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OBJECT AND SPATIAL WORKING MEMORY IN VISUAL SEARCH FOR MULTIPLE TARGETS

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OBJECT AND SPATIAL WORKING MEMORY IN VISUAL SEARCH FOR MULTIPLE TARGETS[4]

Visual search for multiple targets is especially error prone. One of these errors is called subsequent search misses (SSM) and represents a decrease in accuracy at detecting a second target after a first target has been found. One of the possible explanations of SSM errors is working memory resource depletion. Four experiments investigated the role of different kinds of working memory in SSM errors. The first experiment investigated the role of object working memory using a classical color change detection task. In the second and the third experiments, a modified change detection task was applied, using shape as the relevant feature. In the fourth experiment, a spatial working memory task was used to reveal the role of spatial working memory in SSM. The second and the third experiments revealed interference between working memory and visual search tasks, whereas in the first and the fourth experiments interference was not found. The results are discussed in terms of specific working memory deficit in SSM errors.

JEL Classification: Z.

Keywords: visual attention, visual search, multiple targets, working memory, subsequent search misses

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Introduction

Visual search is a process of searching for targets among distracters. This task is very important in everyday life, as well as for some jobs (e.g. radiology, baggage screening). Nevertheless, visual search is error prone. One of these errors is called subsequent search misses (SSM) and is observed in dual-target visual search (e.g. Adamo, Cain, & Mitroff, 2013). SSM is the decrease in accuracy at detecting a second target after a first target has been found.

The nature of SSM is as yet unspecified. The first explanation of this phenomenon was proposed in radiological studies and supposed the second target omission to be related to a premature ending of the search. After finding the first target, the subject becomes “satisfied” with this result and does not search for any other possible targets (Tuddenham, 1962). Therefore, this phenomenon has been called satisfaction of search. However, searchers do continue searching after the first target is found (e.g. Fleck, Samei, & Mitroff, 2010), which means that the “satisfaction” is not the only reason for SSM.

Alternative theories suggest the role of target similarity and resource depletion. According to perceptual set theory, the first-found target creates a perceptual bias so the subject is more likely to find perceptually similar targets and less likely to find the targets that are perceptually dissimilar. Recent experiments (Gorbunova, 2017) provided the support for this theory as the SSM effect decreased with an increase in the number of shared features in two targets. Moreover, the SSM effect depends not only on the perceptual, but also on the conceptual target similarity (Biggs et al., 2015). The possible underlying mechanisms of the perceptual set can refer to perceptual priming or guidance. Still, the nature of how exactly this perceptual bias works is not completely clear. One of the possible mechanisms involves the role of working memory which is used to store target representations. This brings us to the third possible explanation of SSM errors – the resource depletion account (Cain & Mitroff, 2013).

The resource depletion account suggests that cognitive resources (e.g. working memory) are consumed by the first-found target. The first-found target identities and/or locations are stored in the working memory at the time of the subsequent search which leaves few resources to find a second target. Cain, Biggs, Darling & Mitroff (2014) provided support for this theory. Dividing one multiple-target search into several single-target searches, separated by unrelated trials, effectively freed the working memory resources and eliminated SSM errors. Moreover, removing already found targets from the display or making them salient and easily segregated color singletons improved subsequent search accuracy (Cain & Mitroff, 2013).

Overall, both the perceptual bias and the resource depletion accounts predict that working memory plays a key role in the SSM effect. Nevertheless, the exact kind of working memory resources which cause resource depletion are not yet defined. They could be target identities (object working memory) or the explored spatial locations (spatial working memory). Experiments on standard single-target visual search tasks revealed the role of both object and spatial working memory. Woodman, Luck & Schall (2007) investigated the role of object working memory in visual searches. The participants performed a visual search task during the delay interval of a visual working memory task, a standard change-detection task, and separately. The two tasks were found to interfere with each other (interference for the visual search task was measured by slopes sizes) when the search targets changed from trial-to-trial, which implies the targets representations were encoded in the visual working memory during the visual search. Woodman & Luck’s (2004) experiments involved the comparison of a visual search task performed during the retention interval of a spatial working memory task, and a visual search task tested in isolation. The spatial working memory task included a location change detection task, in which the subjects had to memorize the locations of two sequentially presented dots. After the retention interval two dots were displayed simultaneously and the participants had to give a response to indicate whether a location change was detected. Visual search efficiency was impaired when the search and the memory tasks were performed concurrently, as compared with when the search task was performed separately.

