Chapter #15

DO DIFFERENT TYPES OF SPATIAL WORKING MEMORY LOAD AFFECT VISUAL SEARCH DIFFERENTLY?

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ABSTRACT
Working memory (WM) has repeatedly been shown to be an important factor in visual search. For instance, there is evidence that both spatial and visual WM load lead to a decrease in search performance while search efficiency has been reported to be affected by spatial WM load only. In three experiments, we tested how two different types of spatial WM load affect visual search performance and efficiency. Participants had to memorize the spatial locations of two or four items presented either serially (Experiment 1) or simultaneously (Experiments 2 and 3) prior to a search for a target letter in a display of 5, 10 or 15 letters. In Experiment 3, participants additionally performed a verbal WM task. The results showed that, compared to a no-load condition, search performance decreased in the two- and four-load conditions, regardless of the type of spatial WM load. No response time difference was found between the two and four-load conditions. Furthermore, the additional verbal WM task had no effect on search performance. Finally, and in contrast to previous findings, search efficiency was not affected by either type of spatial WM load suggesting that search performance, but not search efficiency, is affected by spatial WM load.

Keywords: visual attention, visual search, working memory load.

1. INTRODUCTION

Visual search is an everyday behavior in which we search for one or more target objects within a set of non-targets, so called distractors. In laboratory settings, visual search paradigms are often used to investigate attentional processes. Usually, participants are required to make a manual response regarding the absence or presence of a target in a search display that consists of a number of search items. The main variables of interest are commonly search performance (i.e., response times), search accuracy (e.g., target hits and misses) and search efficiency (i.e., search rate per additional item in the display). Also, the measurement of the eye movements during search (so called saccades) is a further method to investigate visual search and its related processes (e.g., Duchowski, 2017; see Carter & Luke, 2020 for a recent review). Theories of selective attention propose a distinction between parallel and serial visual search (e.g., Treisman & Gelade, 1980, Treisman, 1988, Wolfe, 1994). In a *parallel search* (feature or "pop-out"), the target is distinct in one dimension from a set of rather homogeneous distractors (e.g., a blue ball among red balls) and can hence be found immediately and regardless of the number of objects in the search display. As a result, in parallel searches, response times are not affected by the presence or absence of the target. In a *serial search*, the search items are more heterogeneous and therefore must be searched serially to determine whether the target is present or not. Consequently, serial target-absent searches last longer than target present searches because participants have to check all items in order to make a valid decision. In serial target-present searches, participants on average find the target when they have searched through the halfway of the display (see e. g. Wolfe, 2020, for a review).

For a long time, one of the most important questions was whether and to what extent memory is involved in visual search. Horowitz and Wolfe (1998) claimed in their seminal publication that visual search is memoryless: i.e., that we do not use memory when searching for targets. In their study, participants were asked to find a target letter T in a display of L-shaped distractor letters. The target was present in half of the trials. They implemented two conditions: a random and a static condition. In the random condition, the locations of the stimuli changed every 111 msec, whereas in the static condition the item locations were fixed throughout the search. Therefore, in the random condition the usage of memory was not possible whereas in the static condition search would benefit from memory as the letter position can be remembered, which should lead to a more efficient search. Surprisingly, the results indicated that the search efficiency was comparable in both conditions. Hence, Horowitz and Wolfe (1998) suggested that visual search does not rely on memory processes. However, most of the research which has emerged after this study has shown that memory plays an important role in visual search (e.g., Kristjánsson, 2000; Gilchrist & Harvey, 2000; Lleras, Rensink, & Enns, 2005; Shen & Jiang, 2006; Beck, Peterson, Boot, Vomela, & Kramer, 2006; Körner & Gilchrist, 2008; Höfler, Gilchrist, & Körner, 2014, 2015; Körner, Höfler, Ischebeck, & Gilchrist, 2018; Hout & Goldinger, 2015) and the interest of research shifted to the question on the properties of this memory. For instance, Beck, Peterson, Boot, Vomela, & Kramer (2006) suggested that not individual features but rather the locations of the presented stimuli are memorized in visual search. However, we showed that, when the same display has to be searched twice, participants can profit from the about last four items they had previously inspected during the first search. Participants can then use the item identity and location information of these items to enhance search performance in the second search (Körner & Gilchrist, 2007; Höfler et al., 2014; Höfler et al. 2015).

