Exploring the contributions of spatial and non-spatial working memory to priming of pop-out

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Abstract *Priming of pop-out* (PoP) refers to the facilitation of performance that occurs when a target-defining feature is repeated across consecutive trials in a pop-out oddball search task. The underlying mechanism of PoP has been poorly understood and raises important questions about how our visual system is guided by past experiences, even during bottom-up processing. Lee, Mozer, and Vecera (*Attention, Perception, & Psychophysics*, 71, 1059–1071, 2009) demonstrated that PoP remained unaffected by a concurrent non-spatial visual working memory (VWM) load, and they concluded that PoP occurs through feature gain modulation, essentially eliminating the contribution of memory representations in VWM to PoP. In the present study, we followed up on those results by (a) replicating the null effect of non-spatial VWM load on PoP and (b) examining the effect of spatial VWM load on PoP. The results showed that spatial VWM load does interfere with PoP, supporting the notion that spatial VWM is involved in PoP. In Experiment 2, we extended this finding by manipulating VWM load and observing its consequence on the magnitude of PoP. Increasing spatial VWM load decreased the amount of PoP observed, in a dose-dependent manner, whereas changes in non-spatial VWM load did not. Contrary to Lee et al.'s conclusions, these results suggest that VWM resources appear to contribute to the occurrence of PoP, supporting the theory that PoP is, in fact, a multilevel process in which the deployment of spatial attention, relying on VWM representations, plays an important role.

Keywords Priming · Visual search · Visual working memory · Singleton search

Recent experience in even some of the simplest visual search tasks can have profound impact on visual attention. Perhaps the most well-known example of this is in the phenomenon known as priming of pop-out (PoP; Maljkovic & Nakayama, 1994, 1996, 2000). In Maljkovic and Nakayama's experiments, participants were presented with three diamonds, with either the left or the right side of each diamond missing (see also Bravo & Nakayama, 1992). Among the three, one diamond had a unique color, while the other two were the same color. The task was to locate the color-oddball target (e.g., a red target among green distractors) and to report which side was missing from the target. Before any given trial, participants were unaware of what color the target would be. Instead, the authors proposed that the uniqueness of the target would cause it to “pop-out” among the items in the display (but see Buetti, Cronin, Madison, Wang, & Lleras, 2016; Tseng, Glaser, Caddigan, & Lleras, 2014, for a challenge to the claim that the oddball item pops out in the display). Critically, the authors found that search was significantly facilitated (by 40–100 ms) by repetition of the target-defining feature—that is, when the target's color remained constant across trials (i.e., a red-target trial followed by another red-target trial) rather than switching (i.e., a red-target trial followed by a green-target trial). This intertrial priming effect was dubbed “priming of pop-out” and indicated that even an a priori easy visual search can be very sensitive to recent past experience. In fact, recent experience has now been proposed to be its own type of attentional bias, alongside the more traditional “top-down” (or current goals) and “bottom-up” (or physical salience) sources of variance (see Awh, Belopolsky, & Theeuwes, 2012).

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Several studies have since delineated several important characteristics of PoP. Unlike other priming effects, which can last for days or weeks (i.e., semantic priming; Squire, Shimamura, & Graf, 1987), the duration of PoP is relatively short. The memory trace of a target feature influences PoP for only five to eight trials, or 15–30 s (Maljkovic & Nakayama, 1994, 1996, 2000). In other words, if participants have once responded to a certain target color, their response to a target of the same color five trials later is still slightly faster than their response to a different target color, regardless of the target colors seen during the intervening trials. On the basis of this result, Maljkovic and Nakayama proposed that PoP relies on short-lived memory representations with underlying mechanisms that are different from the long-lasting memory responsible for traditional priming effects. Furthermore, Kristjánsson and Driver (2008) demonstrated that one can separate the effects of target repetition from the effects of distractor repetition in PoP, and that both types of repetitions play roles in PoP (see also Lamy, Antebi, Aviani & Carmel, 2008).

However, the type of memory representation involved in mediating the effect is not well understood. For instance, PoP has also been shown not to rely on explicit, voluntary control. When participants were unexpectedly asked to recall the attributes of previous targets (i.e., red, for color) during a series of singleton-search trials, they generally recalled only one previous target (Maljkovic & Nakayama, 2000). Although the level of explicit memory for the target was very poor, PoP remained intact. This provides evidence that PoP does not rely on explicit memory representations of the visual attributes from previous trials. Additionally, Maljkovic and Nakayama (1994) explored how predictably, explicitly knowing the identity of the upcoming target facilitated search and influenced PoP. In one block, the target color stayed the same without exception, enabling participants to anticipate the color of the target in the next trial. In another block, the target color strictly alternated between two colors across trials, allowing participants to still predict the color of an upcoming trial. Contrasted with those two conditions, in one block the target color was determined at random (i.e., 50% chance of a switch). If PoP occurs on the basis of explicit predictability, search would be facilitated when participants had perfect knowledge of the upcoming target color. Specifically, response times (RTs) should be faster when the target color either always stayed the same or regularly alternated from one to another, than when the target's color switched at random. In contrast to predictions, however, the results of the study showed that the RTs of trials with a predictable color switch (i.e., 100% alternation) were slower than the RTs of trials with a single color (i.e., 100% stay). Between these two extremes, RTs increased linearly as the number of alternations increased. In sum, PoP was not affected by the predictability of the target color in the next trial, indicating that PoP is immune to the observer's explicit knowledge or expectations, but rather is driven solely by the repetition or switch of the target color.

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

Many researchers have proposed that visual working memory (VWM) plays a crucial role in visual search, within its limited capacity. It is commonly thought that once attention is deployed toward an item, the item would be automatically encoded in VWM and would be compared to a template of target representation (e.g., Bundesen, 1990; Duncan & Humphreys, 1989). Concerning the allocation of attention to each item, it has also been proposed that the template of target representation would be stored in VWM, and that it would bias attention in favor of the processing of an item similar to the target's representation (Desimone & Duncan, 1995; Duncan & Humphreys, 1989). Lee et al. (2009; see also Mozer, Shettel, & Vecera, 2006) directly investigated whether VWM plays a role in PoP, by adopting a dual-task paradigm. In their experiments, participants were asked to maintain four colored patches in VWM while they performed a color-oddball search task. In the search task, three Landolt-C shapes were presented on the periphery, and neither the color of the target nor the color of distractors overlapped with any of the memory items. If PoP was the result of a memory of the previous target, then the priming should have decreased when the concurrent memory task loaded VWM to capacity. However, PoP was not affected by the presence of the secondary task. On the basis of this result, researchers concluded that PoP was not driven by the top-down guidance of representations stored in VWM. Furthermore Lee et al. proposed that, instead of VWM, feature gain modulation (see Wolfe, Butcher, Lee, & Hyle, 2003) was most likely responsible for the occurrence of PoP.

