Cognition 164 (2017) 74–86

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Original Articles

Compensation mechanisms that improve distractor filtering are short-lived

Ayala S. Allon [a,*], Roy Luria [a,b]

[a] The School of Psychological Sciences, Tel-Aviv University, Israel
[b] Sagol School of Nueroscience, Tel-Aviv University, Israel

ARTICLE INFO

Article history:
Received 7 November 2016
Revised 10 March 2017
Accepted 29 March 2017

Keywords:
Visual working memory
Filtering ability
Spatial attention
Distractor suppression

ABSTRACT

We investigated possible compensation mechanisms for improving filtering of distractors from entering visual Working Memory (WM). Participants preformed a change-detection task in which three targets, six targets, or three targets along with three distractors (the filtering trial) were randomly presented. In six experiments, we tried to reduce the filtering cost, calculated as the difference in accuracy between the three targets and the filtering condition, by either cueing the possible locations of the distractors using placeholders (that could be either fixed throughout the experiment or change every trial; i.e., location cue), or by providing the location cue coupled with a warning cue singling the upcoming filtering trial. Results revealed that the filtering cost was not reduced by a fixed location cue (Experiment 1 and Experiment 5). However, the fixed location cue coupled with a warning cue (Experiment 2 and Experiment 5) or a location cue that changed positions every trial (Experiment 6), were sufficient to reduce the filtering cost. Additionally, longer preparation interval for filtering trials did not further reduce the filtering cost (Experiment 3). We argue these findings support that in the context of visual WM, spatial filtering settings can only be held for a limited amount of time. Thus, these filtering settings must be reactivated in order to be effective and to reduce the filtering cost.

1. Introduction

Our cognitive system deals with a highly crowded environment, and cannot fully process all of the incoming stimuli. In order to guide behavior towards task related goals, one needs to focus attention towards the relevant information in the environment and filter out irrelevant information. However, filtering irrelevant information is not a prefect process, and attention can be involuntarily allocated to stimuli in the environment, even if they are irrelevant to the current task. Yet, completely ignoring irrelevant information may result in missing important changes in the environment that require adjustment of ongoing behavior (Lahav & Tsal, 2013; Tsal & Makovski, 2006). Over the years, research on filtering irrelevant information has mainly focused on studying the various conditions under which individuals demonstrate poor filtering ability, resulting in a decrement in task performance (i.e., filtering cost) in either accuracy, response speed or both (e.g., Anderson, Laurent, & Yantis, 2011; Eriksen & Eriksen, 1974; Folk, Leber, & Egeth, 2002, 2008; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994; MacLeod, 1991; Stroop, 1935; Theeuwes & Godijn, 2002; Yantis, 1996). Therefore, it is important to understand which compensation mechanisms are available in order to overcome poor filtering of irrelevant information.

Many studies have shown that using cues that mark the relevant information can help focus attention to that information and improve performance (e.g., Luck, Hillyard, Mouloua, & Hawkins, 1996; Luria & Vogel, 2011; Posner, 1978, 1980; Posner, Snyder, & Davidson, 1980; Ravizza, Uitvlugt, & Hazeltine, 2016; Schmidt, Vogel, Woodman, & Luck, 2002). For example, Nakayama and Mackeben (1989) applied a visual search task in which a cue signaling target location was either visible throughout the trial (sustained cuing) or appeared shortly before the search array (transient cuing). Sustained cuing improved search performance, even when the cue was absent but the observer had knowledge about target location, suggesting a sustained component of attention that is subjected to voluntary control. Furthermore, transient cuing improved performance when the cue appeared only shortly before the search array, but not when it appeared at longer durations before target onset, and this improvement was not modulated by prior knowledge about target location. Nakayama and

* Corresponding author at: The School of Psychological Sciences, Tel-Aviv University, Tel-Aviv 6997801, Israel.
E-mail address: ayalaall@post.tau.ac.il (A.S. Allon).

http://dx.doi.org/10.1016/j.cognition.2017.03.020

Mackeben suggested that this finding indicated a transient component of attention that can be summoned quickly to a location in the visual field but then cannot be sustained at that position. Overall, Nakayama and Mackeben (1989) provided evidence for at least two distinct attentional mechanisms that can aide performance in a crowded environment: a sustained component of attention that is subjected to voluntary control and an earlier transient component that is not subjected to voluntary control.

Note that in these studies the cues were used to mark possible targets positions, and not distractors. However, in everyday life when searching for a target, individuals often know the location of the irrelevant items instead of the location of the relevant items. For instance, when picking up your son from kindergarten, you know he does not like to swing, so you will probably not start looking for him on the swing or near it. Studies that did focus on cueing the distractors using visual search tasks and target identification tasks have shown that cuing implicitly or explicitly the location of the upcoming distractor reduced distractor processing interference (Arita, Carlisle, & Woodman, 2012; Beck & Hollingworth, 2015; Leber, Gwinn, Hong, & O'Toole, 2016; Munneke, Heslenfeld, Usrey, Theeuwes, & Mangun, 2011; Munneke, Van der Stigchel, & Theeuwes, 2008; Van der Stigchel, Heslenfeld, & Theeuwes, 2006; Van der Stigchel & Theeuwes, 2005; Watson & Humphreys, 1997). Conversely, cuing a feature of the distractor did not ameliorate performance (Beck & Hollingworth, 2015). Accordingly, the present study focused on highlighting the possible distractor spatial positions. Further studies showed that this reduction in distractor related interference was accompanied in an anticipatory activation in the occipital cortex contralateral to the expected distractor, with no additional activity in occipital cortex contralateral to the target (Ruff & Driver, 2006). These findings were taken to support an inhibitory attentional mechanism that can suppress expected distractor locations in a top-down manner, thus helping to optimize filtering of irrelevant information and select relevant information for further processing (Munneke et al., 2008; Watson & Humphreys, 1997).

In the context of visual WM, it has been argued that the ability to filter out irrelevant information, and more specifically the ability to prevent irrelevant information from entering the limited visual WM workspace underlies individual differences in visual WM capacity (Awh & Vogel, 2008; Fukuda & Vogel, 2009, 2011; Gaspar, Christie, Prime, Jolicœur, & McDonald, 2016; Jost, Bryck, Vogel, & Mayr, 2011; Jost & Mayr, 2016; McNab & Klingberg, 2008; Owens, Koster, & Derakshan, 2012; Vogel & Awh, 2008). For example, Vogel, McCollough, and Machizawa (2005, Experiment 2) used a bilateral change-detection task in which participants were briefly presented with a memory array consisting of colored squares, followed by a retention interval (of about 1 s), and then a test array in which participants indicated whether the test array was identical or different from the remembered memory array (i.e., when one of the squares changed its color). An arrow cue presented before the memory array pointed to the left or to the right side of the display, or pointed to one of the quarters on the left or the right side of the display (e.g., top left quarter). The arrow cue singled participants whether they should memorize all items on that side (e.g., to memorize all colored squares on the left side of the display), or memorize only part of the items on that side (e.g., to memorize only the colored squares at the top left quarter of the screen which served as targets), and ignore the rest of the items on that side (i.e., colored squares at the bottom left quarter of the screen which served as distractors).

Therefore, participants were cued about the spatial area in which targets were about to appear and were cued about the appearance of the upcoming filtering trial (i.e., targets along with distractors). Participants performed the task while a neural marker that reflects the number of items encoded and maintained in visual WM was recorded (i.e., Contralateral Delayed Activity; CDA; Luria, Balaban, Awh, & Vogel, 2016; McCollough, Machizawa, & Vogel, 2007; Vogel & Machizawa, 2004; Vogel et al., 2005). Vogel et al. (2005) results showed that high-capacity individuals successfully filtered out the distractors, such that their CDA amplitude did not differ when comparing a condition with two targets with a condition with two targets and two distractors. Conversely, low-capacity individuals were not able to filter out the irrelevant items from entering the visual WM workspace, and their CDA amplitude in a condition that included two targets and two distractors was higher than a condition with two targets.

This study and other studies which provided cues in change-detection visual WM tasks, provided cues about possible targets positions (Ravizza et al., 2016; Schmidt et al., 2002; Woodman, Vecera, & Luck, 2003), and not about possible distractors positions. Hence, it is not clear whether cues that mark the distractors can compensate and by that improve the ability to filter out irrelevant information from entering the limited visual WM workspace, and this was the purpose of the current study.

We investigated whether a location cue (i.e. placeholders) that marked the locations of distractors, or a combination of a location cue and a filtering warning trial cue singling the upcoming filtering trial (i.e., the appearance of targets along with distractors), can improve filtering performance in a visual WM task. In six experiments, participants performed a change-detection task in which either three targets, six targets, or three targets along with three distractors appeared in the memory array. We sought to test whether performance in the filtering condition will improve when the cue is present relative to cue absent blocks, such that the filtering cost, which was calculated as the difference in accuracy between the three targets condition and the three targets with three distractors condition, will be smaller in cue present blocks relative to filtering cost in cue absent blocks. In addition, given the arguments associating filtering ability with individual differences in WM capacity (Vogel et al., 2005), we sought to test whether using these cues for filtering distractors will be more beneficial for individuals with high or low visual WM capacity, such that their filtering cost for cue present blocks will be smaller.

To anticipate the results, the location cue did not reduce the filtering cost when the distractors' locations were fixed throughout the experiment (Experiment 1 and Experiment 5). However, using the fixed location cue coupled with a filtering trial warning cue was able to reduce the filtering cost (Experiment 2 and Experiment 5). We argue that these findings support that in the context of visual WM, spatial filtering settings of the distractors can only be held for a limited amount of time. Thus, to compensate for poor filtering of irrelevant information from entering the limited visual WM workspace, the filtering settings need to be reactivated. When only the fixed location cue was used, the filtering settings contained constant distractor positions throughout the experiment. To reduce the filtering cost, the filtering settings had to be continuously active throughout the whole cue present trials (i.e., filtering and non-filtering trials) to enable the compensation mechanisms to suppress the distractors.

