence. Therefore, working memory only tracks when the location repetition sequence starts and is not further updated. This is in sharp contrast to the P3b findings from Experiment 2, in which color repetitions led to linear increases in P3b after the 2nd repetition. I also found that, similar to Experiment 1 findings, P3b was keeping track of whether color repeated from the previous trial or not such that color

repetitions led to greater P3b amplitudes than response alone or no feature repetitions. RTs were also faster for trials where color repeated, regardless of response repetition, compared to response alone or no feature repetitions. Therefore, working memory representations keep track of color and these representations might have been driving the faster RTs for color repetitions. However, working memory representations do not keep track of location repetitions. This finding, along with the P170 findings in Experiment 2 and LRP findings in Experiment 3 contradicts the view that the same memory system underlie priming of pop-out and priming of location (Maljkovic & Nakayama, 1996).

The RT data suggested that the new location of the target after a repetition sequence ended changed with the proximity of the new location to the old. Specifically, when the new target location was the opposite of the old location, RTs were faster. This means that the scope of attention (Posner, 1980) involves target location and its opposite to some extent. In this experiment, I had less than adequate signal-to-noise ratio (i.e., not enough sequence start trials per location) to evaluate which ERP components would have changed with the proximity of the new location to the old one. Answering this question, preferably by including more locations, will help better evaluate how attention interacts with the memory representations in visual search.

CHAPTER 5

GENERAL DISCUSSION

In this study I investigated the memory representations underlying priming of pop-out through three experiments. Results from Experiment 1 showed that repetition of color, not response, led to priming of pop-out. Although this effect was large with smaller set sizes (i.e., Set Sizes 4 and 6), it diminished with the largest set size (i.e., Set Size 12). In Set Size 4, the ERP measures of working and long-term memory, P3b and P170, respectively, tracked RT differences between repetition types, such that both memory measures showed increases with color repetition. As with RTs, the P3b differences between color and response repetition trials were reduced greatly in Set Size 12. This finding suggests that working memory guides attention (Chun, Golomb, & Turk-Browne, 2011; Duncan & Humphreys, 1989; Soto, Humphreys, & Rothstein, 2007) in priming of pop-out when target colors vary between trials and sequential repetition of target color is not common (cf. Experiment 2).

Results from Experiment 1 along with results from previous studies (Bravo & Nakayama, 1992; Maljkovic & Nakayama, 1994) demonstrated that priming of pop-out is very much dependent on the number of distractors in the search array when target

identity (i.e., target color) is allowed to vary (i.e., variable mapping). However, when target identity is kept constant throughout an experimental block (i.e., target color does not vary), the set size effect disappears. Several researchers (Bravo & Nakayama, 1992; Julesz, 1984; Koch & Ullman, 1985; Nakayama, 1990) argued that when the color of distractors are homogenous, larger set sizes render the odd-colored target easier to be attended. That is, with larger set sizes the target truly pops out whereas with a small set size the pop-out effect of target with the odd-color is reduced. However, when the target identity does not change throughout an experimental block (i.e., consistent mapping), the target seems to pop-out regardless of the number of homogeneously colored distractors it is surrounded by. The memory measure driving priming of pop-out should have tracked this set size effect: confirming this prediction, P3b displayed a robust set size effect, indicating that the amount of contextual updating in working memory depends on the extent of the pop-out effect of the target.

P3b, the measure of working memory updating, was also consistently greater in consistent mapping trials compared to variable mapping trials in all set sizes. A visual comparison of the topography of P3b between consistent and variable mapping trials indicates that the distribution of this effect was essentially the same in consistent and variable mapping trials, denying the interpretation that this positivity was essentially the Late Positive Component commonly observed in long-term memory paradigms for better recalled items (Rugg & Curran, 2007). This finding suggests that working memory is constantly updated in consistent mapping trials. Although long-term memory representations are likely to underlie performance in consistent mapping trials (Logan, 1988b; 1990) by guiding attention to the consistency of the target (Duncan &

Humphreys, 1989), in this experiment, working memory was also active. One of the possible reasons behind this finding is that participants in Experiment 1 were not aware that target would have remained the same color in some of the experimental blocks (i.e., consistent mapping blocks). Therefore, throughout the consistent mapping blocks they might have been suspicious that the target color might change any time, which would require them to keep track of the target color.

In Experiment 2, target color was sequentially repeated, with sequence lengths of 3, 5, or 7. RTs became faster with more repetitions and speeding-up of RTs was very well described by a power function. This finding alone might suggest that long-term memory representations underlie performance (Logan, 1988b, 1990) in sequential color repetitions. Color repetitions modulated P170, the measure of long-term memory, supporting the idea that long-term memory representations guide attention to the target in priming of pop-out quickly. This finding is in line with the P170 finding from our lab (Reinhart & Woodman, 2013) in a conventional visual search task where participants were informed about the identity of the target before the onset of the search array. The P170 findings from the present study and the Reinhart and Woodman study indicate that in both priming of pop-out and conventional visual search, long-term memory representations could drive behavior.