The *feature gain modulation* account is based on the idea that the color oddball receives the most activation on a salience map because of its featural contrast (Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). Selection of the oddball (to complete the task) further increases its salience. Overall, a “gain increase” occurred for the specific feature that defined the target on a given trial, and thus if, on the following trial, the same feature were present in the display, the salience score for items containing that feature would be heightened. Because the target's feature value would stay the same across multiple trials, the residual of the gain on the feature would build up, resulting in increasingly facilitated responses. Though the feature gain modulation account offers one possible explanation for why PoP occurs, recent data from our lab

have out in question whether such an account is actually plausible. In Buetti, Cronin, Madison, Wang, and Lleras (2016), we demonstrated that it is quite unlikely that participants find the target in an oddball task by computing the feature contrast between target and distractors, and we further proposed that the oddball itself might actually not be popping out of the display, as has been proposed in the past. The reason is as follows: When one manipulates set size in an oddball search task, the RTs at low set sizes (3 or 4) are surprisingly long (in the 600-ms range), and the RTs decrease as set size increases. This “negative” search slope had been attributed to a larger feature contrast between the target and distractors: The more distractors there are, the more featurally “unique” the target is, and thus the easier it is to find (see, e.g., Bravo & Nakayama, 1992; Meeter & Olivers, 2006). Although intuitively appealing, this proposal assumes that participants are finding the target because of the existence of that low-level target–distractor contrast signal, yet we are not aware of evidence that such a signal exists. In fact, there is evidence that at the set sizes typically used in PoP studies, the signal (if present) does not play a critical role in helping participants find the target. In the Buetti et al. study, we compared the RT-by-set-size functions obtained with identical displays when the target was fixed across trials and when it was a color oddball (as in PoP tasks). If the low-level target–distractor contrast signal helped participants find the target, this facilitation should occur both when the target was fixed and when it was an oddball, because this form of low-level (physical) salience should be computed in both types of displays. Yet, when the target was fixed, RTs increased as set size increased. In other words, the “presumed” increased target–distractor contrast failed to facilitate the search task in that condition. Incidentally, at low set sizes, when the target was fixed, RTs were almost 200 ms faster than in the oddball search task, again with identical displays. Buetti et al. concluded that is quite unlikely that the target in oddball search displays was actually popping out (see also Meeter & Olivers, 2006; Olivers & Meeters, 2006; Rangelov, Müller, & Zehetleitner, 2013, for similar claims). Overall, these findings call into question the underlying assumption of the feature gain modulation account: that the feature contrast was the guiding signal moving participants’ attention toward the oddball target.¹ Finally, it is also

worth clarifying that we are not arguing that a *salient* target in a large-set-size display does not benefit from repetition across trials (it does; see Becker & Ansorge, 2013). Simply, sparse displays in oddball tasks tend to produce PoP (as well as a similar effect known as the *distractor preview effect*, or DPE²) effects, and this can occur in the absence of any strong “pop-out” signal from the target itself. That being said, the relationship between salience, feature contrast, and intertrial priming is certainly complex.

Overall, there is reason to doubt the feature gain modulation account of PoP, and thus, still reason to question the type of memory representations at play in the phenomenon. Furthermore, despite Lee et al.’s (2009) finding, VWM may still play a role in PoP, because not all types of representations stored in VWM were investigated in that study. Baddeley and Hitch (1974; Baddeley, 2000; Baddeley & Logie, 1999) proposed a multicomponent model of working memory, which postulates that a memory is composed of subdivisions of specified functions—such as the phonological loop, episodic buffer, and visuospatial sketchpad. Within the visuospatial sketchpad (Baddeley & Hitch, 1974), the visual memory load can be either spatial or non-spatial. On the basis of this distinction, earlier studies have suggested that spatial and non-spatial representations in VWM are processed by separate mechanisms and can have distinct influences on search behavior (J. J. Kim, Kim, & Chun, 2010; S.-Y. Kim, Kim, & Chun, 2005; Oh & Kim, 2004; Woodman & Luck, 2004; Woodman, Vogel, & Luck, 2001). In particular, by adopting a dual-task paradigm, one line of research has demonstrated that spatial VWM loads influence the efficiency of a visual search, whereas non-spatial VWM load does not (Oh & Kim, 2004; Woodman & Luck, 2007; Woodman et al., 2001). This result indicates that a spatial VWM task exclusively impaired search because maintaining the spatial locations presented in the VWM task impaired spatial attention.

Lee et al. (2009) only tested the influence of loading non-spatial VWM on PoP, and did not investigate the possible effects of loading spatial VWM. Their rationale was that loading VWM would significantly decrease PoP if VWM was the mechanism responsible for PoP. Thus, it was argued that the dual task of singleton search and a non-spatial-VWM-load task would overflow VWM’s capacity (about four; Luck & Vogel, 1997) if observers stored the information of a target’s history in VWM. However, previous research adopting the dual-task interference paradigm has consistently shown that

¹ It is worth noting that in the groundbreaking work by Bravo and Nakayama (1992) on pop-out search tasks, the authors argued that the bottom-up signal strengthens with increasing set size, leading to a negative search slope whenever tasks require focused attention for completion. In contrast, Buetti et al. (2016) argued that the more items there are, the easier it is to reach the conclusion regarding which color is the distractor color (and to act accordingly). To be clear, the strengthening of the bottom-up signal with increasing set size probably does happen, but only at larger display densities than those used by Buetti et al. and by Bravo and Nakayama. Buetti et al. argued that if the bottom-up signal were really improving with increasing set size, they should have found this effect on RTs in the focused-attention task that they used (fixed-target discrimination task), yet they did not. Rather than RTs decreasing with set size in that task, they increased (logarithmically) with set size.

² The DPE is observed in oddball search tasks when one intermixes target-absent and target-present trials. The DPE reflects a tendency to be much slower and less accurate to select a target on a target-present trial (e.g., a red oddball item) when its target-defining characteristic (red) was associated with the absence of targets in the preceding target-absent trial (i.e., when all items in the preceding trial were red). See Goolsby, Grabowecky, and Suzuki (2005) and Lleras, Kawahara, Wan, and Ariga (2008). The effect is observed in temporal tasks, as well (Lleras, Kawahara, & Levinthal, 2009), and transfers across spatial and temporal tasks (Levinthal & Lleras, 2008).

a non-spatial VWM task did not affect a concurrent visual search. In other words, maxing out non-spatial VWM capacity may not necessarily interfere with attentional selection during visual search. That said, if, as proposed by Buetti et al. (2016), performance in the color-oddball task is not driven by “featural” contrast, but instead requires some degree of attention to all three items in the display (to figure out which item is different from the other two; see also Tseng et al., 2014), then loading spatial VWM may in fact have a substantial effect on PoP by interfering with participants’ ability to attend to and compare those items. The goals of the present study were therefore to follow up on the Lee et al. study and to explore whether loading spatial VWM does indeed reduce PoP in a load-dependent manner.