We suggest that filtering settings about spatial locations of the distractors could only be activated for a limited amount of time, which is why the fixed location cue was not sufficient to reduce the filtering cost. Nonetheless, when the fixed location cue was combined with a warning cue, singling participants the appearance of the upcoming distractors along with targets, it enabled the reactivation of the filtering settings for filtering trials, resulting in a reduced filtering cost. After replicating the effect ruling out certain confounds, we moved to test a prediction derived by such a *short-lived* compensation mechanism.

2. Experiment 1

In Experiment 1, we sought to test whether a cue that marks the locations of the distractors and was previously found to reduce distractor interference (e.g., Munneke et al., 2008), could reduce irrelevant items from entering the limited visual WM workspace, resulting in a reduced filtering cost relative to a cue absent condition. To this end, on cue present blocks we marked the distractors' locations and kept these locations fixed throughout the experiment (i.e., fixed location cue). Thus, the possible locations of the distractors were perfectly predictable on cue present blocks. At face value, having fixed distractor locations marked by a cue, should help filtering ability and reduce the filtering cost. Note that the locations of the targets were always random (on both cue present and cue absent blocks) and that on cue absent blocks, the distractors locations were randomly determined.

2.1. Method

Participants. Sixteen students from Tel-Aviv University (9 females, $M = 24.43$ years, $SD = 3.23$) participated in a 45 minuets experimental session for either course credit or payment of 30 shekels (about 8$). Participants in all six experiments gave their informed consent after the procedures of a protocol approved by the Ethics Committee at Tel-Aviv University. Participants in all six experiments had normal or corrected-to-normal visual acuity and reported normal color-vision.

Apparatus. Stimuli were presented on 23-inch light emitting diode monitor with a 120 Hz refresh rate, using 1920×1080 resolution graphics mode. Participants were seated approximately 60 cm from the monitor.

2.1.1. Stimuli and procedure

Filtering change-detection task. Participants preformed a change-detection task (e.g., Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001) in which they were presented with a black fixation cross (i.e., "+") for 800 milliseconds (ms), followed by an array of colored pacmans for 200 ms (memory array), and were asked to remember only the colors of the pacmans (e.g., Vogel et al., 2005). Then, the memory array disappeared for 900 ms (retention interval); followed by the test array in which one colored pacman (a test probe) appeared at one of the previous locations of the pacmans in the memory array. Participants made an unspeeded response via button press ("Z" and "/" on the computer keyboard, counterbalanced across participants) to indicate whether the color of the test probe was the same as the color of the pacman (with equal probability for same and different test probes). Participants were informed that only the color of the pacman could change, and that the orientation of the test probe was always the same as the orientation of the pacman that appeared at that location in the memory array. On a third of the trials, three colored pacmans (i.e., targets) were presented along with three colored circles used as distractors, (i.e., the filtering condition). On the rest of the trials, arrays of either three or six pacmans were presented (targets only conditions). All stimuli had a radius of approximately 0.75° of visual angle, and the mouth of the pacman was a sixth of the size of the pacman. All stimuli were randomly positioned within a $18° \times 18°$ region on the video monitor upon a grey background with the constrain that the minimal distance between each two stimuli was at least 2.7° of visual angle (center to center). The color of each stimulus was randomly selected (without replacement) from a set of eight colors: black, blue, cyan, green, pink, red, white and yellow. On changed trials the changed item was replaced with a color not presented in the memory array. Due to a programming error in Experiments 1–2, on cue absent blocks the changed item appeared at the same position along the X axis (randomly determined for each participant), and at a random coordinate along the Y axis. This mistake did not occur in the cue present blocks. Note that the 3T and 6T conditions showed similar level of accuracy, when comparing between the cue absent blocks (with the mistake) and cue present blocks (without the mistake). In addition, we replicated the results of this Experiment (see Experiment 5) and of Experiment 2 (see Experiment 3 and Experiment 5) without the programming error. One hundred and twenty trials were presented for each condition (three targets, six targets, three targets with three distractors) in six intermixed blocks of 60 trials each. In order to cue the locations of the distractors, on half of the blocks (i.e., cue present blocks), the colored circles appeared within placeholders in the form of black frames (See Fig. 1). The placeholders appeared in fixed locations in all three conditions of the cue present blocks (i.e., in the 3T, 6T, and 3D3T conditions; Fixed location cue) in order to mark the spatial positions of the distractors (the fixed locations were randomly determined for each participant). Namely, on cue present blocks, the placeholders appeared continuously on filtering and non-filtering trials. Note that the targets never appeared within the placeholders. Thus, the spatial positions of the distractors, but not the targets, were known in advance. The spatial positions of the targets were randomly determined on each trial, with the restriction that there will be no overlap between the positions of the placeholders and the positions of the targets. All placeholders had a radius of approximately 1° of visual angle, and had thickness of about 0.02° of visual angle, and the distractors were positioned in the center of the placeholder. Participants were told that the placeholders will appear in fixed positions throughout all of the cue present blocks, that only the distractors will appear within the placeholders, and that the targets will never appear within the placeholders. Moreover, participants were highly encouraged to use the location cue in order to maximize their performance in the filtering trials. Ten practice trials were given before each Cue condition.

Accuracy (i.e., Hits plus Correct Rejection rates) analysis showed that the order of the blocks (i.e., cue absent blocks first or cue present blocks first) did not interact with the Cue × Condition interaction in any of the six experiments. Therefore, we analyzed the data across the order of the blocks in all experiments. We also analyzed the results in all six experiments using K estimate as a dependent measure by applying standard formula (Cowan, 2001; Pashler, 1988). The formula is $K = S \times (H - F)$, where K is the memory capacity, S is the size of the memory array, H is the observed hit rate, and F is the false alarm rate. Following Shipstead, Lindsey, Marshall, and Engle (2014), on filtering conditions the number of relevant items was used as the size of the memory array (i.e., S). The K analysis showed the same results regarding the filtering cost (see Supplementary Material). In addition, we analyzed the results in all six experiments using A' (i.e., Hit rate minus False Alarm rate; Macmillan & Creelman, 1996; Pollack & Norman, 1964). The A' analysis showed the same results regarding the filtering cost in all six experiments (see Supplementary Material).

Visual Working Memory Capacity Estimates: Change-detection task. Before the filtering change-detection task participants performed a change-detection task with colored squares (e.g., Fukuda & Vogel, 2009; Luck & Vogel, 1997; Vogel et al., 2001) in order to estimate their visual WM capacity. Participants were presented with arrays of four or eight colored squares for 150 ms (memory array); the squares then disappeared for 900 ms (retention interval), and then a colored square (a test probe) appeared at one of the previous locations of the items in the memory array. Participants made an unspeeded response via button press ("Z" and "/" on the computer keyboard, counterbalanced across participants) to indicate whether the color of the test probe was the same as the color of the square that appeared at the

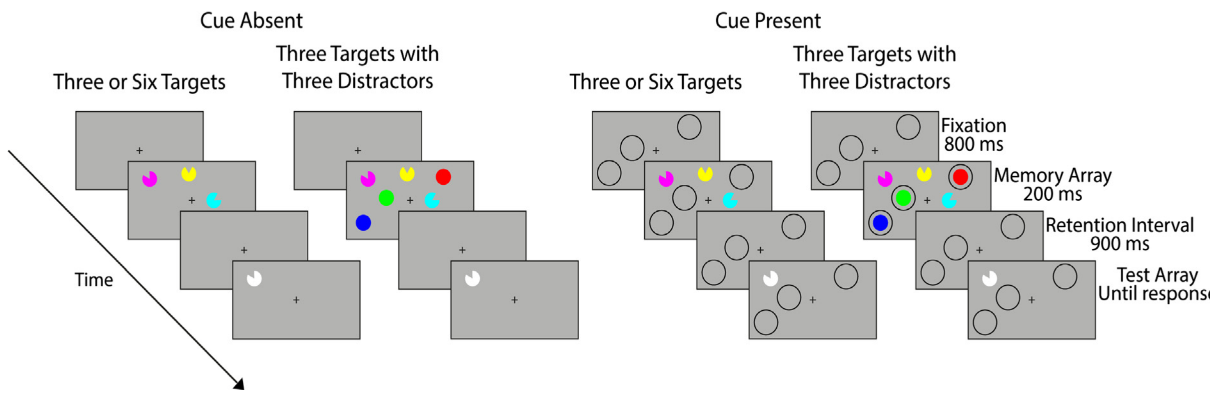

Fig. 1. Example for a non-filtering (i.e., three targets or six targets) and a filtering trial (i.e., three targets along with three distractors) in the cue absent and cue present blocks in Experiment 1. Pacmens served as targets and colored circles served as distractors. To cue the locations of the distractors, on cue present blocks distractors appeared within black frames (i.e., placeholders). The placeholders appeared in fixed locations in all three conditions of the cue present blocks (i.e., three targets, six targets, or three targets with three distractors). The spatial positions of the targets were randomly determined on each trial, with the restriction that there will be no overlap between the positions of the placeholders and the positions of the targets. For cue absent blocks, the spatial positions of the targets were randomly determined for all three conditions, and the spatial positions of the distractors were randomly determined for filtering trials.

same location in the memory array (with equal probability for same and different test probes). Sixty trials were presented for each array size in one intermixed block. Each color square subtended approximately 1.24° × 1.24° of visual angle and was randomly positioned within a 16.6° × 16.6° region on the video monitor upon a grey background with the constrain that the minimal distance between each two stimuli was at least 2° of visual angle (center to center). The color of each square was randomly selected (without replacement) from a set of nine colors: black, blue, brown, cyan, green, orange, pink, red, and yellow. On changed trials the changed item was replaced with a color not presented in the memory array. The accuracy for each individual was transformed into a K estimate (separately for each set size) following standard formula as used in the filtering change-detection task. These two values were averaged to form a single visual WM capacity estimate (K).