Thus, there are two potential candidates for working memory resources falling under resource depletion thereby causing the second target omission in dual-target visual search: target identities (object working memory) and observed locations (spatial working memory). Based on the data from perceptual and conceptual target similarity, object working memory representations seem more likely. In this article, we address the issue of the particular kind of working memory falling under resource depletion in dual-target visual search.

Four experiments investigated the role of working memory in SSM errors using different tasks. In Experiment 1 we used a color change-detection task similar to Woodman et al. (2007). In Experiment 2 a modified change detection task with shape features was used. Experiment 3 was also a change-detection task with fewer shapes. Experiment 4 investigated the role of spatial working memory using the Woodman & Luck (2004) location-change detection task. In all four experiments, three conditions were used: a single visual search task, a single working memory task and a combined visual search + working memory task. If the dual-target visual search and the working memory task require the same resources, two kinds of interference are expected: first, the search in the dual-target condition would be worsened by the additional working memory task, and second, the response accuracy in the working memory task would worsen with an additional dual-target visual search task. Thus, failing to see interference will falsify the accounts in which object or spatial storage underlies the SSM effect.

Experiment 1

Method

Participants

30 volunteers, 3 male and 27 female, students of National Research University Higher School of Economics participated in the study. All of them were native Russian speakers with normal or corrected to normal vision. The age varied between 17 and 22 years (*M* = 18.93, *SD* = 1.14). All participants were naive to the experimental hypothesis.

The experiment included three conditions: a working memory (WM) task, a visual search (VS) task and a combined task for working memory and visual search (VS + WM). The order of presentation was counterbalanced across subjects. Articulatory suppression was used during the whole experiment to avoid the possibility of verbal coding.

Apparatus

Participants sat in a dark room 45 cm from a 19 in. LACIE electron 19 blue III monitor (screen resolution 1024 × 768, refresh rate 85 Hz). Stimuli were displayed with Psychopy v. 1.82.01, OS Ubuntu. Participant answers were registered with a standard keyboard and mouse.

Working memory task

Stimuli

The stimuli were squares of highly-discriminable colors: white, black, red, green, blue, yellow. On each trial, four squares were displayed arranged around a fixation cross at the top, bottom, left and right. The stimuli size was 1.15° × 1.15°. The stimuli were presented on a gray background (CIE $xy = 0.273, 0.304$; luminance = 40.897 cd/m^2) and the colors of the stimuli were varied each trial. There were always 4 items per display.

Procedure

At the beginning of the trial, a sample array with four colored squares was displayed for 500 ms. This was followed by 4000 ms ISI. After that, the test array appeared. The time limit for test array was 2000 ms, after that the test array was replaced with the sign "?", appearing at the center of the screen. The participant's task was to remember the initial colors of the squares of the sample array and to report if the test array is the same as the sample array or not. The response was given with two predefined buttons ("N" and "Z") on the keyboard. The participant pressed the "space" bar on the keyboard to begin the next trial. The participant could take the small breaks during the experiment. The participants were instructed to perform both fast and accurately.

The condition consisted of 100 trials. On 50% of trials the test array was identical to the sample array, and on the other 50% the color of one randomly selected square was replaced by a color that was not present in the sample array.

A training session of 5 trials preceded the experiment.

Visual search task

Stimuli

The stimuli were rectangles with gaps which could be at the top, bottom, right or left. The stimuli size was 1.38° × 0.93°. The stimuli could have various levels of salience: high (CIE *xy* = 0.272, 0.297; luminance = 14.155 cd/m^2), medium (CIE *xy* = 0.272, 0.301; luminance = 21.653 cd/m^2) and low (CIE *xy* = 0.272, 0.303; luminance = 28.475 cd/m^2). On each trial, there were around 33% stimuli of each type. A target cue was displayed at the beginning of the trial and had black color (CIE *xy* = 0.267, 0.262; luminance = 1.073 cd/m^2). The stimuli were presented on gray background (CIE *xy* = 0.273, 0.304; luminance = 40.897 cd/m^2). There were always 20 items per display. On each trial there were one, two or no targets present. For one target, it could be high-salient or low-salient, for two targets, one was always high-salient and the other was always low-salient.