Experiment 1

Experiment 1 was designed as a replication and extension of Lee et al.’s (2009) study. In Experiment 1A, we loaded non-spatial VWM while participants performed a color-oddball task in the periphery, and in Experiment 1B, we simply changed the load to a spatial VWM load. Though the design of the experiment was similar to that of Lee et al., the present experiment varied from Lee et al.’s design in two major ways. First, both the single-task and dual-task conditions were tested within the same group of participants (Lee et al. had used a between-subjects comparison). Second, we changed the stimuli in the color-oddball task and asked participants to report the shape of the color oddball (instead of the gap in a Landolt-C).

Methods

Participants In all, 26 participants for Experiment 1A and 22 participants for Experiment 1B performed a 50-min-long experiment to earn either monetary reward or course credit at the University of Illinois at Urbana-Champaign. All participants were required to have normal or corrected-to-normal vision, including normal color vision. The data from participants who showed poor performance (below 80% mean accuracy in search or 65% mean accuracy in the VWM task) were excluded from further analysis. According to these criteria, the data for 20 participants in each experiment were submitted for further analysis.

Apparatus and stimuli All stimuli were generated and presented by programs written in MATLAB with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The programs ran on 3.4 GHz Pentium IV Windows PCs and the display of the experiment was presented on a 17-inch monitor running at 85 Hz with a resolution of $1,024 \times 768$. All responses were recorded with a keyboard.

A white, doughnut-shaped fixation point (approximately 0.3°) was displayed at the center of a black ($0, 0, 0$; 1.88 cd/m^2 ; CIE XYZ = 0.43, 0.30, 0.17) screen. The stimuli for the singleton search consisted of circles and triangles in red ($255, 0, 0$; 29.68 cd/m^2 ; CIE XYZ = 72.02, 42.11, 4.83) or green ($0, 255, 0$; 98.22 cd/m^2 ; CIE XYZ = 67.53, 127.67, 19.46). Each stimulus subtended approximately 0.9° at a viewing distance of approximately 50 cm. In each trial, three search items were randomly presented within an approximately $7.4^\circ \times 5.6^\circ$ region of display. The display appeared in one of four quadrants, excluding the $2.4^\circ \times 2.4^\circ$ region around the center of the screen, which was reserved for presenting the stimuli in the VWM tasks. The stimuli for the VWM task included four rectangular, colored patches (Exp. 1A) or two white dots (Exp. 1B). In Experiment 1A, the colors of the items were randomly selected from among six choices: white ($255, 255, 255$; 106.86 cd/m^2 ; CIE XYZ = 113.10, 121.92, 157.06), yellow ($255, 255, 0$; 123.76 cd/m^2 ; CIE XYZ = 103.63, 134.81, 19.13), blue ($0, 0, 255$; 14.63 cd/m^2 ; CIE XYZ = 33.26, 22.37, 173.37), purple ($160, 32, 240$; 32.05 cd/m^2 ; CIE XYZ = 62.30, 40.09, 200.73), brown ($120, 60, 60$; 14.87 cd/m^2 ; CIE XYZ = 16.21, 12.28, 9.92), and cyan ($0, 255, 255$; 111.04 cd/m^2 ; CIE XYZ = 94.61, 133.51, 211.24). There was no overlap of color among the four items to be remembered. Each colored patch subtended approximately 0.9° and appeared at one of four fixed locations within the $2.4^\circ \times 2.4^\circ$ region around the fixation point—one above, one below, one to the left, and one to the right. Also, each colored patch was centered $1.4^\circ \times 1.4^\circ$ from the fixation point. In Experiment 1B, two white dots replaced the four colored patches. Each dot subtended approximately 0.3° and appeared in one of 24 locations on the circumference of a circular formation, which subtended $2.4^\circ \times 2.4^\circ$ around the center.

Procedure The procedure and timing are illustrated in Fig. 1a and b for Experiments 1A and 1B, respectively. In the single-task conditions of both experiments, each trial was initiated with a sign of “Ready” for 1 s. A white, doughnut-shaped fixation point followed, presented at the screen center for 500 ms. The display for singleton search then followed, keeping the fixation point at the center. Participants’ task was to locate an item of an odd color among the three items clustered in one of the four quadrants, and to report whether the target’s shape was a circle or a triangle by pressing the “>.” or “/?” key as quickly and as accurately as possible. The search display disappeared immediately after the response, or 2 s after the onset in the case of no response. When the search display disappeared in less than 2 s, a blank screen with a fixation point was presented instead of the display of the next task, to identically control the durations of the tasks. The blank screen with its fixation point remained in effect for another 2 s to make the time course consistent with the VWM task in the dual-task condition.

Fig. 1 Description of the stimuli and procedure of Experiments 1A and 1B in the dual-task condition. Sequence A depicts Experiment 1A, in which the VWM task was to remember the identities of four colors. Sequence B shows Experiment 1B, in which the VWM task was to remember the locations of two white dots. In both experiments, the visual search task was to find a color oddball and to report its shape. The search display was presented in one of the four quadrants of the display, and these locations did not overlap with the locations used in the VWM task (enlarged here for illustrative purposes). In the single-task condition, only the visual search display was presented, but the time course of the trial was controlled to remain identical to that of the dual-task condition

In the dual-task condition of Experiment 1A, each trial started with a “Ready” sign for 1 s, as in the single-task condition. Afterward, a 500 ms fixation point followed, and four colored patches were presented for 1 s (a memory task display) while keeping the fixation point at the center. The participants’ task was to remember the colors of four rectangular patches, regardless of their locations. After 500 ms of blank screen, the singleton-search display appeared. As in the single-task condition, in the case of a response faster than 2 s, a blank screen with the fixation point remained in effect to keep the retention intervals of the VWM task consistent. A memory probe display composed of four colored patches was then presented. To indicate that it was a probe display, a “??” sign replaced the fixation point at the center. In half the trials, the display was identical to the memory task display. In the other half, one of the four colored patches changed its color from the one presented in the memory task display. The participants’ task was to determine whether the probe display was the same as what they remembered: If they remembered the display they pressed “z”; if not, “x.” If no response was recorded for 2 s, the trial was automatically terminated.

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

either of the two dots had changed its location from the memory task display. If a change did occur, it consisted of one of the two dots moving two locations along a circular array containing 24 predetermined locations.

In both Experiments 1A and 1B, the main manipulation was the intertrial repetition or switch of the search target’s color. In half the trials, the color of the target was the same as that in the previous trial (a “repeat” condition). In the other half of the trials, the color of the current target and the previous target differed (“switch” condition). Participants performed two blocks of 128 trials—one block apiece for the single search task and the dual task, respectively. The order of the blocks was counterbalanced. At the beginning of each block, 20 unanalyzed practice trials were provided. Throughout the experiment, participants were instructed to repeat “a, b, c, d” or “one, two, three, four,” which served as a form of articulatory suppression to prevent participants from encoding the items in the VWM task auditorily rather than visually.