2.2. Results and discussion

Filtering change-detection task. The data in all six experiments was aggregated and organized before the statistical analysis using *prepdat* – An R package for preparing experimental data for statistical analysis (Allon & Luria, 2016). Trials with RTs lower than 100 ms or higher than 2000 ms were removed from further analysis resulting in excluding 2.43% of the trials. A repeated measures analysis of variance (ANOVA) with Cue (cue absent blocks, cue present blocks) and Condition (three targets- 3T, six targets- 6T, three targets with three distractors- 3T3D) as within-subjects independent variables on accuracy rate as a dependent variable showed a main effect of Condition ($F(2,30) = 102.41$, MSE = 0.27070, $p < 0.001$, $\eta_p^2 = 0.87$). Planned comparisons showed that accuracy for the 3T3D condition was lower than accuracy for the 3T condition ($F(1,15) = 25.60$, MSE = 0.003217, $p < 0.001$, $\eta_p^2 = 0.63$), indicating a filtering cost, and higher than accuracy for the 6T condition ($F(1,15) = 146.57$, MSE = 0.001340, $p < 0.001$, $\eta_p^2 = 0.90$), indicating a filtering gain. There was no Cue × Condition interaction ($F(2,30) = 1.18$, MSE = 0.00228, $p = 0.31$; see Fig. 2). Planned comparisons showed that the filtering cost was similar in cue present blocks and cue absent blocks ($F < 1$), suggesting that the location cue did not improve filtering cost in visual WM. There were no differences in the 3T and 6T conditions between the cue present blocks and cue absent blocks ($F(1,15) = 1.74$, MSE = 0.000885, $p = 0.20$; $F(1,15) = 2.47$, MSE = 0.003575, $p = 0.13$; in the 3T and 6T conditions, respectively).

Surprisingly, the results from Experiment 1 showed that participants demonstrated similar filtering costs on location cue absent blocks and location cue present blocks. Although the location cue was sustained throughout the entire experiment, clearly indicating the locations of the distractors, and even though these positions remained constant, thus making the locations perfectly predictable, it was not sufficient to improve the filtering costs in visual WM. Therefore, in the next experiment we added another cue to see whether the combination of two cues would be sufficient to reduce the filtering cost.

3. Experimemt 2

In Experiment 2 we sought to test whether informing participants that the upcoming trial is a filtering trial (i.e., targets along with distractors) in addition to cuing the distractors' locations, will succeed in preventing the distractors form entering visual WM, thus reducing the filtering cost.

3.1. Method

Participants. Sixteen students from Tel-Aviv University (10 females, $M = 24$ years, $SD = 1.65$) participated in a 45 minuets experimental session for either course credit or payment of 30 shekels (about 8$).

Apparatus. The same apparatus was used as in Experiment 1.

3.1.1. Stimuli and procedure

Filtering change-detection task. Participants preformed a change detection task similar to the one in Experiment 1 except for the following. In addition to the fixed location cue that was as in Experiment 1, in order to cue the appearance of the upcoming filtering trial on cue present blocks, the fixation cross that appeared before the memory array briefly changed its color from black (200 ms) to white (400 ms; i.e., filtering warning cue), and then to black again (200 ms; see Fig. 3). Thus, participants were cued about the appearance of the upcoming filtering trial and knew in advanced were the distractors, but not the targets, will appear. As in Experiment 1, participants were told that the placeholders will appear in fixed positions throughout all of the cue present blocks, that only the distractors will appear within the placeholders, and that the targets will never appear within the placeholders. Participants were highly encouraged to use both cues

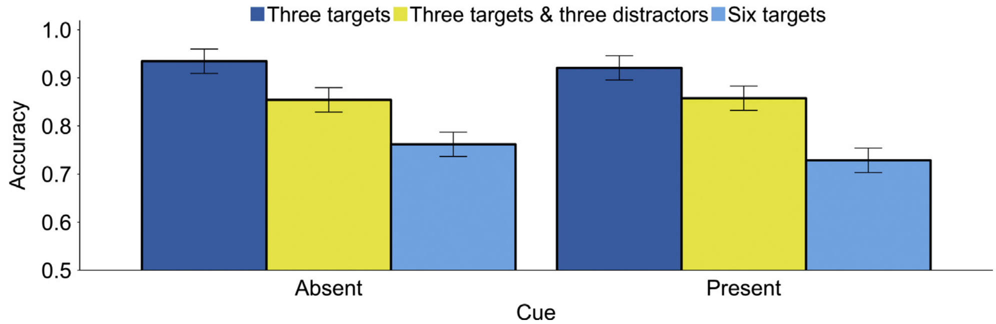

Fig. 2. Results from Experiment 1. Accuracy as a function of the Fixed Location Cue and Condition. Error bars represent the 95% confidence intervals according to Loftus and Masson (1994).

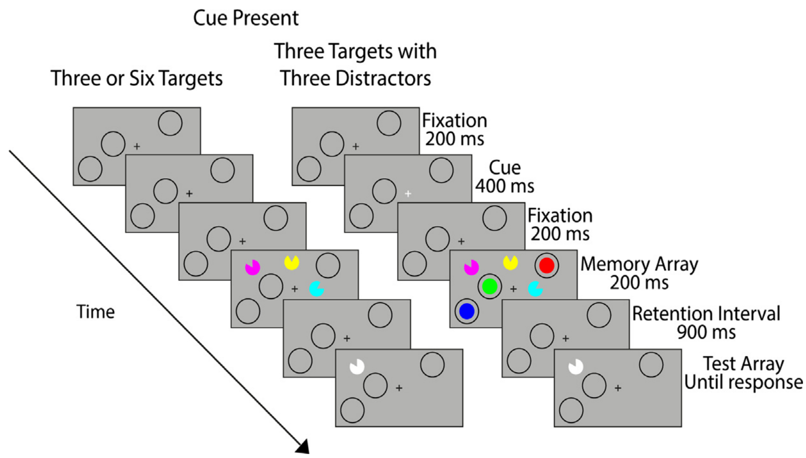

Fig. 3. Example for a non-filtering (i.e., three targets or six targets) and a filtering trial (i.e., three targets along with three distractors) in the cue present blocks in Experiment 2. In addition to the fixed location cue that was as in Experiment 1, on filtering trials the fixation before the memory array briefly changed its color from black (200 ms) to white (400 ms) and then to black again (200 ms). Cue absent blocks were as in Experiment 1.

(i.e., the white fixation cross and the placeholders) in order to maximize their performance in the filtering trials.

Visual Working Memory Capacity Estimates: Change-detection task. Participants preformed the change-detection task as in Experiment 1.

3.2. Results and discussion

Filtering change-detection task. Trials with RTs lower than 100 ms or higher than 2000 ms were removed from further analysis resulting in excluding 2.44% of the trials. A repeated measures ANOVA was conducted as in Experiment 1. The ANOVA showed a main effect of Condition ($F(2,30) = 171.79$, MSE = 0.00184, $p < 0.001$, $\eta_p^2 = 0.91$). However, this time there was a Cue × Condition interaction ($F(2,30) = 6.55$, MSE = 0.00310, $p = 0.004$, $\eta_p^2 = 0.30$; see Fig. 4). Importantly, planned comparisons showed that the filtering cost was lower for cue present blocks relative to cue absent blocks ($F(1,15) = 6.86$, MSE = 0.002515, $p = 0.01$, $\eta_p^2 = 0.31$), suggesting that participants needed both the filtering warning cue and the location cue to improve their filtering performance. In addition, in cue absent blocks, performance was better in the 3T condition relative to the 3T3D condition ($F(1,15) = 52.08$, MSE = 0.001897, $p < 0.001$, $\eta_p^2 = 0.77$). This difference was also significant in the cue present blocks ($F(1,15) = 5.47$, MSE = 0.003016, $p = 0.03$, $\eta_p^2 = 0.26$), thus indicating a residual filtering cost in both cue absent and cue present blocks. There were no differences in the 3T and 6T conditions between the cue present and cue absent blocks ($F < 1$; $F(1,15) = 2.53$, MSE = 0.004938, $p = 0.13$, $\eta_p^2 = 0.14$; in the 3T and 6T conditions, respectively).

The results from Experiment 2 showed reduced filtering costs in visual WM when participants knew that distractors are about to appear and where they appear. This is in contrast to the findings from Experiment 1 in which the location cue alone did not improve the filtering cost. We argue these findings along with the results from Experiment 1 support the existence of a short-lived compensation mechanism for distractor suppression.

The results from Experiment 1 are inconsistent with previous studies (e.g., Munneke et al., 2008; Ruff & Driver, 2006) in which a cue about the location of the distractor was found to reduce distractor interference and improve search performance for a single target. However, note that there are a few differences between the task used in Experiment 1 and the tasks used in these previous studies. First, in Experiment 1 the task demand was to remember multiple targets as opposed to searching or identifying a single target in previous studies. Most importantly, in Experiment 1 the location cue was continuously visible at the same position throughout the cue present trials, whereas in previous studies the cue for the distractor pointed to a different location on each trial (e.g., Munneke et al., 2008).

