Title:

Spatial and feature-based suppression in working memory

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Abstract

Working memory (WM) can guide attention towards items similar to its content, both based on features and locations maintained in WM. So far, however, this has only been demonstrated with memory items that are relevant and thus maintained with a positive weight. The finding that negative attention templates can support the suppression of upcoming distractors raises the question whether items can also be stored with a negative priority in WM. We let participants memorize the exact hue of a memory target that was presented among not-to-be-encoded memory distractors. Before their WM was probed, they performed a visual search task in which they had to find a target among distractors. When the search target was presented in the same color as an item suppressed from WM, response times (RTs) were longer than for a target presented in the same color as the memory target. Similarly, when the search target was presented at the same location as an item suppressed from WM, RTs were longer than for a target presented at the same location as the memory target. Our results suggest that items can be maintained in WM with a negative priority and then support the suppression of subsequent similar stimuli. Such items with negative priority in WM may be what constitutes negative attentional templates.

Significance

Current models of visual attention conceptualize goal-driven (top-down) attention deployment to be based on templates stored in working memory (WM). Recent studies demonstrated the important role of suppression of salient distractors for efficient attention deployment. For example, rejection templates were hypothesized to allow top-down anticipatory suppression of an upcoming distractor. The present study shows that both feature and location of items suppressed from WM can guide attention away from such features and locations in a visual search task. Thus this study provides first evidence that items can assume a negative status in WM, which supports the notion of rejection templates.

Introduction

Visual selective attention can be guided in a goal-directed (top-down) manner towards targets (stimuli a person intends to find) by making use of attentional templates, visual mental representations of a specific stimulus. Working Memory (WM) plays key role in top-down attention deployment because it temporarily stores attentional templates (Carlisle et al., 2011; Downing & Dodds, 2004; Hollingworth & Beck, 2016; Olivers et al., 2006; Soto et al., 2005; van Moorselaar et al., 2014; Wolfe et al., 2004; Woodman et al., 2007). The guidance of attention by templates has been demonstrated in experiments combining WM and attention tasks. For example, Olivers et al. (2006) let participants first encode the color of an item into WM. After a retention interval, WM was probed by letting participants identify the original color from a set of colors. During the retention interval, participants performed a visual search task in which they had to find a target presented amongst distractors and report its identity. One of the distractors could be a color singleton and either show the same or a different color as the item maintained in WM. The authors found that the color distractor captured attention more when it matched the color of the item in WM than a neutral color (Olivers et al., 2006; see also Soto et al., 2005). While some studies suggest that only one item can have a priority high enough in WM to guide attention (Downing & Dodds, 2004; van Moorselaar et al., 2014), other studies found that WM can also guide attention when participants had to keep more than one item in WM (Beck & Hollingworth, 2017; Soto & Humphreys, 2008) albeit guidance is stronger for a single item (Hollingworth & Beck, 2016). Attention deployment can also be guided by spatial representations in WM: participants gave faster and more accurate responses to targets visual search tasks when they appeared in the same location as a stimulus being held in WM (Awh et al., 1998)

Recently, it has been demonstrated that in addition to enhancing relevant information, actively suppressing irrelevant information contributes to efficient attention deployment

(Feldmann-Wüstefeld et al., 2020; Gaspelin & Luck, 2018). This raises the question whether similar to attentional templates that guide attention, negative attentional templates may support suppression of anticipated, irrelevant but potentially distracting stimuli. Such anticipatory suppression has been found when participants received feature cues (Arita et al., 2012; Conci et al., 2019; Moher & Egeth, 2012; Reeder et al., 2017) or spatial cues (Munneke et al., 2015; Ruff & Driver, 2006; Wang et al., 2019) informing them about an upcoming distractor. In line with the notion of negative templates, these studies found less interference by distractors if participants knew their feature or location in advance. However, it is not clear whether items can be maintained in WM with a negative priority. Thus, it has also been suggested that cues informative of distractors are not resulting in templates stored in WM, but in spatial recoding (Beck & Hollingworth, 2015) or the creation of positive templates of uncued features (Becker et al., 2015).

Notwithstanding that, it has also been demonstrated that suppression contributes to WM processes (Feldmann-Wüstefeld & Vogel, 2019; Gaspar et al., 2016). Feldmann-Wüstefeld & Vogel (2019) found that salient distractors in a change detection task elicit a Pd component, indicative of active suppression. Participants with a high WM capacity showed larger Pd amplitudes, suggesting their better WM performance may be partially due to more pronounced suppression of distractors from WM. The Pd sustained throughout the entire retention interval (termed contralateral delay activity of positive polarity, CDAP) which suggests that suppression was applied after distractors had already disappeared. It is unclear, however, whether the sustained suppression in WM was feature-based or spatial. That is, the locations previously occupied by distractors may have been spatially suppressed, or the distractor colors may have been globally suppressed in WM.