Results

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

Experiment 1A: Non-spatial VWM load Mean RTs and accuracy were analyzed with a two-way repeated measures analysis of variance (ANOVA), including Intertrial Repetition and Task Condition as factors (see Fig. 2). Only correct search responses made within the allowable time range (150–2,000 ms) were included for analysis.³ In addition, in the dual-task condition, only trials in which participants responded correctly to the memory task were considered. In the single-task condition, the mean RTs were 895.38 and 940.96 ms in the repeat and switch conditions, respectively. In the dual-task condition, the mean RTs were 1,069.89 and 1,108.54 ms in the repeat and switch conditions, respectively. A two-way repeated measures ANOVA on RTs (Fig. 2a) revealed a main effect of repetition, $F(1, 19) = 24.798, p < .001, \eta^2 = .566$, and a main effect of task, $F(1, 19) = 18.820, p < .001, \eta^2 = .498$, but there was no interaction between the two conditions, $F(1, 19) < 1$. We observed a clear advantage of repetition, both in the single task, $t(19) = 5.217, p < .001$, Cohen’s $d = 1.17$, and in the dual task, $t(19) = 2.666, p = .015, d = 0.60$. Though RTs were slower in the dual-task condition, $t(19) = 4.338, p < .001$,

³ The overall search accuracy was high (93.15%), and the majority of responses (96.33%) were made within the allowable time range.

Fig. 2 Results of Experiment 1A (non-spatial VWM task). The data are presented as a function of two conditions: repetition (repeat vs. switch in the search task) and task condition (single vs. dual). Panels A and B demonstrate mean RTs and accuracies, respectively, in the search task.

Error bars show the within-subjects standard errors of the amounts of priming (i.e., the difference between the repeat and the switch conditions) in the single-task and dual-task conditions, respectively

$d = 0.97$, the amounts of priming did not differ in the two task conditions, $t(19) < 1$.

For the single-task condition, the mean accuracies were 95.61% and 93.68% in the repeat and switch conditions, respectively. In the dual-task condition, the mean accuracies were 91.66% and 91.67% in the repeat and switch conditions, respectively. A two-way repeated measures ANOVA on accuracy (Fig. 2b) revealed no main effect of either repetition, $F(1, 19) = 1.604$, $p = .22$, $\eta^2 = .078$, or task, $F(1, 19) = 3.288$, $p = .086$, $\eta^2 = .148$. The interaction between the two conditions was not significant, either, $F(1, 19) = 1.902$, $p = .18$, $\eta^2 = .091$.

In the dual-task condition, the mean accuracies in the VWM task were 82.50% and 83% in the repeat and switch conditions, $t(19) < 1$.

In the single-task condition, the mean accuracies were 93.74% and 92.40% in the repeat and switch conditions, respectively. In the dual-task condition, the accuracies were 89.51% and 90.3% in the repeat and switch conditions, respectively. A two-way repeated measures ANOVA on accuracy (Fig. 3b) revealed a marginal main effect of task, $F(1, 19) = 3.64$, $p = .072$, $\eta^2 = .161$, but neither a main effect of repetition, $F(1, 19) < 1$, nor an interaction between the two conditions, $F(1, 19) = 1.509$, $p = .234$, $\eta^2 = .074$.

In the dual-task condition, the mean accuracies in the VWM task were 88.2% and 87.29% in the repeat and switch conditions, respectively. The results of a paired t test showed no difference, $t(19) < 1$.

Discussion

Experiment 1B: Spatial VWM load The data analysis for Experiment 1B was identical to that of Experiment 1A (see Fig. 3). Only correct responses that were made after 150 ms and before 2,000 ms were included for the analysis.⁴ In the single-task condition, the mean RTs were 986.59 and 1,082.87 ms in the repeat and switch conditions, respectively. In the dual-task condition, the mean RTs were 1,082.94 and 1,130.17 ms in the repeat and switch conditions, respectively.

The results of a two-way repeated measures ANOVA on the mean RTs (Fig. 3a) show a main effect of repetition, $F(1, 19) = 48.702$, $p < .001$, $\eta^2 = .719$, and a main effect of task, $F(1, 19) = 5.219$, $p = .034$, $\eta^2 = .215$. There was also a significant interaction between the two conditions, $F(1, 19) = 10.031$, $p = .0051$, $\eta^2 = .346$. Evidence for PoP was found in both the single-task condition, $t(19) = 6.703$, $p < .001$, $d = 1.50$, and the dual-task condition, $t(19) = 4.224$, $p < .001$, $d = 0.94$, with slower RTs in the dual-task condition, $t(19) = 2.285$, $p = .034$, $d = 0.51$. Critically, the amount of priming was smaller in the dual-task condition, $t(19) = 2.750$, $p = .013$, $d = 0.61$.

In Experiment 1, RTs were faster when the target's color was repeated, indicating that PoP was observed (Maljkovic & Nakayama, 1994). Experiment 1A replicated the findings from Lee et al (2009): The magnitude of PoP was not influenced by a concurrent non-spatial VWM task. More importantly, Experiment 1B demonstrated that the magnitude of PoP decreased when spatial VWM was loaded. In an additional analysis, we confirmed that the pattern of weakened PoP in the dual-task condition of Experiment 1B was consistently observed at both fast and slow RTs. That is to say, when RTs were split into fast and slow RTs (for each participant according to each condition's median RT), the PoP in fast trials was larger in the single-task than in the dual-task condition, and the PoP in slow trials was also larger in the single-task than in the dual-task condition. This was confirmed by the fact that the two-way interaction (repetition by task) was significant, $F(1, 19) = 5.349$, $p = .032$, $\eta^2 = .220$, whereas the three-way interaction (including RT level, fast vs. slow) was not significant, $F(1, 19) = 2.847$, $p = .107$, $\eta^2 = .130$. The same pattern was observed when the data were split into four quartiles (from the fastest to the slowest RT quartile; see Figs. 4 and 5), with no significant modulation of the effect of spatial VWM on PoP by RT speed, $F(3, 57) = 1.657$, $p = .186$, $\eta^2 = .080$, whereas the

⁴ As in Experiment 1A, the overall search accuracy was high (91.49%), and the majority of responses (94.79%) were made within the allowable time range.

Fig. 3 Results of Experiment 1B (spatial VWM task). The data are presented as a function of two conditions: repetition (repeat vs. switch in the search task) and task condition (single vs. dual). Panels A and B

demonstrate mean RTs and accuracies in the search task, respectively. Error bars show the within-subjects standard errors of the amounts of priming

interaction between repetition and task was again significant, $F(3, 57) = 6.416$, $p < .001$, $\eta^2 = .252$. In sum, we can confidently conclude that the spatial VWM decreased the magnitude of the PoP in the dual-task condition, as compared to the single-task condition. Of course, this conclusion is limited by the fact that the manipulation of spatial VWM was confounded with the single–dual task manipulation. Although we did not find an analogous reduction when non-spatial VWM was loaded (Exp. 1A), the conclusion remains less than optimal. Furthermore, the conclusion that spatial VWM plays a direct role in PoP would be much strengthened if loading spatial VWM produced a dosed effect on PoP. Experiment 2 was designed to investigate this issue.