One possible explanation for the results in Experiment 1 is that marking the distractors positions was not salient enough to suppress their processing. However, this seems unlikely since these positions were clearly visible and did not change throughout the experiment. Another possible explanation is that in the context of visual WM, filtering settings can only be held for a limited amount of time: In both Experiment 1 and Experiment 2, the placeholders which served as the location cue were present at fixed positions in each of the cue present trials, even when no distractors

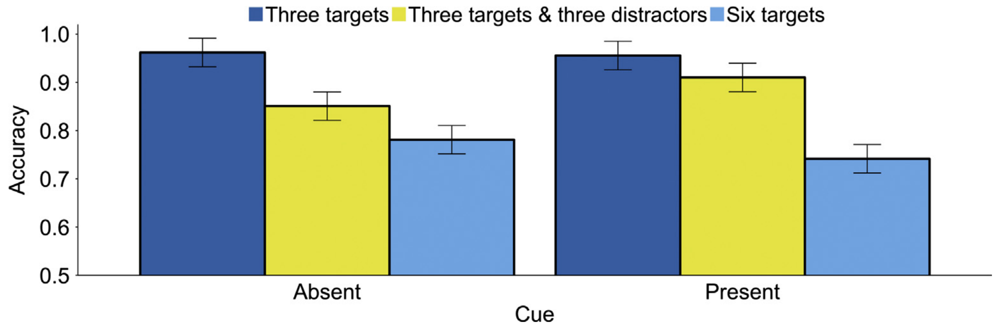

Fig. 4. Results from Experiment 2. Accuracy as a function of the Warning Cue with Fixed Location Cue and Condition. Error bars represent the 95% confidence intervals according to Loftus and Masson (1994).

appeared (i.e., the 3T and 6T conditions). This means that in Experiment 1 for filtering to be most effective, the filtering settings which contained locations of the distractors marked by the placeholders had to be actively suppressed throughout the whole cue present trials (i.e., filtering and non-filtering trials). In other words, participants were required to constantly filter out the distractors' positions, because a filtering trial was unpredictable. However, in Experiment 2 the appearance of the filtering trial was predicted by the warning cue, enabling participants to use the location cue to suppress the distractors only on filtering trials. Accordingly, we propose one can use the location cue to suppress the distractors only for a limited short duration. This makes filtering the distractors throughout the entire cue present trials impossible, which is why the fixed location cue alone in Experiment 1 was not sufficient to reduce the filtering cost. In Experiment 2 the warning cue enabled the filtering settings of the distractors to be active for a short duration, resulting in a reduced filtering cost.

Note that the filtering warning cue in Experiment 2 was confounded with a temporal cue. Namely, the Stimulus Onset Asynchrony (SOA) between the warning cue and the memory array was always 600 ms, which made the onset of the memory array for filtering trials perfectly predictable. Therefore, it is possible that the temporal predictability of the memory array for filtering trails aide performance rather than the reactivation of the filtering setting by the warning cue. This possibility was addressed in Experiment 3.

4. Experiment 3

In Experiment 3 we sought to replicate the results found in Experiment 2 and to disentangle the warning cue from the temporal cue. To this end, in cue present filtering trials we manipulated the SOA between the warning cue and the memory array, to have a short (200 ms) and long (800 ms) intervals between the cue and the memory array. Thus, the memory array onset was no longer constant relative to the warning cue, reducing temporal predictability. Note that participants might use this interval to actively prepare for a filtering trial in a similar way the task-switching literature found that longer preparation interval is used to reduce the task switching-cost (Meiran, Chorev, & Sapir, 2000; Meiran & Daichman, 2005). However, if the cue only reactivates the filtering settings, without actively preparing for a filtering trial, then we should not expect the longer interval to further reduce the switching-cost, such that both SOAs should reduce the filtering cost relative to a cue absent condition, but to the same extent.

4.1. Method

Participants. Sixteen students from Tel-Aviv University (11 females, $M = 22.75$ years, $SD = 2.46$) participated in a 60 minuets experimental session for either course credit or payment of 40 shekels (about 10$).

Apparatus. The same apparatus was used as in Experiment 1.

4.1.1. Stimuli and procedure

Filtering change-detection task. Participants preformed a change detection task similar to the one in Experiment 2 except for the following. Participants were presented with a black fixation cross (i.e., "+") for 1000 ms before the memory array. On cue present blocks, in addition to the location cue as in Experiment 1 and Experiment 2, on filtering trials the fixation cross before the memory array briefly changed its color from black (200 ms) to white (150 ms; i.e., the filtering warning cue), and then to black again. The black fixation which followed the filtering warning cue and appeared before the memory array either appeared for 50 ms or 650 ms (randomly intermixed in cue present blocks), resulting in a short (200 ms) or long (800 ms) preparation time between the filtering warning cue and the memory array. In the cue absent blocks values of the filtering condition were randomly assigned before the analysis to "dummy variables" of the same preparation times (i.e., 200 ms or 800 ms) as in filtering trials in the cue present blocks in order to perform the subsequent repeated measures ANOVA. Two hundred and forty trials were presented for each Condition (3T, 6T, 3T3D) in 12 intermixed blocks of 60 trials each. Order of the cue present and cue absent blocks was counterbalanced between participants as in Experiment 1.

Visual Working Memory Capacity Estimates: Change-detection task. Participants preformed the change-detection task as in Experiment 1.

4.2. Results and discussion

Filtering change-detection task. Trials with RTs lower than 100 ms or higher than 2000 ms were removed from further analysis resulting in excluding 2.23% of the trials. A repeated measures ANOVA with Cue (cue absent blocks, cue present blocks) and Condition (3T, 3T3D with short SOA, 3D3T with long SOA, 6T) as within-subjects independent variables on accuracy rate as a dependent variable revealed a main effect of Condition and Cue ($F(3,45) = 66.08$, $MSE = 0.00242$, $p < 0.001$, $\eta_p^2 = 0.81$; $F(1,15) = 5.53$, $MSE = 0.00248$, $p = 0.03$, $\eta_p^2 = 0.26$; for Condition and Cue, respectively). More importantly, there was a Cue × Condition interaction ($F(3,45) = 6.69$, $MSE = 0.00152$, $p < 0.001$, $\eta_p^2 = 0.30$; see Fig. 5). Planned comparisons showed that the filtering cost (across SOAs) was lower in cue present blocks relative to cue absent blocks ($F(1,15) = 25.92$, $MSE = 0.000552$, $p < 0.001$, $\eta_p^2 = 0.63$), suggesting that the combination of the filtering warning cue and the location cue improved filtering costs in visual WM, replicating the results from Experiment 2. Furthermore, long SOA did not further reduce the filtering cost. In the cue present blocks,

Fig. 5. Results from Experiment 3. Accuracy as a function of the Warning Cue with Fixed Location Cue and Condition. Error bars represent the 95% confidence intervals according to Loftus and Masson (1994).

performance was not better in the 3T3D condition with short SOA relative to the 3T3D condition with long SOA ($F < 1$). In addition, in cue absent blocks, performance was better in the 3T condition relative to the 3T3D condition ($F(1,15) = 51.19$, MSE = 0.001414, $p < 0.001$, $\eta_p^2 = 0.77$). This difference was also significant for cue present blocks ($F(1,15) = 13.40$, MSE = 0.000745, $p = 0.0023$, $\eta_p^2 = 0.47$), indicating a residual filtering cost in both the cue absent and cue present blocks. There were no differences for the 3T and 6T conditions between the cue present and cue absent blocks ($F < 1$; $F(1,15) = 1.05$, MSE = 0.002056, $p = 0.31$, $\eta_p^2 = 0.06$; in the 3T and 6T conditions, respectively).

The results from Experiment 3 showed reduced filtering costs on cue present blocks relative to cue absent blocks, replicating the results from Experiment 2. However, longer SOA before the memory array of a filtering trial did not further reduce the filtering cost relative to a shorter SOA. Therefore, the results support the notion that the warning cue does not result in active preparation for a filtering trial.

5. Experiment 4

The distractors in Experiments 1–3 always appeared in fixed locations that were clearly marked by placeholders throughout the cue present blocks. It is possible that the fixed distractors' locations, and not the placeholders, provide the critical spatial information needed to reduce the filtering cost found in Experiments 2 and 3. Experiment 4 was similar to Experiment 2, such that the distractors appeared in fixed positions throughout the cue present blocks and a warning cue appeared before a filtering trial throughout the cue present blocks. However, unlike Experiment 2, no placeholders were presented. Therefore, the locations of the distractors were perfectly predictable throughout the cue present blocks but they were not marked by the placeholders. We hypothesized that if the placeholders, and not the fixed locations, provide the critical spatial information needed to reduce the filtering cost, then the filtering cost would not be improved when only the locations of the distractors are fixed and the placeholders are missing.

5.1. Method

Participants. Sixteen students from Tel-Aviv University (12 females, $M = 22.93$ years, $SD = 2.65$) participated in a 60 minuets experimental session for either course credit or payment of 40 shekels (about 10$).

Apparatus. The same apparatus was used as in Experiment 1.

5.1.1. Stimuli and procedure

Filtering change-detection task. Participants preformed a change detection task similar to the one in Experiment 2 except for the following. On cue present blocks the fixation cross changed its color before a filtering trial as in Experiment 2, but the distractors appeared in fixed locations without placeholders, and the targets never appeared in those locations in either of the 3T, 6T, or 3T3D conditions. On the remaining blocks the distractors appeared in random locations as in the cue absent blocks in Experiment 3. Two hundred and forty trials were presented for each condition (i.e., the 3T, 6T, 3D3T conditions) in 12 intermixed blocks of 60 trials each. Participants were told that the distractors will appear in fixed positions throughout all of the cue present blocks, and that the targets will never appear within these positions. Moreover, participants were highly encouraged to use this information and the warning cue in order to maximize their performance on filtering trials.

Visual Working Memory Capacity Estimates: Change-detection task. Participants preformed the change-detection task as in Experiment 1.

5.2. Results and discussion

Filtering change-detection task. Trials with RTs lower than 100 ms or higher than 2000 ms were removed from further analysis resulting in excluding 4.87% of the trials. A repeated measures ANOVA with Cue (cue present blocks, cue absent blocks) and Condition (3T, 3T3D, 6T) as within-subjects independent variables on accuracy rate as a dependent variable showed a main effect of Condition ($F(2,30) = 130.08$, MSE = 0.00282, $p < 0.001$, $\eta_p^2 = 0.89$). Planned comparisons showed that accuracy in the 3T3D condition was lower than accuracy for the 3T condition ($F(1,15) = 66.92$, MSE = 0.003542, $p < 0.001$, $\eta_p^2 = 0.81$), indicating a filtering cost. In addition, accuracy in the 3T3D condition was higher than accuracy in the 6T condition ($F(1,15) = 49.39$, MSE = 0.002736, $p < 0.001$, $\eta_p^2 = 0.76$), indicating a filtering gain. Most importantly, there was no Cue × Condition interaction ($F < 1$; see Fig. 6). Planned comparisons showed that the filtering cost in the cue present blocks was similar to the filtering cost in the cue absent blocks ($F < 1$). In addition, there were no differences in the 3T and 6T conditions between the cue present and cue absent blocks ($Fs < 1$).