Overall, the concept of working memory (WM) proposes a system of limited capacity that consists of three components: a verbal storage system (the phonological loop), a visual storage system (the visuospatial sketch) and a central executive (e.g., Baddeley, 2003; Baddeley & Logie, 1999). The interplay of these subsystems ensures that information can be temporally stored and manipulated. Moreover, and important for the current work, it also implies that location and object information are handled by and stored in working memory subsystems. Previous research has indeed indicated that WM– and especially spatial WM - is an important factor in visual search (e.g., Oh & Kim, 2004; Woodman & Luck, 2004; Manginelli, Geringswald, & Pollmann , 2012). In experiments in which the influence of different types of WM on visual search is investigated, participants are typically presented with a set of objects and are asked to memorize the locations (to test for the influence of visuo-spatial WM) or specific features (to test for visual WM) of the presented objects while performing a subsequent visual search task. If visual search relies on the respective type of WM, one would expect to see a negative effect in terms of search performance as well as search efficiency when WM load is increased because there are less resources left for the visual search task. Typically, findings show that overall search performance decreases in such dual-task paradigms. This means that the search takes longer due to the memory load regardless of the type of WM load (visual or spatial; e.g., He & McCarley, 2010, Oh & Kim, 2004; Woodman & Luck, 2004). In contrast, the findings regarding WM load on search efficiency (i.e., the search rate per additional item in the display) are rather unclear. For instance, Woodman, Vogel, and Luck (2001) showed that memorizing object features such as no, two or four object colors prior search affected search performance but had no effect on search efficiency. Solman, Cheyne, and Smilek (2011) analyzed the eye movements of their participants while they searched a display under different visual WM load conditions and found similar findings as Woodman et al. (2001). Solman et al. (2011) found that fixations were made farther away from the search items (i.e., they were less precise) and previously inspected locations were more often refixated when a visual WM load was added. On the other hand, it has been demonstrated that memorizing the spatial location of objects affected both performance and efficiency. For instance, Oh and Kim (2004) had participants memorize four item locations prior to the search task (searching for an upright L among rotated L-shaped objects) in a dual-task condition and compared the search performance and efficiency with a search-alone condition. Their results showed that search times increased in the dual-task condition whereas search efficiency decreased. The same pattern of results was also reported by Woodman and Luck (2004). They had participants memorize two item locations prior to the search and also showed that participants needed longer to find the target in the dual-task condition and that the search efficiency was worse compared to the search-only condition. Moreover, findings from Anderson, Mannan, Rees, Sumner, and Kennard (2008) suggested that also verbal WM load affects search efficiency in serial searches to the same extent as spatial WM load.

Oh and Kim (2004) had participants memorize four item locations at once prior to the search task, whereas in Woodman and Luck (2004), they had to memorize two serially presented item locations prior to the search to prevent participants from forming a shape-based mental representation that would not require spatial WM resources. However, these different presentations of WM load (all at once vs. serially) could have actually affected search differently. Moreover, in both studies, participants were required to perform an articulatory suppression task throughout the experimental trial. It is unclear whether this verbal task might have even increased the effect of the visuo-spatial WM load. In the following experiments, we therefore wanted to test in greater detail whether and how different types visuo-spatial WM load affect a visual-search task that consists of letter stimuli. In all experiments, we had participants search for a target letter in a letter display with 5, 10, or 15 different letters while they were additionally asked to memorize the locations of zero, two or four squares. In Experiment 1, these squares were presented serially; in Experiments 2 and 3, they were presented at once. In Experiment 3, participants were additionally required to perform an articulatory suppression task. For all experiments, we expected a decrease in search performance when WM load is added such that the searches should last longer with increasing WM load. However, we expected that the effect of WM load on search efficiency, as measured by the search rate, depends on the type and the amount of WM load. That is, increasing WM load should lead to less efficient searches (steeper search rates), and this effect should be more pronounced in Experiment 3 (verbal and spatial WM load) than in Experiment 2 (spatial WM only). Furthermore, we expected search efficiency to be more affected when the to-be-remembered locations were presented serially than if they were presented all at once (Experiments 1 vs. Experiment 2).