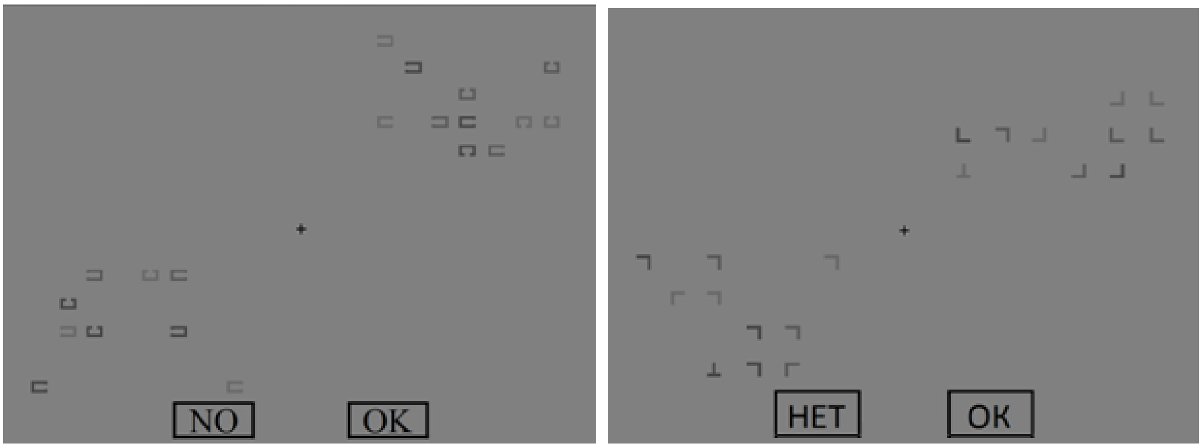

Fig. 1. An example of visual search display in Experiments 1, 2 and 3 (on the left) and in Experiment 4 (on the right). The “HET” button means “NO”.

The stimuli were displayed at the corners of the screen (upper left and lower right on the 50% of the trials and upper right and lower left on the 50% of the trials) in order not to infer with the WM task stimuli. In the dual-target condition, the targets could appear in different zones in 50% of trials and in the same zone in 50% of trials.

There were “NO” and “OK” buttons at the bottom of the screen, size each 6.43° × 3.25°. These buttons were used for participant answers. An example of visual search display is presented in *Figure 1*.

Procedure

The experiment consisted of 160 trials. In 40 trials the target was not present (catch-trials), 80 trials included one target (40 trials with a high-salient target and 40 trials with a low-salient target), 40 trials included two targets. The order of presentation was randomized.

The participant’s task was to find all the target stimuli or report their absence. The type of target stimuli (the gap location) was indicated at the beginning of each trial at the center of the screen using a black image of the target stimuli. This image was displayed for 1000 ms.

The participants reported the target stimuli by clicking them with the mouse. The participant reported the absence of target stimuli by clicking the “NO” button at the bottom of the screen. The participant made two clicks in each trial. For two targets, one click on each target was made. For one target, the first click was on target and the second on “OK” button. For no targets, two clicks on “NO” button were made. After the first target was found, it was still present on the screen.

Each trial had a limit of 20 s., after which the screen cleared. The participant pressed the “space” bar to begin the next trial. The participant could take the small breaks during the experiment. The participants were instructed to perform both fast and accurately.

A training session of 5 trials preceded the experiment.

Visual search + working memory task

Stimuli

The stimuli were the same as the WM and VS tasks.

Procedure

The trial started with the target presentation (1000 ms), followed by a 500 ms ISI. After that, the sample display with the WM task was displayed for 500 ms, followed by a 500 ms ISI. Then the search array was displayed. After the participant finished searching for targets (after two mouse clicks), a 500 ms ISI appeared, and the participant gave the answer to the memory task. An example of experimental trial is presented in *Figure 2*.