The results from Experiment 4 showed that a combination of a filtering warning cue and fixed locations for the distractors without the presence of placeholders were not sufficient to improve filtering costs. Potentially, participants could have held these locations in memory and suppress these locations as soon as they saw the filtering warning cue. However, the results of the current experiment demonstrate that the filtering warning cue must have explicit spatial information provided by the location cue in order to activate the short-lived filtering settings.

6. Experiment 5

In Experiment 5 we sought to replicate the effect of the filtering cost reduction, this time in a within experiment design. In the experiments thus far, we manipulated the presence of the location

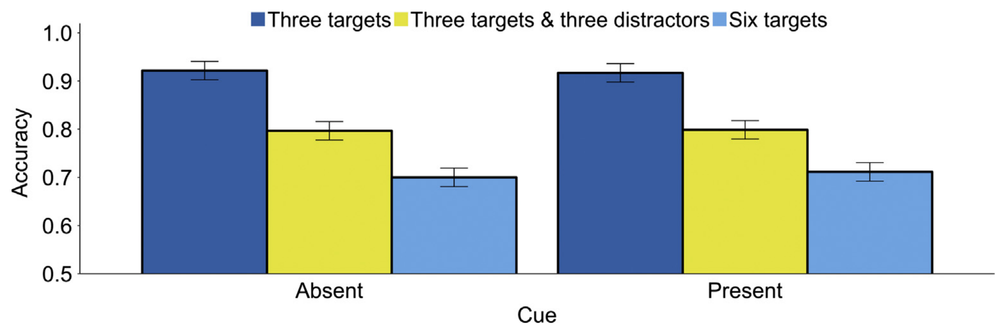

Fig. 6. Results from Experiment 4. Accuracy as a function of the Warning Cue with Fixed Locations and Condition. Error bars represent the 95% confidence intervals according to (Loftus & Masson, 1994).

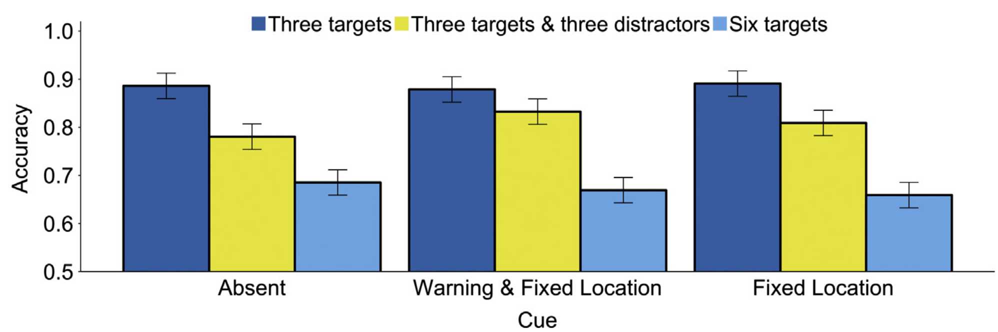

Fig. 7. Results from Experiment 5. Accuracy as a function of Cue and Condition. Error bars represent the 95% confidence intervals according to Loftus and Masson (1994).

cue or the presence of the location cue along with the warning cue in separate experiments. However, in Experiment 5 in the cue present blocks we used the location cue or the location cue along with the warning cue in the same experiment, and compared them to cue absent blocks. We expected to find a reduction of the filtering cost relative to cue absent blocks when both cues (i.e., combined cues) were presented together but not when the location cue was presented alone.

6.1. Method

Participants. Sixteen students from Tel-Aviv University (10 females, $M = 23.56$ years, $SD = 3.49$) participated in a 60 minuets experimental session for payment of 40 shekels (about 10$).

Apparatus. The same apparatus was used as in Experiment 1.

6.1.1. Stimuli and procedure

Filtering change-detection task. Participants preformed a change detection task similar to Experiment 1 except for the following. On half of the cue present blocks, before a filtering trial, the fixation briefly changed its color from black to white and to black again as in Experiment 2. Thus, on half of the cue present blocks participants had only the location cue of the placeholders marking the fixed locations of the distractors, and in the remaining cue present blocks participants had both the filtering warning cue and the location cue as in Experiment 2. Participants performed 12 blocks of 60 trials each. Half of the blocks were cue present blocks and the remaining blocks were cue absent blocks. Order of the blocks was counterbalanced as in Experiment 1. On cue present blocks, half of the participants alternately started with a combined cue block and then did a location cue block and so on, and the remaining half started with a location cue block and then did a combined cue block and so on. Participants were informed about the cues as in Experiment 1 and Experiment 2 and were encouraged to use them to improve filtering performance.

Visual Working Memory Capacity Estimates: Change-detection task. Participants preformed the change-detection task as in Experiment 1.

6.2. Results and discussion

Trials with RTs lower than 100 ms or higher than 2000 ms were removed from further analysis resulting in excluding 1.77% of the trials. A repeated measures ANOVA with Cue (absent, warning and fixed location, location) and Condition (3T, 6T, 3T3D) as within-subjects independent variables on accuracy rate as a dependent variable showed a main effect of Condition ($F(2,30) = 139.85$, $MSE = 0.00403$, $p < 0.001$, $\eta_p^2 = 0.90$). Most importantly, there was a Cue × Condition interaction ($F(4,60) = 2.63$, $MSE = 0.00249$, $p = 0.04$, $\eta_p^2 = 0.14$; see Fig. 7). Planned comparisons showed that the filtering cost in the warning and fixed location cue present blocks was smaller relative to cue absent blocks ($F(1,15) = 8.97$, $MSE = 0.001574$, $p = 0.009$, $\eta_p^2 = 0.37$), replicating the results from Experiment 2 and Experiment 3. In addition, the filtering cost in the location cue present blocks was similar to the filtering cost in the cue absent blocks ($F(1,15) = 1.24$, $MSE = 0.001806$, $p = 0.28$, $\eta_p^2 = 0.07$), replicating the results form Experiment 1. The filtering cost in the warning and fixed location cue present blocks was similar to the filtering cost in the location cue present blocks ($F(1,15) = 2.40$, $MSE = 0.002122$, $p = 0.14$, $\eta_p^2 = 0.13$). As in the previous experiments, there was a difference between the 3T and 3T3D conditions in the cue absent, warning and fixed location cue, and the location cue conditions ($F(1,15) = 40.20$, $MSE = 0.002218$, $p < 0.001$, $\eta_p^2 = 0.72$; $F(1,15) = 7.16$, $MSE = 0.002086$, $p = 0.012$, $\eta_p^2 = 0.35$; $F(1,15) = 11.68$, $MSE = 0.004584$, $p = 0.003$; for the cue absent, warning and fixed location cue, and the location cue conditions, respectively).

In accordance with our hypothesis, the results from Experiment 5 showed a reduced filtering cost on combined cues present blocks (i.e., warning and location cue) relative to cue absent blocks. For

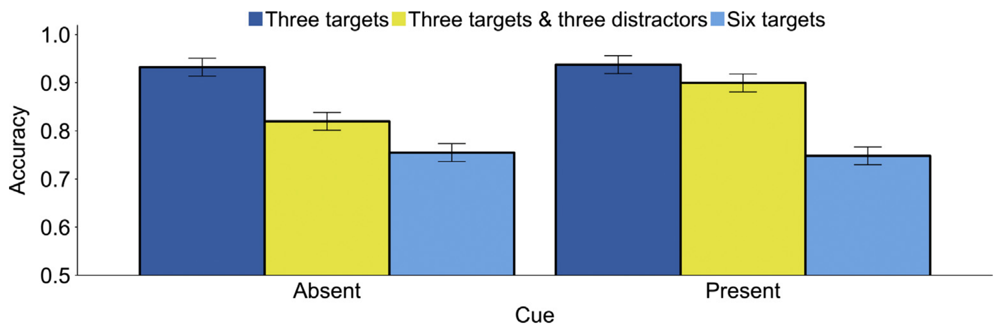

Fig. 8. Results from Experiment 6. Accuracy as a function of the Variable Location Cue and Condition. Error bars represent the 95% confidence intervals according to Loftus and Masson (1994).

location cue present blocks, the filtering cost was similar to the filtering cost in the cue absent blocks. These results replicate the results from Experiments 1–3 in a within experimental design.

7. Experiment 6

The results thus far support the idea according to which the spatial distractor filtering settings are short-lived. The warning cue together with the fixed location cue enabled the compensation mechanisms to be active for a short duration, because the filtering settings were reactivated in filtering trials, which resulted in a reduced filtering cost. However, using only fixed locations without a warning cue for the filtering trial did not result in a reduction of the filtering cost, presumably because it was not possible to hold onto the filtering settings throughout the experiment. This explanation makes the following counter intuitive prediction: while using fixed placeholders did not reduce the filtering cost, changing the positions of the distractors every trial should reduce the filtering cost. The reason is that changing the distractors positions every trial should reactivate the filtering settings, because different locations would have to be suppressed on each trial. To support this prediction and provide further support for these short-lived compensation mechanisms, in Experiment 6 we implemented the location cue alone (without a warning cue), but this time varied the location of the placeholders on each trial.

7.1. Method

Participants. Sixteen students from Tel-Aviv University (14 females, $M = 22.37$ years, $SD = 1.86$) participated in a 45 minuets experimental session for either course credit or payment of 30 shekels (about 8$).

Apparatus. The same apparatus was used as in Experiment 1.