2. METHOD

2.1. Design

In all three experiments, a 3 (memory condition) × 3 (search condition) × 2 (target presence) within-subjects design was used. That is, participants had to memorize either 0, 2, or 4 item locations (no vs. low vs. high memory load) before searching a display consisting of either 5, 10 or 15 letter items. Participants indicated the search target's presence (present vs. absent) in the task via button press. That is, they pressed the left button of a two-button response box for an "absent" response and the right button for a "present" response. The target was absent on half of the trials. The variation of the memory condition was block-wise and counterbalanced across participants; all other factors were varied randomly within the blocks. We measured manual response times from display onset to the manual response as the main dependent variable.

2.2. Participants

We recruited 20 participants in Experiment 1 (18 female, 2 male; M = 23.3 years; SD = 2.2), 20 in Experiment 2 (16 female, 4 male; M = 23.8 years; SD = 3.9) and 24 participants in Experiment 3 (12 female, 12 male; M = 23.2 years; SD = 2.3). This sample size is similar to previous experiments on this topic (He & McCarley, 2010, Oh & Kim, 2004; Woodman & Luck, 2004). All participants reported normal or corrected-to-normal vision. All of them gave written informed consent before the start of the experiment and received course credit for their participation. The experiments were approved by the ethics committee of the University of Graz.

2.3. Apparatus, stimuli and procedure

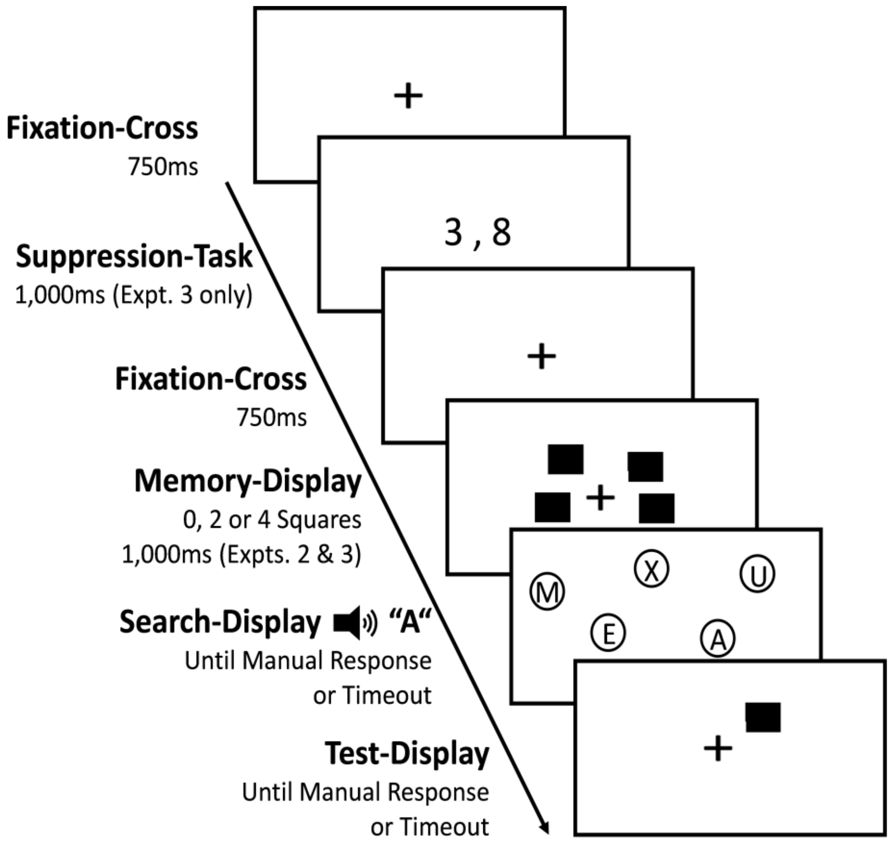
In all experiments, a fixation cross was presented at the center of the display for 750 ms at the beginning of a trial (see Figure 1). Furthermore, in Experiment 3, two different numbers (randomly selected from the numbers 1 to 9), were then presented for 1,000 ms and the participants were asked to repeat these numbers aloud throughout the whole trial. Then the fixation cross was presented again for 750 ms, followed by the memory display for 1,000 ms. Participant's task was to memorize the location of 0, 2 or 4 light grey squares (0.9 x 0.9 degrees of visual angle; d.v.a.) that were located randomly at 12 possible locations around the center of the display.