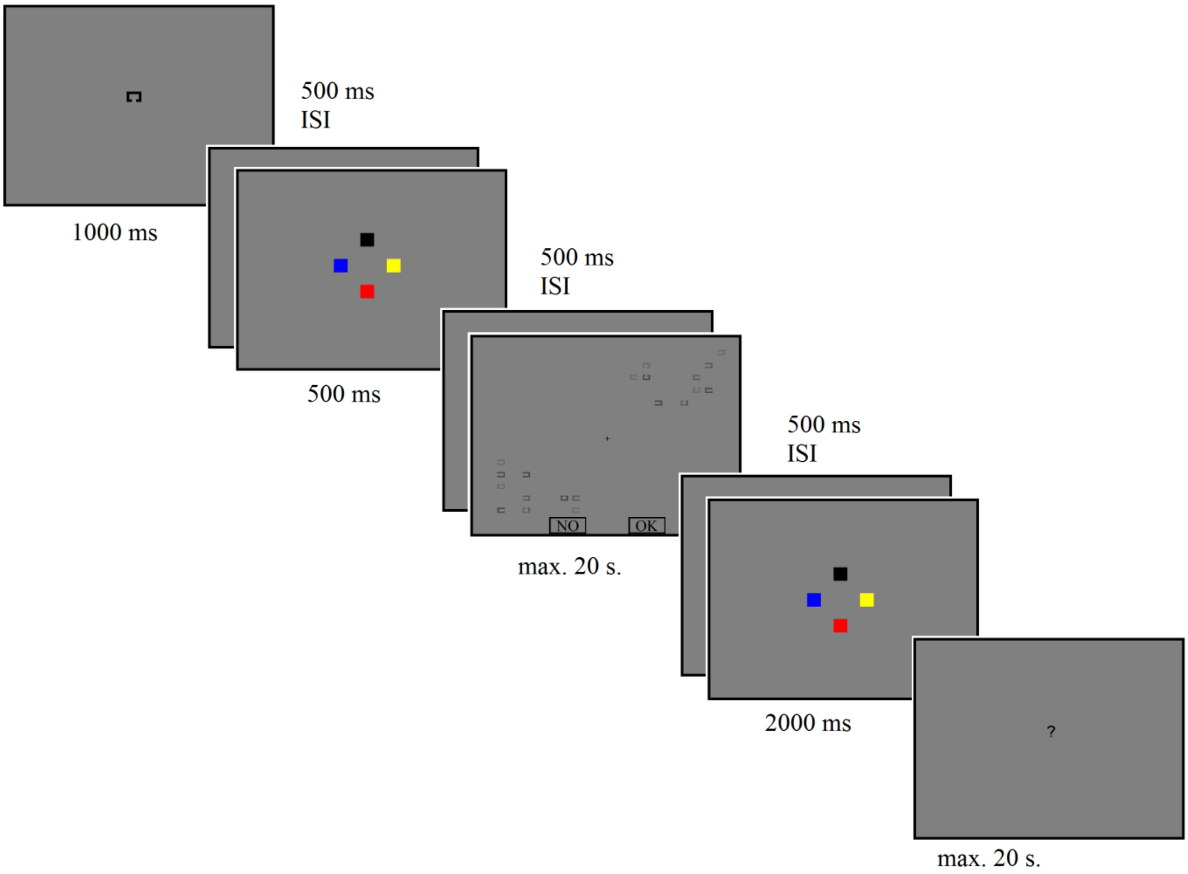

Fig. 2. Example of the stimulus sequence on a single trial for combined condition on experiment 1. For better picture quality, the relative sizes of memory task squares, target at the beginning of the trial and the "?" sign are twice the actual size.

This condition consisted of 160 trials. In 40 trials the target was not present (20 trials without changing the color of the squares, 20 trials changing the color of the squares), 80 trials included one target (40 trials with high-salient target (20 trials without changing the color of the squares, 20 trials changing the color of the squares) and 40 trials with low-salient target (20 trials without changing the color of the squares, 20 trials changing the color of the squares)), other trials included two targets (20 trials without changing the color of the squares, 20 trials changing the color of the squares). The order of presentation was randomized.