7.1.1. Stimuli and procedure

Filtering change-detection task. Participants preformed a change-detection task similar to the one in Experiment 1 except for the following. Participants performed 24 blocks of 30 trials each, with all of the three conditions (i.e., the 3T, 3T3D, and 6T conditions) intermixed within the blocks. On cue present blocks, the colored circles appeared within placeholders in the form of black frames. However, unlike in Experiment 1 in which the placeholders appeared in fixed locations throughout of the cue present blocks, this time the placeholders changed their locations on *each trial* in the cue present blocks. Note that the targets never appeared within the placeholders. Thus, the spatial positions of the distractors, but not the targets, were clearly marked from the beginning of each trial. There were 120 trials in each of the Cue (cue present, cue absent) × Condition (3T, 3T3D, 6T) conditions. Participants were told that the placeholders will appear in random positions on each trial throughout all of the cue present blocks, that only the distractors will appear within the placeholders, and that the targets will never appear within the placeholders. Moreover, participants were highly encouraged to use the location cue in order to maximize their performance in the filtering trials.

Visual Working Memory Capacity Estimates: Change-detection task. Participants preformed the change-detection task as in Experiment 1.

7.2. Results and discussion

Filtering change-detection task. Trials with RTs lower than 100 ms or higher than 2000 ms were excluded from further analysis resulting in excluding 3.31% of the trials. A repeated measures ANOVA was conducted as in Experiment 1. The ANOVA revealed a main effect of Condition ($F(2,30) = 95.57$, MSE = 0.00285, $p < 0.001$, $\eta_p^2 = 0.86$). Most importantly, there was a Cue × Condition interaction ($F(2,30) = 14.20$, MSE = 0.00123, $p < 0.001$, $\eta_p^2 = 0.48$; see Fig. 8). Planned comparisons showed that the filtering cost was lower in cue present blocks relative to cue absent blocks ($F(1,15) = 20.93$, MSE = 0.000784, $p < 0.001$, $\eta_p^2 = 0.58$), suggesting that using a variable location cue was sufficient to reduce filtering cost. In addition, in cue absent blocks, performance was better in the 3T condition relative to the 3T3D condition ($F(1,15) = 61.48$, MSE = 0.001647, $p < 0.001$, $\eta_p^2 = 0.80$). This difference was also present in the cue present blocks ($F(1,15) = 14.78$, MSE = 0.000784, $p = 0.001$, $\eta_p^2 = 0.49$), thus indicating a residual filtering cost in both cue absent and cue present blocks. There was no difference between the cue present and cue absent blocks in the 3T and 6T conditions ($Fs < 1$).

In accordance with our hypothesis, the results of Experiment 6 showed reduced filtering costs when using a variable location cue in which placeholders marking the positions of the distractors changed location every trial. These findings support a short-lived compensation mechanism for distractor suppression. Despite using location cues, changing their positions on each trial activated the filtering settings more frequently, which enabled to reduce the filtering cost.

8. WM capacity and filtering costs

Previous findings have shown that high visual WM capacity individuals are better at filtering irrelevant items relative to low visual WM capacity individuals (e.g., Vogel et al., 2005). Namely, high-capacity individuals are better at constraining what is encoded within the WM workspace; by successfully filtering out irrelevant information and maintaining only task relevant information. Low-capacity individuals, on the other hand, have lower filtering ability, and therefore their memory capacity gets filled with irrelevant information, limiting their ability to process task

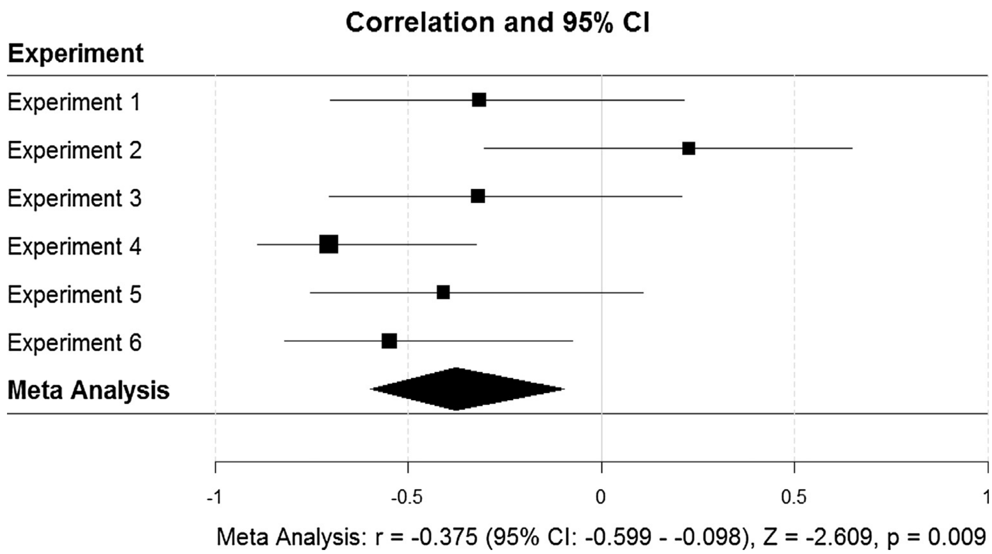

Fig. 9. Meta-analysis of the correlations in all six experiments between WM capacity and filtering cost in the cue absent blocks. The analysis was carried out using the Comprehensive Meta-Analysis software (Borenstein, Hedges, Higgins, & Rothstein, 2014), and assumed random effects models. The forest plot was created using the *forestplot* R package (Gordon & Lumley, 2017). Each line in the plot represents a single experiment in the study. The squares represent the correlation in each study and the horizontal lines represent the 95% confidence interval (CI). The square size represents the relative weights assign to that experiment in the meta-analysis. The bottom line (i.e., the Meta Analysis line) represents the combined results of the six experiments. The black diamond represents the weighted average correlation, and the width of the diamond represents the 95% CI of the combined correlation.

relevant information. We performed a meta-analysis (see Fig. 9) on the six experiments to measure the relationship between WM capacity and filtering cost in the cue absent blocks and to see whether high-capacity individuals will have lower filtering costs relative to low-capacity individuals, thus corroborating previous findings. The combined correlation was $r = -0.375$, and 95% confidence interval were between -0.599 and -0.098, $p = 0.009$. Note that this correlation is weaker when compared to previous studies that used a neural marker as an index for the individual filtering cost (e.g., $r = 0.62$,[1] $p < 0.001$; Experiment 2, Vogel et al., 2005). Presumably, this neural marker is more sensitive to individual differences in filtering ability than the accuracy measure used in the current study.

The meta-analysis allowed us to examine the filtering cost at the aggregated level, incorporating the effect from all six experiments. Indeed, when looking at this correlation within each experiment, it was not significant in most cases. Another possible analysis is to measure this correlation for all subjects together ($N = 96$). This analysis yielded a similar result ($r = -0.34$, $p < 0.001$; See Fig. S1 in Supplementary Material).

This negative correlation demonstrates that high-capacity individuals had lower filtering costs to begin with, suggesting that they have less room to improve when relying on the filtering cues relative to low-capacity individuals. If, indeed, low-capacity individuals were able to benefit more from the cues than high-capacity individuals, we should expect visual WM capacity to correlate with filtering cost improvement between the cue absent and cue present blocks. However, this was not the case: the correlation between the individual WM capacity and the filtering cost improvement (defined as filtering cost in the cue absent blocks minus filtering cost in the combined cues blocks, calculated only across Experiments 2, 3, 5 and 6 in which the cues improved performance) was not significant ($r = -0.05$, $p = 0.63$). This suggests that although the initial filtering mechanism is related to the individual visual WM capacity, the ability to reduce filtering cost by using the cues implemented in the current study does not depend on the individual visual WM capacity.

[1] In Vogel et al. (2005) the correlation between filtering ability (or filtering efficiency as Vogel et al. termed it) and visual WM capacity was positive because filtering ability was calculated based on the CDA amplitude for the three conditions (two targets, two targets with two distractors, four targets), which resulted in a positive filtering ability score ranging between 0 and 1 for each participant. Therefore, the correlation computed between this filtering ability score and visual WM capacity resulted in a positive correlation.

9. General discussion

The purpose of the current study was to investigate whether cues that mark irrelevant information can help compensate for poor filtering of irrelevant information entering the limited visual WM capacity workspace. In six experiments, participants preformed a change detection task in which three targets, six targets, or three targets along with three distractors were presented in the memory array. To cue the distractors, participants were given either a fixed location cue, marking the fixed locations of the distractors (Experiment 1 and Experiment 5), a filtering warning cue, singling the appearance of the upcoming distractors along with the targets (Experiment 4), a combination of a fixed location cue and a filtering warning cue (Experiment 2, Experiment 3, and Experiment 5), or a variable location cue, marking the locations of the distractors that changed from trial to trial (Experiment 6). The results revealed that the filtering cost was not reduced relative to a cue absent condition when a fixed location cue was used (Experiment 1 and Experiment 5). However, using a combination of the fixed location cue and a filtering warning cue did reduce the filtering cost (Experiment 2 and Experiment 5). Additionally, a longer interval between the filtering warning cue and the memory array did not result in actively preparing for a filtering trial (Experiment 3). Moreover, this filtering cost improvement was not due to the fixed positions of the distractors (Experiment 4). Lastly, a variable location cue was able to reduce the filtering cost (Experiment 6). As for individual differences in visual WM capacity, we found that high-capacity individuals were better at filtering out irrelevant items relative to low-capacity individuals when no cues were given. We now turn to discuss the possible mechanisms responsible for these findings.

We argue that these findings support the idea that spatial filtering settings in the context of visual WM can only be held for a short limited amount of time, similar to the transient component suggested by Nakayama and Mackeben (1989). Thus, to compensate for poor filtering of irrelevant information from entering visual WM, these filtering settings need to be reactivated. One possible explanation for the transient nature of these mechanisms is that we are not wired to ignore the same positions for a long time. Remnants of ontogenetic history may also influence the attentional processing priorities of the attentional system by aiming the system to respond to potential stimuli in the environment that may impose an immediate danger which demands a quick change in behavior (Avital-Cohen & Tsal, 2016). Although these processing priorities were very essential to keep a person's life a long time ago, studies have shown that they probably still have an effect on behavior (e.g., New, Cosmides, & Tooby, 2007; Öhman, Flykt, & Esteves, 2001). Thus, while focusing on the current task is highly important, one also needs to monitor the environment for possible relevant changes that might demand adjustment of ongoing behavior.