Along with long-term memory representations, ERP components indexing working memory was also modulated by sequential color repetitions. P3b consistently increased with the number of color repetitions, indicating that target color information was updated into working memory throughout a repetition sequence. However, greater P3b amplitudes were correlated with slower reaction times through the end of repetition

sequences. On the contrary, smaller P170 amplitudes, indicative of higher long-term memory activation, were correlated with faster RTs in the same time window (Repetition 6 and 7). These correlational analyses suggest that although both working and long-term memory representations keep track of target color repetitions, employment of long-term memory representations might be the reason behind speeding-up of RTs.

The involvement of working memory was also demonstrated by modulation of the CDA and parietal alpha power with target color repetitions. As measured by the CDA, information about color was not maintained in working memory until the 6th repetition. However, the maintenance activity sharply increased at the 6th target color repetition. A similar effect was found for parietal alpha power, the measure of encoding of information to working memory. Parietal alpha power consistently increased until the 6th color repetition, indicating that less color information was encoded into working memory. However, parietal alpha power sharply decreased (i.e., alpha power suppression) at the 6th repetition, indicating a stronger encoding of color information to working memory. A possible reason why the 6th color repetition led to substantial changes in working memory measures is that a system keeps track of probabilities of when the repetition sequence will end. In the 6th color repetition, it is certain that color will repeat one more time and then the repetition sequence will end. Therefore, with this sequence length information, it might be advantageous to increase reliance on working memory at the 6th repetition and allow long-term memory to reset for the upcoming repetition sequence. Actually, the finding that P170 increased (i.e., decrease in the long-term memory process indexed by P170) sharply at the 7th repetition supports this dynamic picture of different memory representations driving performance in accordance with the

length of the sequence. It is an open question how the ERP and EEG measures of different memory systems will change when the length of the sequence is randomized, therefore cannot be extracted. According to this interpretation, the sequence end effects should vanish with random repetition lengths and long-term memory should be the dominant guide of attendance in sequential priming of pop-out.

The CDA and parietal alpha suppression findings described above seem to contradict the P3b findings, which is another working memory ERP measure. CDA and parietal alpha suppression could be considered to have been more sensitive to the cognitive demands of particularly the sixth repetition whereas P3b was sensitive to repetition throughout the color repetition sequence. One possible reason behind this discrepancy might be the robustness of the CDA and parietal alpha suppression as measurements of visual working memory in this specific type of visual search. Although modulation of CDA with target repetition was reported for visual search tasks in which the upcoming target was to be kept in memory over a maintenance interval (e.g., Carlisle et al., 2011; Reinhart & Woodman, 2013), other visual search tasks that did not include such maintenance intervals did not lead to remarkable CDA like ERPs (e.g., Woodman & Luck, 1999, 2003). However, Luck and Hillyard (1990) reported increases in P3b with target repetitions in a visual search without a target maintenance interval, which is similar to the current task. The robustness of CDA and parietal alpha suppression as measures of visual working memory in priming of pop-out tasks should be ensured with replications of the findings from Experiment 2.

Although P3b, CDA, parietal alpha power, and P170 results from Experiment 2 suggested that both working and long-term memory representations were related to

RTs in sequential repetition of colors in Experiment 2, it looks like there is a cost to maintaining working memory representations of the target color. RTs were slower when the previous sequence was longer. Importantly, the only ERP memory component that also showed a similar effect was the CDA: the CDA amplitude observed in the first trial of a new repetition sequence was greatest when the previous sequence was 7 repetitions long. The slowing down of RTs after long sequences of repetition might be related to working memory representations guiding attention slower than usual after the target color switch in the first trial of a sequence. This suggests the possibility that swapping target and distractor colors led to proactive interference in working memory. This effect might disappear when the number of possible target colors, which was two across all experiments in the current study, is increased. With increased number of potential target colors, the possibility of proactive interference in the first trial of the repetition sequence will be reduced.