A training session of 5 trials preceded the experiment.

Results

For the visual search, accuracy and reaction time for conditions with two targets and one low-salient target were compared to the single visual search task and to the combined task. For the combined task, the analysis was conducted only for the correctly answered working memory task trials. The accuracy analysis calculated the percentage of correct answers for second low-salient target if the first high-salient target was found. Reaction time (RT) was calculated separately for the first and for the second mouse click. RT was calculated only for correct trials. RTs higher and lower than 2 SD's for each participant were excluded from the analysis.

For working memory, accuracy was compared to the single working memory task and for the combined task (for the one low-salient target and for the dual-target condition).

Data analysis was performed using SPSS 20.0. Repeated measures analyses of variance (rmANOVA) was used. Greenhouse-Geisser corrections were applied for significant Mauchly's sphericity tests. For visual search, the factors included the WM load (the VS task compared to the VS + WM task) and the number of targets (the one low-salient target condition compared to the dual-target condition). For working memory, the factor was the additional VS task (the WM compared to the combined condition with one low-salient target and two targets). Pairwise comparisons (with Bonferroni adjustment) were used.

The data for the one high-salient target condition and the no-target condition were not used in the statistical analysis but are reported in *Table 1*.

Visual search

Accuracy

RmANOVA revealed a significant effect for the number of targets, $F(1, 29) = 26.94$, $p = .000$, $\eta p^2 = 0.482$. The effect of the WM load is not significant, $F(1, 29) = 0.38$, $p = .54$, $\eta p^2 = 0.013$. The interaction is not significant, $F(1, 29) = 0.78$, $p = .38$, $\eta p^2 = 0.026$. The results are presented in *Figure 3*.

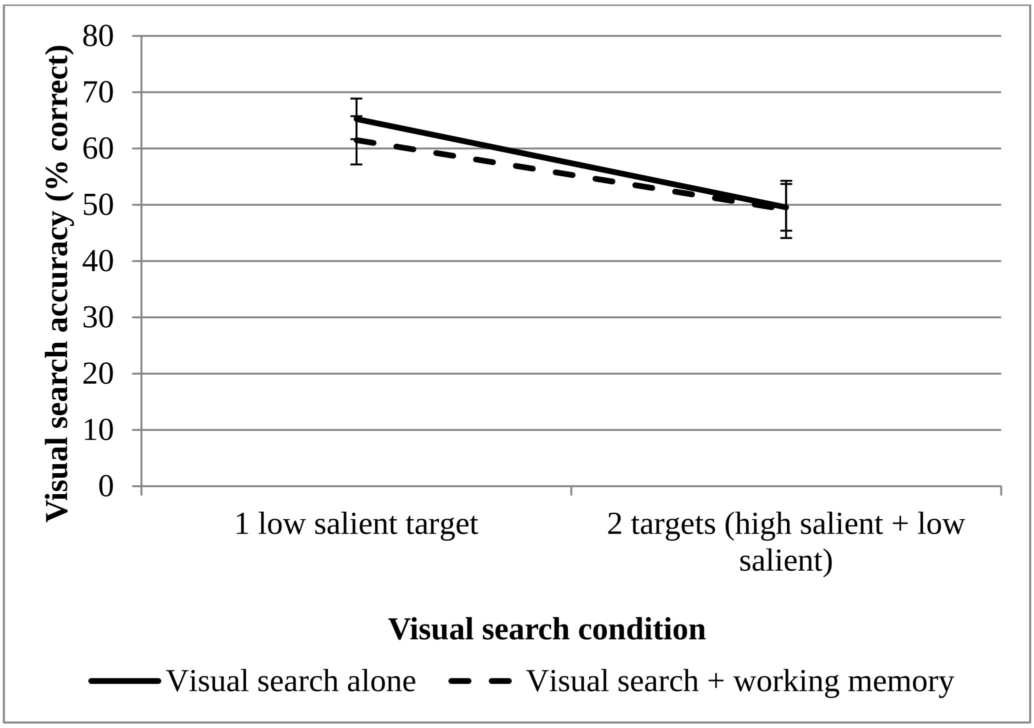

Fig. 3. The results of experiment 1 (accuracy data for visual search). Error bars represent standard error means.