In this study we will use a variation of the WM-guided search paradigm (Olivers et al., 2006; Soto et al., 2005). We will let participants suppress items from WM, similar to Feldmann-

Wüstefeld & Vogel (2019) and then use the same (versus different) distractor features and locations in a search task performed during the retention interval. If suppressed items affect search performance, this would be first evidence that negative priorities can be represented in WM, a prerequisite for negative attentional templates. Further, the question whether the feature (Experiment 1) and/or the location (Experiment 2) of items suppressed from WM affect the visual search task will allow conclusions about the nature of WM suppression. Suppression in WM may be feature-based, spatial, or both.

Method

Participants

In Experiment 1, eighteen volunteers aged 18-30 years ($M = 20.6$, $SD = 2.8$), sixteen female, one left-handed, participated. In Experiment 2, twenty-three volunteers aged 18-24 years ($M = 19.9$, $SD = 1.6$), twenty female, three left-handed, participated. Participants were naive to the paradigm and objectives of the study and received course credit as compensation. All experiments were conducted with the written understanding and consent of each participant. The University of Southampton ethics committee approved experimental procedures.

Apparatus

Participants were seated at a standard desk in a dimly lit chamber in front of an LCD computer screen (BenQ XL2430T; 120 Hz refresh rate; 61 cm screen size in diameter; 1920×1080 pixels) placed at 75 cm distance from participants. An IBM-compatible computer (Dell Optiplex 9020) controlled stimulus presentation and response collection using PsychToolbox MATLAB routines. Participants responded with button presses on a standard British QWERTY keyboard that was placed in front of them.

Stimuli

All items were presented on a black screen. Memory displays contained one square (side length 1.1°) serving as the target and one or two circles (diameter 1.2° ; same area as square) serving as distractors that were presented on an imaginary circle with a radius of 1.9° (Experiment 1) or 3° (Experiment2), see Fig. 1. In Experiment 1, items were equidistant to one another, i.e. 180° (one distractor) or 120° (two distractors) apart. The absolute position was randomized in each trial. In Experiment 2, memory items were presented on two/three of the four cardinal positions of the imaginary circle (randomly assigned). The colors of the targets and distractors were selected randomly from a set of four color categories, with three hues for each color category. Each category was only used once per memory display. The following color categories and RGB values were used: Yellow: [255 248 50; 255 204 85; 230 255 68]; Red: [255 40 24; 255 80 80; 255 77 37]; Green: [27 255 65; 97 255 94; 92 255 11]; Blue: [31 53 255; 78 51 255; 74 119 255].

Search displays always showed four U-shaped items (side length 0.7°) placed at each of the cardinal positions of an imaginary circle with a diameter of 3° . Three search items had an opening at the top or bottom, serving as distractors. One search item had an opening to the right or left, serving as the target. The target appeared equally often in each of the four positions. In Experiment 1, memory and search items never occupied the same location and the randomized positions of target and distractor in the memory display were non-predictive of the target position in the search display. Search targets either had the same color as the memory target (memorized color condition), the same color as the memory distractor (ignored color condition), a color that was not used in the memory display (neutral color condition), or were grey (RGB 60-60-60; no color condition). All three distractors were grey. In Experiment 2, memory and search items occupied the same location and all items in the search display were grey. The memory items were non-predictive of the target position as the target appeared

equally likely in any of the four locations. The target could appear in the same location as the memory target (memorized location condition), the same location as the memory distractor (ignored location condition) or an unoccupied location (neutral location condition). In both Experiments 1 and 2, the probe display showed two squares (side length 1°) at the same location as the memory target. One item had the same hue as the memory target, the other item had a different hue from the same color category as the memory target.

Figure 1. Stimuli and conditions. The left panel shows a memory display. Participants had to remember the exact hue of the square and ignore two or one (not shown here) circle(s). The right panels show search displays. The U-shape opening to the left or right served as the target, the remaining U-shapes were distractors. In Experiment 1 (upper panel), the target could have the same color as the memory target, the memory distractor, or a neutral color, or the same grey as the distractors (not shown here). Memory and search items were never presented in the same location. In Experiment 2, the target could share the location of the memory target, the memory distractor, or an unoccupied location (not shown here). Memory and search items were presented in the same locations.