Which memory representations underlie priming of location in the priming of pop-out search task? Are same memory representations employed during priming of the popping out feature (i.e., color) and priming of location? Maljkovic and Nakayama's (1994, 1996) influential account of priming of pop-out suggested that the same memory system, implicit visual memory, led to these two types of priming. In Experiment 3, I sought to answer these questions by evaluating the shape of the RT speeding-up function with location repetitions and by exploring how the ERP measures of memory systems are modulated with sequential repetition of location. Similar to color repetitions, location repetitions produced a power function speed-up in RTs. As stated above for Experiment 2, this behavioral finding is in line with the view that long-term memory

representations underlie priming of target location. However, in contrast to the case of priming of pop-out, repetition of the location of target stimuli did not lead to modulations of P170, CDA, and parietal alpha power. Although P3b showed an overall effect of location repetition, this effect was due to its sharp increase in the 2nd repetition. The P3b failed to increase after the second repetition, which supports the view that the only information that was updated in working memory in priming of location is that a repetition sequence started. These findings, overall, contradict the idea that priming of pop-out and priming of location in the same task utilizes the same memory system (Maljkovic & Nakayama, 1994, 1996).

In Experiment 3, the shape of the RT speed-up function in priming of location showed that location priming was automatized. However, none of the ERP measures of canonical memory systems (i.e., working and long-term memory) tracked the speeding up of RTs as the target location repeated. Although the number of location repetitions modulated P3b, this effect was caused by the sharp increase in the second presentation of the target location. The amplitude of P3b remained the same afterwards the second presentation. The P3b findings in Experiment 3 suggest that only the information that the location repetition sequence has started is updated into working memory. Yet, no information about color is encoded or maintained in working memory, as indicated by the absence of location repetition effects for parietal alpha power and CDA, respectively. Similarly, the ERP measure of long-term memory, P170, was also not modulated with location repetitions. Overall, these results indicate that different memory representations are employed for repetition of color and location in the priming of pop-out task. The present work cannot answer the question of which memory

representations at which stage of processing are employed for priming of location, yet the possibility that either early perceptual memory representations (e.g., iconic memory) or representations at the response execution stage drives priming of location should be explored in future studies.

The present findings overall demonstrate the prominent and dynamic role of different memory systems in guiding attention. Priming of pop-out is particularly suitable to explore how memory, in its general sense, interacts with attention because this task does not require participants to keep in their memory what the target for visual search will be. Instead, in priming of pop-out, target is defined online at the onset of the search array. However, despite the fact that the identity of the target that participants search for is not known before, memory of the previous target feature still facilitates locating and responding to the target (Experiments 1 and 2). Also, whether or not target features will repeat in sequences or these repetitions will span fewer trials determine the type of memory representations guiding visual search. In the former case, long-term memory representations are likely to guide attention, probably by winning over their race with working memory representations (Logan, 1988b). However, in the latter case, target feature updates in working memory perform the guidance, probably because long-term memory representations are losing the race they are in with working memory (Logan, 1988b). Overall, the phenomenon of priming of pop-out can be understood by resorting to canonical memory systems. My results suggest that a special memory system (e.g., visual implicit memory; Maljkovic & Nakayama, 1994, 1996, 2000) is not necessary to explain this phenomenon. Additionally, results from Experiment 3 indicate that location information is not represented in the same memory system as target feature repetitions;

what guides attention in the case of location repetitions are associations formed between stimulus and location, executed at the response selection stage.

These results also speak to the distinction between stimulus and goal-driven attention (Chun et al., 2011; Corbetta & Shulman, 2002; Egeth & Yantis, 1997; Posner, 1980). Several authors have recently criticized the usefulness of this dichotomy (e.g., Awh, Belopolsky, & Theeuwes, 2012; Hutchinson & Turk-Browne, 2012) and my results also support their stand that target selection history in psychological tasks inform attention dynamically, taking regularities in repetition of target feature and location into account. Many prominent attention theories (e.g., Bundesen, 1990; Chelazzi, Miller, Duncan, & Desimone, 1993; Desimone, 1996; Duncan & Humphreys, 1989; Logan, 1988b, 2002) allow for memory mechanisms that could inform attentional selection although they differ in the type of memory systems they propose for attentional guidance (e.g., long-term memory vs. working memory). Specifying the calculations through which memory systems might guide attention and empirical testing of these claims in visual search tasks that are adequately controlled for feature repetition patterns will be an invaluable step in elucidating how the brain deals with the ever changing but also partially stabilized (Clark, 2013; Rao & Ballard, 1999), environments.

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APPENDICES

APPENDIX A

Parameters and Adjusted Goodness-of-Fit Values From The Power Function Fit to RTs in Experiment 2.