Nonetheless, when the fixed location cue was combined with a filtering warning cue, participants were able to use the fixed location cue to enhance suppression of the distractors only on filtering trials. This enabled the compensation mechanisms to be active for a short duration, because the filtering settings were reactivated in filtering trials, which resulted in a reduced filtering cost. When the location cue varied positions on each trial, it reactivated the filtering template, because different locations were needed to be suppressed on each trial, which also resulted in a reduced filtering cost.

Our findings corroborates previous studies (Arita et al., 2012; Beck & Hollingworth, 2015; Munneke et al., 2008; Munneke et al., 2011; Ruff & Driver, 2006; Watson & Humphreys, 1997), in which a distractor cue in a visual search and target identification tasks improved search durations, suggesting that a cue about the distractors can help modulate attention to filter out irrelevant items. These findings were taken to support an inhibitory attentional mechanism that can suppress expected distractor locations in a top-down manner, thus helping to optimize filtering of irrelevant information and select relevant information for further processing (Munneke et al., 2008; Watson & Humphreys, 1997). Note that in these studies a single cue about the location of the distractor or distractors was sufficient to improve target performance. A possible explanation for the discrepancy between these studies (e.g., Munneke et al., 2008) and the current one is that in Munneke et al. the cue for the distractor pointed to different locations on each trial, which resembles the design of Experiment 6 in the current study in which the location cue also varied from trial to trial. Thus, it might be that in these studies, like in Experiment 6 in the current study, the compensation mechanisms were reactivated because of the variable location cue, which in turn enabled better filtering of the distractors. Therefore, we suggest the results of previous studies (e.g., Munneke et al., 2008; Munneke et al., 2011; Van der Stigchel & Theeuwes, 2005; Van der Stigchel et al., 2006; Watson & Humphreys, 1997) together with the results of the current study provide further support for the existence of short-lived compensation mechanisms for distractor suppression. However, the task used in the current study (change-detection task) is different from tasks used in previous studies (visual search and targets identification tasks). Hence, future research should establish whether the mechanism suggested in the current study and the one suggested in previous studies are actually the same or different mechanisms.

The ability of filtering task irrelevant information has been studied for decades (for a review see Ruz & Lupiáñez, 2002). Studies used various paradigms and focused on the conditions under which this ability fails (e.g., Stroop task: MacLeod, 1991; Stroop, 1935; Flanker task: Eriksen & Eriksen, 1974; Attentional blink: Raymond, Shapiro, & Arnell, 1992; Simon effects: Simon, 1990). The findings of the current study - that the spatial filtering setting of the distractors are short-lived and that the filtering settings need to be reactivated in order to improve performance - have great importance for future studies of filtering ability in various settings and paradigms. In addition, the findings of the current study have importance for developing ways to improve performance in everyday life activities that require filtering of irrelevant information.

In principle, filtering irrelevant information can be achieved by reinforcing target processing or suppressing distractor processing, and previous studies using neural markers suggested these rely on different processes with distinct neural signatures (e.g., Gaspar & McDonald, 2014; Gaspar et al., 2016; Jannati, Gaspar, & McDonald, 2013; Sawaki, Geng, & Luck, 2012; Sawaki & Luck, 2010). Although we do not have direct supporting evidence for one of these options, we think it is more likely that the filtering cost reduction in the current study resulted from enhancement of distractor suppression processes rather than enhancement of target related processes. If target processing rather than distractor suppression was enhanced, then in Experiment 6 in which the placeholders changed location on each trial, we should have expected to observe this enhancement also in target only trials (i.e., the three targets and six targets conditions), when comparing cue present vs. cue absent blocks. However, the results showed that performance for target only conditions was similar in both the cue present and cue absent blocks. Therefore, we think the results of the current study are not in favor of target enhancement.

Another option is that the filtering cost reduction in the current study was due to allocating attention over smaller portions of the display that included possible targets locations rather than due to active suppression of the distractors (Lahav, Makovski, & Tsal, 2012). However, if the location cue resulted in denser distribution of attention, then the filtering cost should have been reduced already in Experiment 1 in which only the location cue was used. Furthermore, the location cue should have resulted in improved performance in the three and six targets conditions relative to these conditions in the cue absent blocks. Yet, the results of the current study do not support this prediction. Therefore, overall we think the results of the current study support an account of distractors suppression.

Our findings are also related to the distinction between reactive and proactive control mechanisms (e.g., Geng, 2014; Sawaki & Luck, 2010, 2011; Sawaki et al., 2012). According to Geng (2014), a proactive control mechanism is intended to prevent attention from being allocated to distractors in the first place. Such mechanism can be activated when distractors' features are known in advance (e.g., when one knows when distractors are going to appear). However, the capture of attention by distractors is inevitable because one does not always have sufficient information for completely preventing attention to be allocated to distractors. In these situations, the distractors would be reactively suppressed after disengaging attention from them. Therefore, it is possible that in the current study when the fixed location cue was employed alone, it activated a proactive control mechanism, but since the cue did not provide enough information about the distractors (i.e., when distractors are about to appear), it failed and the distractors had to be reactively suppressed, resulting in filtering costs. When the fixed location cue was combined with the filtering warning cue, the proactive control mechanism had sufficient information about the distractors, which resulted in improved filtering performance. In conclusion, our findings demonstrate that cues about the distractors can result in better filtering of irrelevant information from entering visual WM, and that spatial filtering settings in the context of visual WM can only be held for a limited amount of time.

Acknowledgements

This research was supported by The Israel Science Foundation Grant No. 1696-13 awarded to Roy Luria.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2017.03.020.

References

Allon, A. S., & Luria, R. (2016). prepdat- An R package for preparing experimental data for statistical analysis. *Journal of Open Research Software, 4*(1), e43. http://dx.doi.org/10.5334/jors.134.

Anderson, B. A., Laurent, P. A., & Yantis, S. (2011). Value-driven attentional capture. *Proceedings of the National Academy of Sciences, 108*(25), 10367–10371. http://dx.doi.org/10.1073/pnas.1104047108.

Arita, J. T., Carlisle, N. B., & Woodman, G. F. (2012). Templates for rejection: Configuring attention to ignore task-irrelevant features. *Journal of Experimental Psychology: Human Perception and Performance, 38*(3), 580–584. http://dx.doi.org/10.1037/a0027885.

Avital-Cohen, R., & Tsal, Y. (2016). Top-down processes override bottom-up interference in the flanker task. *Psychological Science, 27*(5), 651–658. http://dx.doi.org/10.1177/0956797616631737.

Awh, E., & Vogel, E. K. (2008). The bouncer in the brain. *Nature Neuroscience, 11*(1), 5–6. http://dx.doi.org/10.1038/nn0108-5.

Beck, V. M., & Hollingworth, A. (2015). Evidence for negative feature guidance in visual search is explained by spatial recoding. *Journal of Experimental Psychology: Human Perception and Performance, 41*(5), 1190–1196. http://dx.doi.org/10.1037/xhp0000109.

Borenstein, M., Hedges, L., Higgins, J., & Rothstein, H. (2014). Comprehensive meta-analysis (version 3.3.070). Biostat <https://www.meta-analysis.com/>.

Cowan, N. (2001). Metatheory of storage capacity limits. *Behavioral and Brain Sciences, 24*(01), 154–176.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 16*(1), 143–149.

Folk, C. L., Leber, A. B., & Egeth, H. E. (2002). Made you blink! Contingent attentional capture produces a spatial blink. *Perception & Psychophysics, 64*(5), 741–753.

Folk, C. L., Leber, A. B., & Egeth, H. E. (2008). Top-down control settings and the attentional blink: Evidence for nonspatial contingent capture. *Visual Cognition, 16*(5), 616–642. http://dx.doi.org/10.1080/13506280601134018.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 18*(4), 1030.

Folk, C. L., Remington, R. W., & Wright, J. H. (1994). The structure of attentional control: Contingent attentional capture by apparent motion, abrupt onset, and color. *Journal of Experimental Psychology: Human Perception and Performance, 20*(2), 317.

Fukuda, K., & Vogel, E. K. (2009). Human variation in overriding attentional capture. *Journal of Neuroscience, 29*(27), 8726–8733. http://dx.doi.org/10.1523/JNEUROSCI.2145-09.2009.

Fukuda, K., & Vogel, E. K. (2011). Individual differences in recovery time from attentional capture. *Psychological Science, 22*(3), 361–368. http://dx.doi.org/10.1177/0956797611398493.

Gaspar, J. M., Christie, G. J., Prime, D. J., Jolicœur, P., & McDonald, J. J. (2016). Inability to suppress salient distractors predicts low visual working memory capacity. *Proceedings of the National Academy of Sciences, 113*(13), 3693–3698. http://dx.doi.org/10.1073/pnas.1523471113.

Gaspar, J. M., & McDonald, J. J. (2014). Suppression of salient objects prevents distraction in visual search. *Journal of Neuroscience, 34*(16), 5658–5666. http://dx.doi.org/10.1523/JNEUROSCI.4161-13.2014.

Geng, J. J. (2014). Attentional mechanisms of distractor suppression. *Current Directions in Psychological Science, 23*(2), 147–153. http://dx.doi.org/10.1177/0963721414525780.

Gordon, M., & Lumley, T. (2017). Advanced forest plot using "grid" graphics (version 1.7) [R] <http://CRAN.R-project.org/package=forestplot>.

Jannati, A., Gaspar, J. M., & McDonald, J. J. (2013). Tracking target and distractor processing in fixed-feature visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance, 39*(6), 1713–1730. http://dx.doi.org/10.1037/a0032251.

Jost, K., Bryck, R. L., Vogel, E. K., & Mayr, U. (2011). Are old adults just like low working memory young adults? Filtering efficiency and age differences in visual working memory. *Cerebral Cortex, 21*(5), 1147–1154. http://dx.doi.org/10.1093/cercor/bhq185.