In Experiment 1, the 2 or 4 memory items were presented serially for 500 ms and 250 ms respectively (i.e., 1000 ms in total). In Experiments 2 and 3, all memory items were presented at once for 1,000 ms, followed by the search display. The display consisted of 5, 10 or 15 letters. The letters (size: 0.32 d.v.a.) were presented in light grey (RGB: 128, 128, 128) within the grid cells of an invisible 7 × 7 grid (25.9 × 25.9 d.v.a.) and were surrounded by a circle with a diameter of 0.9 d.v.a. For each trial, the letter stimuli were randomly selected from 16 upper-case letters (A, E, F, G, H, K, L, M, O, P, R, S, T, U, X, and Z). The letters were written in Arial font and randomly deviated horizontally and vertically from the center of the grid cell by 0.0 - 0.13 d.v.a. The target letter, which was present in half of the trials, was randomly selected from these l5 letters in the display. In a target-absent trial, the target letter was the one letter from the originally 16 letters that was not presented in the display.

At the beginning of the search, the target letter was announced via head set simultaneously with the onset of the search display. Participant's task was to search for the target in the display and to give a manual present or absent response on the two-button response box. After this manual response, a test display consisted of a single memory item was presented, and participants had to decide via a button press whether the position of the test stimuli matched with one of the to-be-remembered positions from the memory display. In case of the no-load condition, the memory display and the test display remained blank. After this, the display was cleared, and a new trial started.

Participants sat in a darkened, sound-proof cabin at a distance of about 63 cm in front of a 21’’ CRT monitor with a resolution of 1,152 x 864 pixels and a refresh rate of 100 Hz. A chin rest was used to minimize head movements. Stimuli were created using Microsoft Visual C++ 2008 Express Edition. Each participant completed one session of three blocks of 90 trials each, lasting about one hour. As stated above, the memory condition was varied block-wise whereas all other factors within an experiment were varied within blocks. The sequence of memory conditions was counterbalanced across participants. Before each block, 10 practice trials were conducted.

Figure 1.
Sample procedure of a trial in Experiment 3 (Stimuli are not drawn in scale).



3. RESULTS

3.1. Error rates

In all experiments, we excluded data from participants with a higher error rate than 10% in the visual search task or when they conducted the memory task on chance level, as indicated by a binomial test. In Experiment 1, data of 17 participants entered the analysis. The error rate of these 17 participants was M = 3.7 % (SD = 1.6 %) in the search task and M = 18.2 % (SD = 6.9 %, low load) and M = 28.6 % (SD = 5.9 %, high load) in the memory task. A paired *t*-test showed that the error rate for the memory task was significantly higher for the high-load vs. the low-load condition, $t(16) = 6.35$, $p < .001$. In Experiment 2, data from 14 participants were included in the analysis. The error rate in the search task was M = 3.4 % (SD = 2.5 %); the error rate in the two memory tasks was M = 14.5 % (SD = 7.2 % low load) and M = 26.0 % (SD = 9.1 %, high load). This latter difference was reliable, $t(13) = 7.89$, $p < .001$. In Experiment 3, data of four participants had to be excluded from analysis because of the criteria defined above. For the 20 remaining participants, the average error rate for the search task was M = 2.9 % (SD = 2.3 %) and for the memory task M = 16.3 % (SD = 8.0 %, low load) and M = 23.2 % (SD = 8.1 %, high load). A *t*-test for repeated measures indicated again that the error rate for the high-memory load condition was significantly higher than for the low-load condition, $t(19) = 3.87$, $p = .001$.