Procedure

Each trial started with a display showing a fixation cross for 500 ms, see Fig. 2. Participants were told to fixate the cross and not move their eyes or blink until the end of a trial. Subsequently, in addition to the fixation cross a memory display was shown for 500 ms. Participants were asked to memorize the hue of the memory target as precisely as possible and ignore the memory distractors. After the memory display, a first retention interval of 600 ms

with only a fixation cross was shown. The search display followed for 800 ms. Participants were asked to find the target and report whether its opening was to the left or right and press the accordingly labeled key as quickly as possible. After a second retention interval of 400 ms, the probe display appeared and stayed on the screen until participants responded to the probe by pressing an “R” or “L” labeled key to indicate whether the left or right probe had the same color as the memory target. An inter-trial interval of 1000 ms with a blank screen followed before a new fixation cross announced the start of a new trial.

Figure 2. Trial procedure. Participants had to memorize the color and location of the square and ignore the circle(s) in the memory display. At the end of a trial, participants had to decide whether the left square (upper panel) or right square (lower panel) shown in the probe display matched the color of the initially shown square. While participants maintained the memory target in mind, they performed a visual search task in which they had to indicate whether the one horizontally open U-shape opens to the left (lower panel) or right (upper panel). During the periods labeled “Retention interval”, the display was identical to the fixation display.

Prior to the start of the experiment, participants had the opportunity to practice the task until they felt comfortable and performed sufficiently well. All trials were presented in random order across the entire experiment. Both experiments consisted of 16 blocks of 32 trials, i.e. a total of 512 trials. After each block, participants were given feedback about their performance in the preceding block. A mandatory ten second break followed after which participants could choose to either immediately continue to the next block or to extend their break.

Design & data analysis

In both Experiment 1 and 2, there were two factors: Number of memory distractors (one versus two) and Target Type (Experiment 1: memorized color, ignored color, neutral color, no color; Experiment 2: memorized location, ignored location, neutral location). Mean response times (RTs) and error rates for the search task were forwarded to 2x4 (Experiment 1) and 2x3 (Experiment 2) ANOVA for repeated measures. Trials with incorrect memory task performance were excluded to ensure that search task data only includes trials in which a color was successfully stored in working memory. For RT, trials with incorrect search task responses were also excluded. For all experiments, Greenhouse-Geisser correction was applied where appropriate. Effect sizes are reported as partial eta squared (η^2) for ANOVAs and Cohen's d for t-tests. All raw data and analysis scripts can be found on the Open Science Framework (<https://osf.io/49zuv/>).

Results

Experiment 1. Search response times (RTs). RTs were affected by trial type, $F(3,51) = 179.2$, $p < .001$, $\eta^2 = .91$, but not by the number of distractors, $F(1,17) = 0.9$, $p = .359$, $\eta^2 = .05$. There was no interaction of trial type and number of distractors, $F(3,51) = 1.2$, $p = .334$, $\eta^2 = .06$. Follow-up t-tests for dependent measures collapsed across number of distractors compared trial types directly, see Fig. 3. RTs were shorter for memorized colors ($M = 602$ ms) than for ignored colors ($M = 610$ ms), $t(17) = 2.5$, $p = .012$, $d = 0.59$, and marginally shorter than for neutral colors ($M = 607$ ms), $t(17) = 1.7$, $p = .055$, $d = 0.40$. RTs for ignored colors was shorter than for neutral colors, $t(17) = 2.0$, $p = .032$, $d = 0.47$. RTs for no color targets ($M = 691$ ms) were longer than for any condition with colored targets, all $t(17) \geq 14.4$, $p < .001$, all $d \geq 3.40$.

Search accuracy. Accuracy was affected by trial type, $F(3,51) = 14.7$, $p < .001$, $\eta^2 = .46$, but not by the number of distractors, $F(1,17) = 0.1$, $p = .818$, $\eta^2 < .01$. There was no interaction of trial type and number of distractors, $F(3,51) = 0.6$, $p = .564$, $\eta^2 = .03$. Follow-up t-tests for

dependent measures collapsed across number of distractors compared trial types directly. Accuracy for memorized colors ($M = 97.6\%$), ignored colors ($M = 98.0\%$), and neutral colors ($M = 98.0\%$), did not show any reliable differences, all $t(17) \leq 0.8$, all $p \geq .225$, all $d \leq 0.18$. Accuracy for no color targets ($M = 91.7\%$) was lower than for any condition with colored targets, all $t(17) \geq 4.0$, $p \leq .001$, all $d \geq 0.93$.

Memory accuracy. Memory accuracy was comparable for one distractor ($M = 78.8\%$) and two distractors ($M = 78.0\%$), $t(17) = 0.9$, $p = .407$, $d = 0.20$.

Figure 3. Results. Bar plots show the mean response times in milliseconds (left axis) and line plots show mean error rate (right axis). Error bars denote the standard error of the mean, corrected for inter-individual differences (Cousineau, 2005).