Jost, K., & Mayr, U. (2016). Switching between filter settings reduces the efficient utilization of visual working memory. *Cognitive, Affective, & Behavioral Neuroscience, 16*(2), 207–218. http://dx.doi.org/10.3758/s13415-015-0380-5.

Lahav, A., Makovski, T., & Tsal, Y. (2012). White bear everywhere: Exploring the boundaries of the attentional white bear phenomenon. *Attention, Perception, & Psychophysics, 74*(4), 661–673. http://dx.doi.org/10.3758/s13414-012-0275-2.

Lahav, A., & Tsal, Y. (2013). Allocating attention to distractor locations is based on top-down expectations. *The Quarterly Journal of Experimental Psychology, 66*(9), 1873–1880. http://dx.doi.org/10.1080/17470218.2013.768276.

Leber, A. B., Gwinn, R. E., Hong, Y., & O'Toole, R. J. (2016). Implicitly learned suppression of irrelevant spatial locations. *Psychonomic Bulletin & Review, 1–9*. http://dx.doi.org/10.3758/s13423-016-1065-y.

Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review, 1*(4), 476–490. http://dx.doi.org/10.3758/BF03210951.

Luck, S., Hillyard, S., Mouloua, M., & Hawkins, H. (1996). Mechanisms of visual-spatial attention: resource allocation or uncertainty reduction? *Journal of Experimental Psychology, Human Perception and Performance, 22*(3), 725–737. http://dx.doi.org/10.1037//0096-1523.22.3.725.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390*(6657), 279–281. http://dx.doi.org/10.1038/36846.

Luria, R., Balaban, H., Awh, E., & Vogel, E. K. (2016). The contralateral delay activity as a neural measure of visual working memory. *Neuroscience & Biobehavioral Reviews, 62*, 100–108. http://dx.doi.org/10.1016/j.neubiorev.2016.01.003.

Luria, R., & Vogel, E. K. (2011). Visual search demands dictate reliance on working memory storage. *Journal of Neuroscience, 31*(16), 6199–6207. http://dx.doi.org/10.1523/JNEUROSCI.6453-10.2011.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin, 109*(2), 163–203. http://dx.doi.org/10.1037/0033-2909.109.2.163.

Macmillan, N. A., & Creelman, C. D. (1996). Triangles in ROC space: History and theory of "nonparametric" measures of sensitivity and response bias. *Psychonomic Bulletin & Review, 3*(2), 164–170. http://dx.doi.org/10.3758/BF03212415.

McCollough, A. W., Machizawa, M. G., & Vogel, E. K. (2007). Electrophysiological measures of maintaining representations in visual working memory. *Cortex, 43*(1), 77–94. http://dx.doi.org/10.1016/S0010-9452(08)70447-7.

McNab, F., & Klingberg, T. (2008). Prefrontal cortex and basal ganglia control access to working memory. *Nature Neuroscience, 11*(1), 103–107. http://dx.doi.org/10.1038/nn2024.

Meiran, N., Chorev, Z., & Sapir, A. (2000). Component processes in task switching. *Cognitive Psychology, 41*(3), 211–253. http://dx.doi.org/10.1006/cogp.2000.0736.

Meiran, N., & Daichman, A. (2005). Advance task preparation reduces task error rate in the cuing task-switching paradigm. *Memory & Cognition, 33*(7), 1272–1288. http://dx.doi.org/10.3758/BF03193228.

Munneke, J., Heslenfeld, D. J., Usrey, W. M., Theeuwes, J., & Mangun, G. R. (2011). Preparatory effects of distractor suppression: Evidence from visual cortex. *PLoS One, 6*(12), e27700. http://dx.doi.org/10.1371/journal.pone.0027700.

Munneke, J., Van der Stigchel, S., & Theeuwes, J. (2008). Cueing the location of a distractor: An inhibitory mechanism of spatial attention? *Acta Psychologica, 129*(1), 101–107. http://dx.doi.org/10.1016/j.actpsy.2008.05.004.

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research, 29*(11), 1631–1647.

New, J., Cosmides, L., & Tooby, J. (2007). Category-specific attention for animals reflects ancestral priorities, not expertise. *Proceedings of the National Academy of Sciences, 104*(42), 16598–16603. http://dx.doi.org/10.1073/pnas.0703913104.

Öhman, A., Flykt, A., & Esteves, F. (2001). Emotion drives attention: Detecting the snake in the grass. *Journal of Experimental Psychology: General, 130*(3), 466–478. http://dx.doi.org/10.1037/0096-3445.130.3.466.

Owens, M., Koster, E. H. W., & Derakshan, N. (2012). Impaired filtering of irrelevant information in dysphoria: An ERP study. *Social Cognitive and Affective Neuroscience, 7*(7), 752–763. http://dx.doi.org/10.1093/scan/nsr050.

Pashler, H. (1988). Familiarity and visual change detection. *Perception & Psychophysics, 44*(4), 369–378. http://dx.doi.org/10.3758/BF03210419.

Pollack, I., & Norman, D. A. (1964). A non-parametric analysis of recognition experiments. *Psychonomic Science, 1*(1), 125–126. http://dx.doi.org/10.3758/BF03342823.

Posner, M. I. (1978). *Chronometric explorations of mind*. Oxford, England: Lawrence Erlbaum.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*(1), 3–25. http://dx.doi.org/10.1080/00335558008248231.

Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General, 109*(2), 160–174. http://dx.doi.org/10.1037/0096-3445.109.2.160.

Ravizza, S. M., Uitvlugt, M. G., & Hazeltine, E. (2016). Where to start? Bottom-up attention improves working memory by determining encoding order. *Journal of Experimental Psychology: Human Perception and Performance*, doi:http://dx.doi.org/10.1037/xhp0000275.

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance, 18*(3), 849.

Ruff, C. C., & Driver, J. (2006). Attentional preparation for a lateralized visual distractor: Behavioral and fMRI evidence. *Journal of Cognitive Neuroscience, 18*(4), 522–538. http://dx.doi.org/10.1162/jocn.2006.18.4.522.

Ruz, M., & Lupiáñez, J. (2002). A review of attentional capture: On its automaticity and sensitivity to endogenous control. *Psicológica, 23*, 283–309.

Sawaki, R., Geng, J. J., & Luck, S. J. (2012). A common neural mechanism for preventing and terminating the allocation of attention. *Journal of Neuroscience, 32*(31), 10725–10736. http://dx.doi.org/10.1523/JNEUROSCI.1864-12.2012.

Sawaki, R., & Luck, S. J. (2010). Capture versus suppression of attention by salient singletons: Electrophysiological evidence for an automatic attend-to-me signal. *Attention, Perception, & Psychophysics, 72*(6), 1455–1470. http://dx.doi.org/10.3758/APP.72.6.1455.

Sawaki, R., & Luck, S. J. (2011). Active suppression of distractors that match the contents of visual working memory. *Visual Cognition, 19*(7), 956–972. http://dx.doi.org/10.1080/13506285.2011.603709.

Schmidt, B. K., Vogel, E. K., Woodman, G. F., & Luck, S. J. (2002). Voluntary and automatic attentional control of visual working memory. *Perception & Psychophysics, 64*(5), 754–763.

Shipstead, Z., Lindsey, D. R. B., Marshall, R. L., & Engle, R. W. (2014). The mechanisms of working memory capacity: Primary memory, secondary memory, and attention control. *Journal of Memory and Language, 72*, 116–141. http://dx.doi.org/10.1016/j.jml.2014.01.004.

Simon, J. R. (1990). The Effects of an Irrelevant Directional CUE on Human Information Processing. In Robert W. Proctor and T. Gilmour Reeve (Ed.), *Advances in Psychology* (Vol. 65, pp. 31–86). North-Holland <http://www.sciencedirect.com/science/article/pii/S0166411508612182>.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*(6), 643.

Theeuwes, J., & Godijn, R. (2002). Irrelevant singletons capture attention: Evidence from inhibition of return. *Perception & Psychophysics, 64*(5), 764–770.

Tsal, Y., & Makovski, T. (2006). The attentional white bear phenomenon: The mandatory allocation of attention to expected distractor locations. *Journal of Experimental Psychology: Human Perception and Performance, 32*(2), 351–363. http://dx.doi.org/10.1037/0096-1523.32.2.351.

Van der Stigchel, S., Heslenfeld, D. J., & Theeuwes, J. (2006). An ERP study of preparatory and inhibitory mechanisms in a cued saccade task. *Control of Attention and Actions, 1105*(1), 32–45. http://dx.doi.org/10.1016/j.brainres.2006.02.089.

Van der Stigchel, S., & Theeuwes, J. (2005). Our eyes deviate away from a location where a distractor is expected to appear. *Experimental Brain Research, 169*(3), 338–349. http://dx.doi.org/10.1007/s00221-005-0147-2.

Vogel, E. K., & Awh, E. (2008). How to exploit diversity for scientific gain: Using individual differences to constrain cognitive theory. *Current Directions in Psychological Science, 17*(2), 171–176. http://dx.doi.org/10.1111/j.1467-8721.2008.00569.x.

Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature, 428*(6984), 748–751.

Vogel, E. K., McCollough, A. W., & Machizawa, M. G. (2005). Neural measures reveal individual differences in controlling access to working memory. *Nature, 438*(7067), 500–503. http://dx.doi.org/10.1038/nature04171.

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance, 27*(1), 92–114. http://dx.doi.org/10.1037//0096-1523.27.1.92.

Watson, D. G., & Humphreys, G. W. (1997). Visual marking: prioritizing selection for new objects by top-down attentional inhibition of old objects. *Psychological Review, 104*(1), 90.

Woodman, G. F., Vecera, S. P., & Luck, S. J. (2003). Perceptual organization influences visual working memory. *Psychonomic Bulletin & Review, 10*(1), 80–87.

Yantis, S. (1996). Attentional capture in vision. In A. F. Kramer, M. G. H. Coles, & G. D. Logan (Eds.), *Converging operations in the study of visual selective attention* (pp. 45–76). Washington, DC, US: American Psychological Association.