3.2. Search performance

Table 1 shows the mean response times and standard deviations for all load conditions and display sizes averaged across participants' individual means for all three experiments. A 3 × 3 × 3 ANOVA for repeated measures with display size (5, 10, or 15 letters) and load condition (no, low or high-load condition) as within-subjects factors and experiment (1 to 3) as between-subjects factor showed no effect of experiment, $F < 1$, but a significant effect of display size, $F(1.25, 59.96) = 1134.94$, $p < .001$, $\eta_p^2 = .96$. Bonferroni-Holm corrected *t*-tests indicated that participants needed longer to find the target as display size increased (all *p*s < .001), reflecting a standard finding in serial visual search (e.g, Wolfe, 2020). Furthermore, the main effect of load condition was also significant, $F(2, 96) = 28.75$, $p < .001$, $\eta_p^2 = .37$, such that response times increased from the no-load condition to the low-load condition ($p < .001$) while no such difference was found for the low-load vs. high-load condition ($p = .35$). However, none of the interactions were significant (all *p*s > .20).

Table 1.
Mean response times and search rates in ms (standard deviation) for all experiments and conditions.

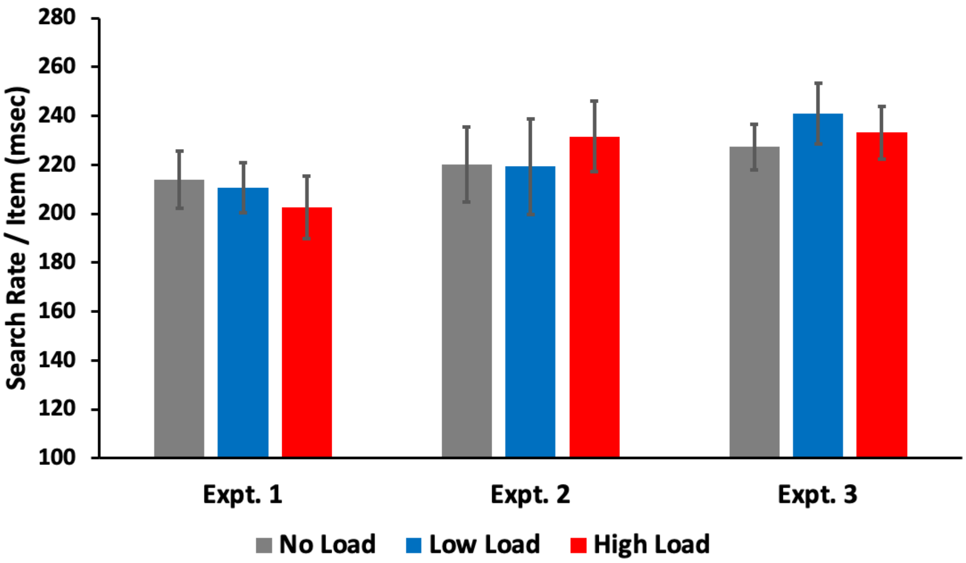
		No load	Low load	High load
Expt. 1	DS 5	1,901 (228)	2,168 (463)	2,265 (637)
	DS 10	3,031 (353)	3,411 (644)	3,433 (773)
	DS 15	4,040 (658)	4,274 (816)	4,291 (950)
	Search rate / item	214 (49)	211 (42)	203 (52)
Expt. 2	DS 5	1,829 (242)	2,217 (448)	2,174 (1,012)
	DS 10	2,931 (403)	3,478 (763)	3,381 (696)
	DS 15	4,061 (685)	4,504 (1012)	4,582 (831)
	Search rate / item	220 (57)	219 (73)	232 (55)
Expt, 3	DS 5	1,931 (250)	2,173 (385)	2,368 (507)
	DS 10	3,139 (445)	3,497 (586)	3,672 (745)
	DS 15	4,205 (589)	4,584 (845)	4,700 (795)
	Search rate / item	227 (42)	241 (56)	233 (48)

Note. DS = Display size.