One possible concern about the methods of Experiment 1A was that the feature VWM task may not have loaded only feature VWM, but also spatial VWM (e.g., Jiang, Olson, & Chun, 2000). This is a valid concern, in theory, but we feel confident that it does not apply to the present experiment. For one thing, the type of feature VWM tasks that have been shown to also load spatial VWM are tasks that include a great degree of spatial uncertainty. Items may change location between the learning and the recognition display, or color swaps may occur (i.e., two locations in the learning display may swap colors in the recognition display). Neither of these design characteristics was present in our experiment. That is, we

always presented the to-be-remembered squares in the same location from trial to trial and from learning to recognition displays. We also had no color swaps; changes were always the replacement of a color with a color not presented in the earlier display. Furthermore, there was constant articulatory suppression during the experiment, and this, too, prevents participants from engaging in color–location bindings of the type, “red on the left, green on the right.” Additionally, to the extent that we can believe the results of Experiment 1B (which we confirmed in Exp. 2C), we now know that spatial VWM load *does* impact (i.e., decrease) PoP magnitude. Thus, because we found no changes in the magnitude of PoP in Experiment 1A, we can be even more confident that the feature VWM task did not also, unintentionally, load spatial VWM, at least not to a meaningful extent. It is also worth remembering that the absence of an effect of feature VWM on PoP in Experiment 1A replicated the results of *seven* experiments by Lee, Mozer, and Vecera (2009). Thus, we can be fairly confident that the feature VWM task we used entailed no meaningful spatial VWM load.

A final concern regarding the results of Experiment 1 is that performance on the VWM tasks was not directly comparable for both types of load. Indeed, the mean accuracy in the VWM task was higher in Experiment 1B than in Experiment 1A. This result indicates that the VWM task in Experiment 1B may have

Fig. 4 Distribution of correct RTs in Experiment 1A (non-spatial VWM task). Panel A illustrates the distribution of mean RTs, split into two RT groups (fast vs. slow RTs, within subjects), by repetition and task conditions. Panel B shows a more detailed distribution of the RT data

by splitting the data into four quantile RT groups. As can be seen in the figure, the difference between the search and repeat bars is about the same magnitude at every level of RT when the single- and dual-task conditions are compared

Fig. 5 Distribution of correct RTs in Experiment 1B (spatial VWM task). Panel A illustrates the distribution of mean RTs, split into two RT groups (fast vs. slow RTs, within each subject), by repetition and task conditions. Panel B shows a more detailed distribution of the RT data by splitting the

data into four quantile RT groups. As can be seen in the figure, the difference between the search and repeat bars is systematically smaller in the dual-task than in the single-task condition, at every level of RT

been easier than the one in Experiment 1A. As a consequence of the much harder VWM task in Experiment 1A, participants could have opted out of the VWM task (or deprioritized performance in that task), thereby leaving PoP unaffected. Such a strategy of giving up on the VWM task could have also occurred in the previous study by Lee et al. (2009), in which the accuracy of their non-spatial VWM task was as low as 74.6% (Lee et al., 2009, Exp. 2A). This question is quite fundamental. If task difficulty were responsible for the unaffected PoP in the dual-task condition, this would support the notion that even non-spatial VWM has a role to play in PoP. The design of Experiment 2 also allowed us to address this concern.

Experiment 2

The results of Experiment 1 tentatively suggested that spatial VWM load interferes with PoP, indicating that spatial VWM plays an integral (yet previously unforeseen) role in PoP. That said, this possible interpretation was complicated by two issues. First, the load manipulation was confounded with the single–dual task manipulation, allowing the possibility that nonspecific dual-task costs were responsible for the pattern in Experiment 1B. Second (and related to the first concern), the overall level of difficulty in the VWM task was much higher in the non-spatial VWM condition than in the spatial VWM condition, allowing the possibility that participants may more often have opted out of the VWM task in the non-spatial than in the spatial VWM condition. Furthermore, if spatial VWM plays a critical role in PoP, one would expect that it would do so in a dose- (or load-) dependent manner: The larger the spatial VWM load, the smaller the PoP ought to be. In this experiment, we investigated this issue by comparing performance (within subjects) in the PoP at two different levels of VWM load. This design allowed us to (a) evaluate whether indeed PoP is reduced in a dose-dependent manner with increasing spatial VWM load; (b) eliminate concerns

about single–dual task confounds in Experiment 1A; and (c) directly address the possibility that the level of difficulty in the non-spatial VWM task was responsible for the absence of a non-spatial VWM load on PoP (the opt-out hypothesis).

To manipulate load, participants were tested with two separate blocks of a dual task composed of a search and a VWM task, with varied load in each block. As in Experiment 1, in Experiment 2 we investigated both non-spatial VWM loads (Exp. 2A) and spatial VWM loads (Exps. 2B and 2C). There was no single-task block in this experiment.

Method

Participants In all, 23, 25, and 31 new participants took part in Experiments 2A, 2B, and 2C, respectively. All participants were required to have normal or corrected-to-normal vision, including normal color vision. After excluding the data of participants who showed poor performance (i.e., below 80% mean accuracy in search, or 65% mean accuracy in the VWM task), the data of 18, 20, and 20 participants in Experiments 2A, 2B, and 2C, respectively, were submitted to further analysis.

Apparatus and stimuli These were identical to those in Experiment 1. As in Experiments 1A and 1B, in Experiment 2A we employed a non-spatial color VWM task in the dual-task condition, whereas in Experiments 2B and 2C we adopted spatial VWM tasks.

Procedure All procedures were identical to those in Experiment 1, with two exceptions (Fig. 6). First, all experiments included two blocks of a dual task composed of a search and a VWM task. Second, in each experiment and each block, the number of items varied in the VWM task. In Experiment 2A, participants were asked to remember and respond to one colored patch or four colored patches in separate blocks (load 1 vs. load 4). Similarly, in Experiment 2B, we asked

Fig. 6 Description of the VWM task at various loads in Experiment 2. Columns A, B, and C depict the different loads used Experiments 2A, 2B, and 2C, respectively. The top row corresponds to the low load in each experiment, and the bottom row corresponds to the high load

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

Results

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

Experiment 2A (load 1 vs. 4) Performance in the non-spatial VWM task confirmed that the two chosen levels of VWM load taxed participants' VWM resources to different extents. In the low-load condition, the mean VWM accuracies were 93.56% and 93.92% in the repeat and switch conditions, respectively. In the high-load condition, accuracy was 83.74% and 86.14% in the repeat and switch conditions, respectively. A two-way repeated measures ANOVA on VWM accuracy showed a main effect of load, $F(1, 17) = 11.093, p = .004, \eta^2 = .395$, confirming that the condition with high non-spatial VWM load (4) was more difficult than that with low non-spatial VWM load (1). No other effect was significant, $F(1, 17) < 1$.