Participant	Parameter a	Parameter b	Parameter c	Adjusted GoF
1	164.020	-0.862	520.251	0.976
2	132.340	-1.860	454.296	0.967
3	123.548	-1.830	602.247	0.977
4	176.240	-1.850	527.972	0.998
5	173.581	-1.817	504.336	0.983
6	189.980	-1.979	554.226	0.960
7	171.961	-1.433	448.801	0.997
8	153.998	-1.930	494.767	0.990
9	103.170	-1.215	431.705	0.994
10	259.665	-1.777	739.293	0.880
11	394.512	-1.343	616.095	0.998
12	206.048	-1.395	497.097	0.987
13	210.649	-2.514	549.850	0.962
14	164.175	-2.657	671.743	0.970
15	138.568	-1.025	459.515	0.990
Grand Average	180.854	-1.677	541.495	0.998

Parameter a: Asymptote of learning. Parameter b: Multiplicative constant indicating the amount of information to be learned. Parameter c: Learning rate. GoF: Goodness-of-fit. Please note that grand average data (i.e., average RTs of all participants across repetitions) were fit separately.

APPENDIX B

Parameters and Adjusted Goodness-of-Fit Values From the Power Function Fit to P3b
Amplitudes in Experiment 2.

Participant	Parameter a	Parameter b	Parameter c	Adjusted GoF
1	-4.955	-1.446	5.914	0.824
2	-2.382	-20.608	8.754	0.149
3	-1.787	-3.059	3.717	0.154
4	0.000	17.976	5.140	0.664
5	-3.852	-1.591	6.252	0.972
6	-4.983	-0.738	10.753	0.547
7	-6.160	-1.239	16.793	0.867
8	-4.006	-1.029	9.189	0.785
9	-15.889	-0.345	21.400	0.953
10	0.790	-0.289	1.557	-0.346
11	-2.813	-8.267	9.753	0.531
12	0.362	1.209	3.066	0.532
13	4.704	0.220	-3.361	0.925
14	0.000	5.019	4.848	0.840
15	-4.005	-1.229	9.136	0.881
Grand Average	-3.364	-1.188	7.793	0.985

Parameter a: Asymptote of working memory updating. Parameter b: Multiplicative constant indicating the amount of information to be updated. Parameter c: Working memory updating rate. GoF: Goodness-of-fit. Please note that grand average data (i.e., average P3b of all participants across repetitions) were fit separately.

APPENDIX C

Parameters and Adjusted Goodness-of-Fit Values From The Power Function Fit to RTs in Experiment 3.

Participant	Parameter a	Parameter b	Parameter c	Adjusted GoF
1	132.305	-1.123	520.344	0.980
2	208.912	-0.569	544.366	0.994
3	118.413	-0.774	477.111	0.987
4	174.073	-0.720	431.076	0.983
5	251.594	-0.678	470.250	0.978
6	316.648	-0.807	579.674	0.992
7	-0.146	3.148	543.596	0.453
8	214.289	-1.354	668.199	0.973
9	173.724	-0.873	600.759	0.691
10	87.554	-1.271	491.297	0.924
11	254.162	-1.453	606.590	0.976
12	175.924	-0.799	490.243	0.961
13	179.543	-0.965	444.940	0.959
14	204.301	-1.543	626.446	0.922
15	176.726	-0.961	510.295	0.986
Grand Average	178.668	-0.967	534.128	0.991

Parameter a: Asymptote of learning. Parameter b: Multiplicative constant indicating the amount of information to be learned. Parameter c: Learning rate. GoF: Goodness-of-fit. Please note that grand average data (i.e., average RTs of all participants across repetitions) were fit separately.

APPENDIX D

Parameters and Adjusted Goodness-of-Fit Values From the Power Function Fit to P3b
Amplitudes in Experiment 2.

Participant	Parameter a	Parameter b	Parameter c	Adjusted GoF
1	-2.974	-23.763	4.594	0.413
2	-2.465	-2.498	6.609	0.851
3	-3.897	-17.516	10.518	0.696
4	3.691	0.348	-0.549	0.832
5	-2.843	-1.606	7.933	0.727
6	-1.282	-1.495	5.629	0.493
7	-1.382	-2.939	5.394	0.761
8	-0.002	3.823	3.774	0.691
9	-2.177	-22.084	11.898	0.377
10	-1.378	-23.269	2.789	0.296
11	-5.731	-1.960	11.602	0.809
12	0.013	2.318	2.078	0.354
13	0.312	1.101	5.343	0.381
14	0.000	17.976	3.990	0.659
15	-5.294	-0.951	4.209	0.812
Grand Average	-2.103	-2.711	6.137	0.989

Parameter a: Asymptote of working memory updating. Parameter b: Multiplicative constant indicating the amount of information to be updated. Parameter c: Working memory updating rate. GoF: Goodness-of-fit. Please note that grand average data (i.e., average P3b of all participants across repetitions) were fit separately.

APPENDIX E

Difference Waves for CDA in Experiment 2.

**Experiment 2 CDA Repetition
Difference Waves**