3.3. Search efficiency

The average search rates, indicated by the search time per item as a function of display size for each experiment, can be found in Table 1 and Figure 2. A mixed-way ANOVA with WM load condition as within-subject and experiment as between-subject factor showed neither a reliable difference across experiments, $F(2, 48) = 1.48$, $p = .24$ nor between WM load conditions, $F < 1$. Also, the interaction was not significant, $F < 1$. This suggests that the different types of WM load used in the experiments did not affect search efficiency.

Figure 2.
Search rate per item for the three experiments depending on the load conditions. Error bars represent the standard error.



4. DISCUSSION

The aim of the current three experiments was to investigate whether and how different types of visuo-spatial working memory load affect a visual search task. To this end, we had participants hold zero, two or four item locations in WM while they performed a visual search task in a letter display. The item locations to-be-memorized were either presented parallel or serially and in one experiment, participants were additionally asked to perform an articulatory suppression task. Previous findings have indicated that spatial WM load affects both visual search performance and search efficiency (e.g., Oh & Kim, 2004; Woodman & Luck, 2004). Partially in line with these findings, we also showed that search performance decreased with increasing spatial memory load. That is, if participants had to memorize two item locations prior to the visual-search task, search times increased compared to a control condition without WM load. This was regardless of whether the search display consisted of five, ten, or fifteen letters and regardless of whether the locations of the memory items were presented simultaneously or serially, or whether participants had to perform an additional verbal suppression task. Moreover, and in contrast to findings from the literature (e.g., Oh & Kim, 2004; Woodman & Luck, 2004), there was no additional increase in the search times from the two-item to the four-item WM load condition in any of the search conditions and experiments. Overall, this suggests that these different types of spatial WM load affected visual search in a similar way. The lack of finding a further decrease of search performance from the two- to the four-item WM condition might also indicate that the two-item load already occupied all WM resources.

Furthermore, although the visuo-spatial tasks affected search performance significantly, we could not replicate the findings from Oh and Kim (2004) and Woodman and Luck (2004) that the additional spatial WM load affected search rates as well. Search did not become more inefficient when spatial WM load was added. Such findings in which search efficiency is not affected by WM load are commonly observed in experiments that use visual WM tasks (e.g., Solman, et al., 2011, Woodman et al., 2001) and it is commonly argued that, as long as the search efficiency is not affected by an additional WM load, also the search process is *not* affected. However, as described above, Solman et al. (2011; see also Solman, Smilek, & Eastwood, 2009) suggested that a (non-spatial) WM load does not necessarily affect search efficiency and the question remains if this is also true for spatial WM loads. They monitored participants' eye movement behavior and investigated the time spent in the three different phases of the search while participants were required to hold up to four object colors in WM: between the onset of the display until the first saccade, between the first saccade and fixation of the target, and between fixation of the target and the manual response. Their findings showed that WM load affected all phases of the search and in which fixations tended to become more imprecise resulting in longer search times. In the light of the current findings, it is therefore possible that eye movement behavior also changed during search when visuo-spatial WM load was increased, although this change is not reflected in the analysis of search efficiency. Hence, additional experiments in which the eye movements are monitored during search are necessary to further investigate these diverging effects of WM load on search performance and search efficiency. A further explanation for this inconsistency regarding the different effect of spatial WM load on search performance and search efficiency was recently provided by Xin and Li (2020). They argued that the increased extent of executive control to maintain a (non-spatial) WM load might decrease the participants' confidence level such that the observed response time differences are mainly due to the stage of response selection. However, it is still unclear and an open question for future research whether such an assumption would hold as true for spatial WM load tasks as used in previous experiments (e.g., Oh & Kim, 2004; Woodman & Luck, 2004) and our work.

Taken together, the current findings demonstrate that different types of spatial WM might affect a visual search to the same extent. This might be of help for future studies that to investigate the influence of spatial WM and visual search with regard to different context (e.g., individual differences in spatial WM; see Takahashi & Hatakeyma, 2011) or in clinical settings.

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ACKNOWLEDGEMENTS

This work was supported by the Austrian Science Fund (FWF): P28546 and P33074. We thank Sarah Nachtnebel for her support during the preparation of this document.

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