The RT results are summarized in Fig. 7. Fewer than 4% of trials were eliminated due to too-short (<150 ms) or too-long (>2,000 ms) RTs. In the low-load condition, the mean correct RTs were 943.1 and 969.37 ms in the repeat and switch conditions, respectively. In the high-load condition, the mean correct RTs were 1,016.53 and 1,047.45 ms in the repeat and switch conditions, respectively.

The results of the two-way repeated measures ANOVA on RTs showed a significant main effect of repetition, $F(1, 17) = 15.675, p = .001, \eta^2 = .480$, and a marginal main effect of load, $F(1, 17) = 4.296, p = .054, \eta^2 = .202$, but no interaction between the two condition variables, $F(1, 17) < 1$. As expected, the RTs of the repeat condition were faster than those of the

switch condition, $t(17) = 3.959, p = .001, d = 0.93$. Though the mean RTs were slower in the high-load condition, $t(17) = 2.073, p = .054, d = 0.49$, the amounts of priming did not differ in the two load conditions, $t(17) < 1$.

In the low-load condition, the mean search accuracies were 94.3% and 94.12% in the repeat and switch conditions, respectively. In the high-load condition, the mean accuracies were 92.41% and 90.75% in the repeat and switch conditions, respectively. A two-way repeated measures ANOVA on search accuracy revealed only a marginal main effect of repetition, $F(1, 17) = 3.503, p = .079, \eta^2 = .171$. Neither a main effect of load, $F(1, 17) = 1.132, p = .30, \eta^2 = .062$, nor an interaction, $F(1, 17) < 1$, was apparent.

In sum, the results of Experiment 2A showed that (a) we successfully induced different levels of performance in the non-spatial VWM task, and yet (b) load failed to interact with repetition in the search task. This result confirms the results of Experiment 1A (as well as those of Lee et al.'s, 2009, study) that non-spatial VWM does not interfere with, and thus is not involved in, PoP.

Experiment 2B (load 1 vs. 2) Unfortunately, an analysis of VWM performance revealed that our manipulation of load had not differentially taxed participants' spatial VWM resources across load conditions. In the low-load condition, the mean VWM accuracy was 90.2% versus 89.15% in the repeat versus the switch conditions, respectively. In the high-load condition, the accuracy was 90.71% versus 91.08% in the repeat versus the switch conditions, respectively. A two-way repeated measures ANOVA revealed no main effect of repetition, $F(1, 19) < 1$; no main effect of load, $F(1, 19) = 1.798, p = .196, \eta^2 = .086$; and no interaction, $F(1, 19) = 2.665, p = .119, \eta^2 = .123$.

The RT results are summarized in Fig. 8. Fewer than 3% of trials were eliminated due to too-short (<150 ms) or too-long (>2,000 ms) RTs. In the low-load condition, the mean correct RTs were 915.15 and 948.49 ms in the repeat and switch conditions, respectively. In the high-load condition, the mean correct RTs were 879.64 and 921.23 ms in the repeat and switch conditions, respectively.

Given that the two different levels of load failed to tax spatial VWM to different extents, one would not expect to find an effect of load on PoP, and indeed we did not find one. A two-way repeated measures ANOVA on RTs revealed a main effect of repetition, $F(1, 19) = 17.917, p < .001, \eta^2 = .485$, but neither a main effect of load, $F(1, 19) = 1.32, p = .26, \eta^2 = .065$, nor an interaction, $F(1, 19) < 1$. For both load conditions, RTs were faster in the repeated condition, $t(19) = 4.233, p < .001, d = 0.95$. In the low-load condition, the mean search accuracies were 93.15% and 92.85% in the repeat and switch conditions, respectively. In the high-load condition, the mean accuracies were 93.82% and 92.18% in the repeat and switch conditions, respectively. A two-way repeated measures ANOVA on

Fig. 7 Results of Experiment 2A (non-spatial VWM task). Panels A and B show mean RTs and accuracies in the search task, respectively. Panel C shows the mean accuracies in the VWM task. Error bars show the within-subjects standard errors of the amounts of priming

accuracy showed no main effect of repetition, $F(1, 19) < 1$; no main effect of load, $F(1, 19) = 1.308$, $p = .266$, $\eta^2 = .064$; and no interaction, $F(1, 19) < 1$.

Experiment 2C (load 2 vs. 4) Analysis of performance in the spatial VWM task confirmed that, unlike in Experiment 2B, the two chosen levels of load significantly and differently taxed spatial VWM resources. The mean VWM accuracies in the low-load condition were 92.29% versus 90.95% in the repeat versus the switch conditions, respectively. In the high-load condition, the VWM accuracies were 87.43% versus

87.11% in the repeat and switch conditions, respectively. A two-way repeated measures ANOVA on VWM accuracy revealed a main effect of load, $F(1, 19) = 5.833$, $p = .026$, $\eta^2 = .235$, confirming better VWM in the low-load than in the high-load condition. Neither a main effect of repetition nor the interaction was significant, $F(1, 19) < 1$.

The RT results are illustrated in Fig. 9. Fewer than 2% of trials were eliminated due to too-short (<150 ms) or too-long (>2,000 ms) RTs. In the low-load condition, the mean correct RTs were 924.86 and 991.06 ms in the repeat and switch conditions, respectively. In the high-load condition, the mean

Fig. 8 Results of Experiment 2B (spatial VWM task). Panels A and B show mean RTs and accuracies in the search task, respectively. Panel C shows the mean accuracies in the VWM task. Error bars show the within-subjects standard errors of the amounts of priming

correct RTs were 814.66 and 838.03 ms in the repeat and switch conditions, respectively.

A two-way repeated measures ANOVA on RTs revealed a main effect of repetition, $F(1, 19) = 20.835, p < .001, \eta^2 = .523$; a main effect of load, $F(1, 19) = 21.942, p < .001, \eta^2 = .536$; and a significant interaction between the two, $F(1, 19) = 8.213, p < .01, \eta^2 = .302$; RTs were faster in the repeat condition, $t(19) = 4.565, p < .0001, d = 1.02$, than in the switch condition, in both the low-load condition, $t(19) = 4.705, p < .0001, d = 1.05$, and the high-load condition, $t(19) = 2.267, p = .035, d = 0.51$ —evidence that PoP was observed at both levels of VWM load—yet the magnitude of PoP was smaller at high than at low load, $t(19) = 2.866, p = .010, d = 0.64$.