Experiment 2. Search response times (RTs). RTs were affected by trial type, $F(2,44) = 22.1$, $p < .001$, $\eta^2 = .50$, but not by the number of distractors, $F(1,22) = 2.8$, $p = .107$, $\eta^2 = .11$. There was no interaction of trial type and number of distractors, $F(2,44) = 2.1$, $p = .155$, $\eta^2 = .09$. Follow-up t-tests for dependent measures collapsed across number of distractors compared trial types directly. RTs were shorter for memorized locations ($M = 654$ ms) than for ignored colors ($M = 661$ ms), $t(22) = 2.4$, $p = .013$, $d = 0.50$. RTs for trials at neutral locations ($M = 641$ ms) were shorter than for targets at memorized, $t(22) = 3.8$, $p = .001$, $d = 0.80$, or ignored locations, $t(22) = 7.7$, $p < .001$, $d = 1.60$.

Search accuracy. Accuracy was not affected by trial type, $F(2,44) = 0.1$, $p = .889$, $\eta^2 < .01$, the number of distractors, $F(1,22) = 0.1$, $p = .798$, $\eta^2 < .01$, nor was there an interaction of trial type and number of distractors, $F(2,44) = 0.1$, $p = .927$, $\eta^2 < .01$.

Memory accuracy. Memory accuracy was comparable for one distractor ($M = 79.8\%$) and two distractors ($M = 80.1\%$), $t(22) = 0.5$, $p = .647$, $d = 0.10$.

Discussion

The key finding of the present study was that attention deployment is biased away from features and locations currently suppressed from working memory (WM). Experiment 1 demonstrated that participants find targets in a visual search task more slowly when targets shared the color of an item that participants needed to suppress from WM compared to a neutral color. We also replicated earlier results showing that attention is deployed more likely towards features maintained in WM compared to neutral colors (Olivers et al., 2006; Soto et al., 2005). Unsurprisingly, targets with no color were most difficult to find as they only differed in shape, but not in color from distractors (Fecteau & Munoz, 2006). Experiment 2 showed that not only features but also spatial position of an items suppressed from WM affects attention deployment: Participants responded more slowly to targets presented at a location that was suppressed from WM compared to locations that were maintained in WM. Targets presented at locations with no memory item at all yielded fastest results, presumably because the short inter-stimulus interval induced forward masking for the memorized and ignored location condition (Macknik & Livingstone, 1998).

Our results indicate that not only can WM content guide attention towards features (Hollingworth & Beck, 2016; Olivers et al., 2006; David Soto et al., 2005) and locations (Awh et al., 2000; Awh et al., 1998) stored with high priority, but also guide suppression towards features and locations stored with a negative priority. Previous studies already demonstrated

varying levels of priority in WM. For example it was suggested that one single item at a time has a strong enough activity in WM to guide attention (Olivers et al., 2011) or that strength of WM guidance depends on how many items compete for WM resources (Hollingworth & Beck, 2016). The present study adds the notion of a negative priority in WM to the notion of varying priority in WM. This is similar to the notion that stimuli can be represented with a negative weight on a priority map based on which attentional selection takes place (Failing et al., 2019; Ferrante et al., 2018; Gaspelin et al., 2015; Wyble et al., 2018).

Negative priority in WM is an important prerequisite for the assumption that negative attentional templates, or “templates for rejection” (Arita et al., 2012; Reeder et al., 2017) support the suppression of anticipated, irrelevant, but potentially distracting stimuli. The assumption of negative templates is that a mental representation of to-be-ignored items is kept in WM to allow attention being biased against such stimuli (or reject them more easily) and thus in turn facilitate processing of relevant information. The present study provides evidence that items can have such a negative priority in WM. This informs studies that found participants can more easily suppress distractors if negative cues inform them in advance about the feature (Arita et al., 2012; Carlisle & Nitka, 2019; Moher & Egeth, 2012; Reeder et al., 2017) or location (Munneke et al., 2015; Ruff & Driver, 2006; Wang et al., 2019) of an upcoming distractor. The present results suggest that participants can use negative cues to establish a stimulus representation with a negative weight in WM, serving as a rejection template.

In addition, the current study sheds light on the finding that distractors in change detection working memory tasks (Luck & Vogel, 1997) are suppressed in a sustained manner that contributes to overall WM performance (Feldmann-Wüstefeld & Vogel, 2019). It was unclear whether the location or features of distractors in WM tasks are suppressed. Based on the present results, distractor features may be globally suppressed, but locations occupied by

distractor may also be suppressed. Thus, WM performance may benefit from both below baseline processing of irrelevant features and locations.

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