In the low-load condition, the mean search accuracies were 93.36% and 92.68% in the repeat and switch conditions, respectively. In the high-load condition, the mean accuracies were 93.59% and 92.79% in the repeat and switch conditions,

Fig. 9 Results of Experiment 2C (spatial VWM task). Panels A and B show the mean RTs and accuracies in the search task, respectively. Panel C shows the mean accuracies in the VWM task. Error bars show the within-subjects standard errors of the amounts of priming

respectively. A two-way repeated measures ANOVA on search accuracy showed a main effect of neither repetition, $F(1, 19) = 1.898, p = .18, \eta^2 = .091$, nor load, $F(1, 19) < 1$, nor an interaction, $F(1, 19) < 1$.

Discussion

Experiment 2 provided relatively clear answers to the questions that had motivated it. In Experiment 2A we examined PoP under two different levels of non-spatial VWM load. One level (load 1) was much easier than the one used in Experiment 1A (and than the high-load condition in this experiment). Yet, despite the much better performance in the VWM task, PoP was unaffected by load. This provides us with some support against the opt-out interpretation of Experiment 1A (that participants had opted out of the VWM

task because it was quite difficult). We can more safely conclude now that non-spatial VWM does not play a role in PoP.

In contrast, Experiment 2C provided evidence that loading spatial VWM decreases PoP in a dose-dependent manner: The larger the load, the smaller the magnitude of PoP. Because this comparison was done within subjects, we can be even more confident that the results of Experiment 1B were not due to the single–dual task confound in that experimental design. Thus, we twice obtained a significant effect of spatial VWM load on PoP. The results of Experiment 2B were a bit surprising, but not overly so. We had anticipated that loading spatial VWM with two items would be more taxing than loading it with just one item. However, an analysis of performance in the VWM task suggested that the manipulation was too subtle, and accuracies did not differ significantly across levels of load. This null effect of the load manipulation in the VWM was also evident in the PoP task, in which load did not modulate the magnitude of PoP. However, given that the two different levels of load did not differentially tax VWM resources, it was expected that load would also fail to modulate PoP. In sum, the results of Experiments 2A–2C confirmed the results of Experiments 1A and 1B: Spatial VWM appears to play an important role in PoP.

One additional aspect of the results that is worth discussing is that in Experiment 2C, the overall RTs *decreased* rather than increased when spatial VWM load was increased. We had expected the opposite pattern. We have no strong mechanistic account for this finding, though we can offer one speculative interpretation of the results. As we indicated in the introduction, our lab has put forward data that challenge the idea that a “featural contrast” drives the selection of the target in three-item color-oddball search tasks like the one used here. In that sense, “priming of pop-out” is a misnomer. Rather, in Tseng et al. (2014) we proposed that the oddball task (with a three-item display) can be understood as an attention/decision-making task. Because the target fails to pop out and participants cannot anticipate a priori what color the target will be, they must attend to all three items and compare them to decide which of the three is different from the other two. This is a much slower and resource-demanding process than selecting a fixed target—which produces efficient search (see Buetti et al., 2016)—even when identical displays are compared. Why would RTs decrease in the high-load condition? We can only speculate that this might be the result of participants being less able to engage in the active selection and comparison of the three items (as was required by the task). Thus, because participants lacked the resources to deploy spatial attention to all three items due to the VWM load, they might have ended up relying on the (weak) low-level visual information that distinguished the target from the distractors, rather than on their own volitional, top-down-driven comparison of the three items. Admittedly, this is only speculation. Further work will be needed in order to explore this possibility. If it is true, it would suggest that three-item oddball searches are much less of a “visually dependent task” than has

previously been thought, and a much more a top-down-dependent task. This interpretation would also be consistent with fMRI data from Kristjánsson, Vuilleumier, Schwartz, Macaluso, and Driver (2007), as well as from Scaf, Ahn, Beck and Lleras (2014), showing that higher-level areas associated with top-down control are involved in both oddball tasks and PoP.

Finally, we believe it is important to note the relatively high number of excluded participants in Experiment 2C (11). Does this high rate of exclusion somewhat limit the generalizability of our results? We do not believe so. For one thing, we set out our exclusion criteria early on in the execution of the project, and we kept it constant across all experiments. We had no way of anticipating that our chosen exclusion criteria would result in such a high level of data loss. This was all the more surprising to us because the inclusion criteria appeared to us to be relatively liberal: We expected performance to be at least 80% correct in the (relatively easy) search task (a color pop-out task requiring a simple shape discrimination for the response). To put this in context, it is not unusual to find in the literature much stricter inclusion criteria for search performance (e.g., Buetti et al., 2016, used a 90% inclusion criterion). Furthermore, the inclusion criterion for performance on the memory task was merely 65% correct. Given that chance performance in the task is 50%, 65% appeared to us a bare minimum to ensure that participants were at least trying to complete the memory task on a significant proportion of trials. In sum, we believe that our inclusion criteria was in fact quite liberal. However, there is little doubt that the experiment itself (verbal suppression + VWM task + search task) was quite demanding, so it is not surprising that many participants may have simply given up out of a lack of motivation or mental fatigue; we simply do not know. What we believe is that a participant who was sufficiently motivated to perform this triple task would likely have surpassed our inclusion criteria. Thus, we believe our results are likely to generalize to participants who actually perform this triple task. Unfortunately, we can say little else about why in this specific experiment we ended up having a higher exclusion rate than in the other four. Future research might avoid this issue by setting the level of difficulty of the memory task according to each participant’s VWM capacity.

General discussion

In the present study, we aimed to explore what memory mechanisms may be involved in the well-known intertrial priming effect, PoP (Maljkovic & Nakayama, 1994, 1996, 2000). Several mechanistic accounts of PoP have been proposed, yet there is still no firm agreement regarding why it arises in the first place, and more important to our present article, little is known regarding what sort of memory stores play a role in facilitating this effect. In the initial study of PoP, Maljkovic and Nakayama (1994) proposed that some form of implicit short-term memory was responsible for it. Wolfe et al. (2003) proposed that the memory in

question was likely a memory trace that persisted in the feature gain modulation system (i.e., where it is decided which features will be biased/boosted by attention, and by how much). This proposal received some partial support from Lee et al.'s (2009) study, since they failed to find any modulation of PoP when non-spatial (featural) VWM was loaded.

Often common to PoP articles is the underlying assumption that in PoP the target actually pops out of the display because of its relative “featural” contrast against the other two distractors. As such, spatial attention only (ever) deploys to one location (the target location), after the initial low-level analysis of the scene is completed. In contrast to this view, Tseng et al. (2014) proposed that the color-oddball task could be understood (and modeled) as an attentional decision task, in which attention is actually actively involved in evaluating *all* items in the display, at least in displays with small set sizes like 3 (the set size used in Maljkovic & Nakayama's, 1994, initial study). The evidence accumulates in this model not toward a perceptual decision (“is this item red?”) but rather toward a functional decision (“is this the target color?”). Tseng et al. used this model to fit saccadic latency and accuracy data: How long did it take for the eyes to leave fixation and did the eyes land at the target (correct) or on a distractor (incorrect). Within this framework, PoP (and the DPE) arises as changes in the biases (or thresholds) in the decision task (not in changes in the salience of items in the actual display). Feature-weighting accounts of PoP (and of the DPE) would have predicted changes in the drift rates of the model, whereas the most consistent finding was that these phenomena were better understood in terms of changes in the decision thresholds. The changes in decision thresholds reflect a simple tendency that for any given color, their functional role tends to persist across trials. That is, for a binding between a specific color (red) and a specific role (target color) to be maintained across trials.

The fact that changes in biases are responsible for PoP is also consistent with studies showing that PoP can be *reversed* as a function of monetary rewards in the visual search task (Hickey, Chelazzi, & Theeuwes, 2010). This follows because we think it is more plausible that monetary rewards change the biases we use in our decision making, rather than the actual physical salience of objects in the world (as was proposed by Hickey et al., 2010). Furthermore, the proposal that PoP arises as a decision-making bias would also explain why relatively high-level areas in the attention control network are actively involved in PoP (Kristjánsson et al., 2007): Attentional control would be required to direct attention to the three items in the display and compare them. Indeed, in Kristjánsson et al.'s study, there was evidence for repetition suppression on target-repeated trials in inferior temporal areas as well as in fronto-parietal areas. Inferior temporal areas are known to process object-related information such as color and shape (see, e.g., Grill-Spector, Kushnir, Edelman, Itzhak, & Malach, 1998; Grill-Spector & Malach, 2001), whereas the

fronto-parietal network is believed to control spatial attention (Kastner & Ungerleider, 2001; LaBar, Gitelman, Parrish, & Mesulam, 1999). Finally, eye movement data on three-item oddball displays like the ones used here also showed that participants were actually relatively *bad* at fixating the target when the target on the current trial differed in color identity from that on the previous trial (Becker, 2008; Caddigan & Lleras, 2010). That is, if targets in these displays were really popping out, one would have expected exceedingly good (perhaps perfect) saccades to the target on every trial, yet that was not the case. When the target color was different from that on the preceding trial, the first saccade *failed to land on the target* on as much as 28% of trials.

The present results are not evidence in favor of Tseng et al.'s (2014) proposal. However, we believe that the pattern of results is more consistent with the view expressed in that article that PoP is an attentional decision-making bias arising in the context of an attentional decision-making task. This stands in opposition to proposals and theories that have argued that PoP reflects low-level feature gain modulations and/or have assumed that the targets in these oddball tasks systematically pop out in the displays. The evidence that oddballs pop out in displays is, in our view, not particularly strong. In fact, our results suggest that spatial attention is required in order to select the items in the search display (i.e., we argue allowing for the comparison process to take place). This follows because, when spatial VWM is taxed, PoP decreases (Exp. 1B), and the more that spatial VWM is loaded, the more PoP diminishes (Exp. 2C). Finally, our results also consistently showed that analogous manipulations of “featural” load failed to interfere with PoP, replicating Lee et al. (2009): The presence in VWM of a small subset of colored squares does not alter the magnitude of PoP, nor does the number of colored squares in VWM modulate it.

Of course, there is an alternative account of the effect of spatial VWM load on PoP: Perhaps spatial VWM is critical to PoP not because spatial VWM is required in order to attend to and inspect search items prior to the selection of the oddball target, but rather because spatial VWM stores the memory trace that is itself responsible for PoP. If one assumes that targets do pop out from these simple three-item search displays, then one can also assume that a memory trace in spatial VWM ties together the location that was selected as a target on the current trial with the identity information about the target itself (i.e., its color). This would be a sort of incidental encoding of the target's color, as a consequence of spatial attention having used that information to program a movement of spatial attention toward a specific location in the display. In a similar vein, the “gaze reorientation” hypothesis argued by Maljkovic and Nakayama (1996) proposes that PoP and position-based priming (in a PoP task) depend on a representation in a “short-term memory,” which is the basis of reorienting eye gaze to an object or location involved in a

sequence of actions. Later eye movement studies (McPeck, Maljkovic, & Nakayama, 1999) supported the gaze reorientation hypothesis by showing that saccades to a target were faster and more accurate when the target color was repeated across trials. This result indicates that the underlying mechanism of PoP is responsible for rapidly reorienting the observer's gaze to a recently foveated target.

Research on transsaccadic memory (Hollingworth, 2009; Richard, Luck, & Hollingworth, 2008) has reported similar findings. In these studies, while participants were maintaining a color in memory, the same color appeared at a different location from the one where it was previously presented. Though participants' initial saccades were directed to the location where the target had initially been presented, they quickly and accurately corrected saccades to the location of the stimulus matching their memory representation. Recently, Hollingworth, Matsukura, and Luck (2013) also showed that saccades to an abrupt onset were faster and more accurate when the onset matched the memory representation. This result suggests that a gaze correction mechanism exists that is aimed at redirecting the eyes toward recently foveated targets whenever and wherever they appear in the display. If this is the same mechanism responsible for PoP, it would suggest that spatial VWM is directly involved in this identity-based refoveating mechanism. One inconsistency, however, is that saccadic RTs in three-item oddball search displays are several hundred milliseconds slower (upward of 300 ms; see Caddigan & Lleras, 2010) than those in the gaze correction experiments reported by Hollingworth and colleagues (around 140 ms). Thus, the temporal dynamics for fast gaze correction do not seem to support target foveation in traditional PoP displays.

Conclusion

The data presented here demonstrated that loading spatial VWM diminishes the magnitude of the PoP effect. We also replicated the absence of an effect of loading non-spatial VWM on PoP. We interpreted these findings within the context of recent findings from our lab that have suggested that the targets in three-item color oddball tasks actually do not systematically pop out (Buetti et al., 2016; Tseng et al., 2014), but actually require an attentive comparison to determine which item is different from the other two before attention can be focused on that one oddball item. This is a substantially longer process than simply moving attention toward a known pop-out (Buetti et al., 2016) or toward a sudden onset (Hollingworth et al., 2013). Within our proposed framework, certain intertrial effects such as PoP (but also the DPE) are simply the results of lingering decision biases from trial to trial. From this perspective, it seems easier to understand the effect of spatial VWM load on performance in the oddball task: Loading spatial VWM decreases the amount of resources

available to actually attend to the search items during the initial comparison stage. These data also present an indirect challenge to previous theories or investigations that have assumed that the target pops out in simple three-item search displays. If the oddball did pop out, it would be difficult to understand why loading spatial VWM would interfere with the minimal execution of one single movement of attention (or of the eyes) toward the pop-out item. That said, this study has opened up more questions than it answers. If the featural contrast of the oddball does not guide attention to the target, what does? Is it really a multi-item comparison process? If so, how is that process affected by increases in the set size in visual search? Clearly, at sufficiently large set sizes, the oddball ought to have a strong featural contrast against the distractors. Does selection, then, occur in fundamentally different ways in large-set-size than in small-set-size displays? Future research will be needed to compare these different alternatives.

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