Reaction time

For the first mouse click, rmANOVA revealed a significant effect for the number of targets, $F(1, 24^5) = 97.99$, $p = .000$, $\eta p^2 = 0.803$. The effect of the WM load is not significant, $F(1, 24) = 0.08$, $p = .787$, $\eta p^2 = 0.003$. The interaction is significant, $F(1, 24) = 7.06$, $p = .014$, $\eta p^2 = 0.227$. Pairwise comparisons revealed no significant differences between different levels of load (the

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[5] The df for RT data is less than 29 because some of the participants failed to find any targets in some conditions, that's why the dataset for RT contained less measurements.

VS task compared to the VS + WM task) both for single low salient target condition, p = .709 and for dual target condition, p = .366.

For the second mouse click, rmANOVA revealed a significant effect for the number of targets, $F(1, 25) = 9.76$, $p = .004$, $\eta p^2 = 0.281$. The effect of the WM load is not significant, $F(1, 25) = 0.30$, $p = .590$, $\eta p^2 = 0.012$. The interaction is significant, $F(1, 25) = 5.22$, $p = .031$, $\eta p^2 = 0.173$. Pairwise comparisons revealed no significant differences between different levels of load (the VS task compared to the VS + WM task) both for single low-salient target condition, p = .720 and for the dual-target condition, p = .897.

The results are presented in *Figure 4* and *Figure 5*.

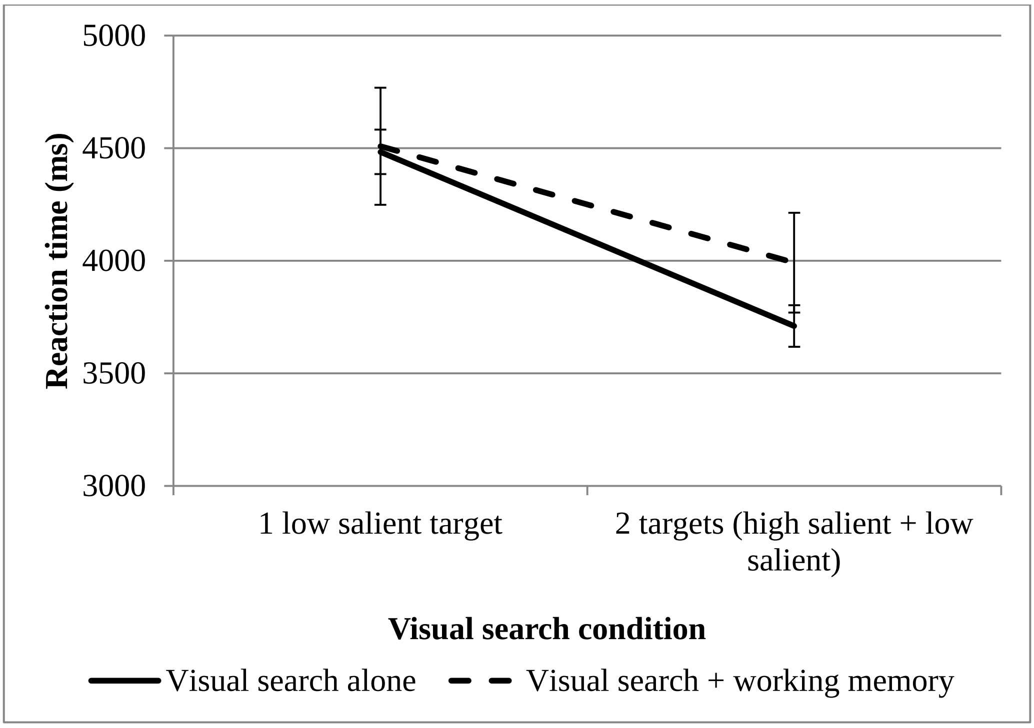

Fig. 4. The results of experiment 1 (RT of the first mouse click for visual search). Error bars represent standard error means.

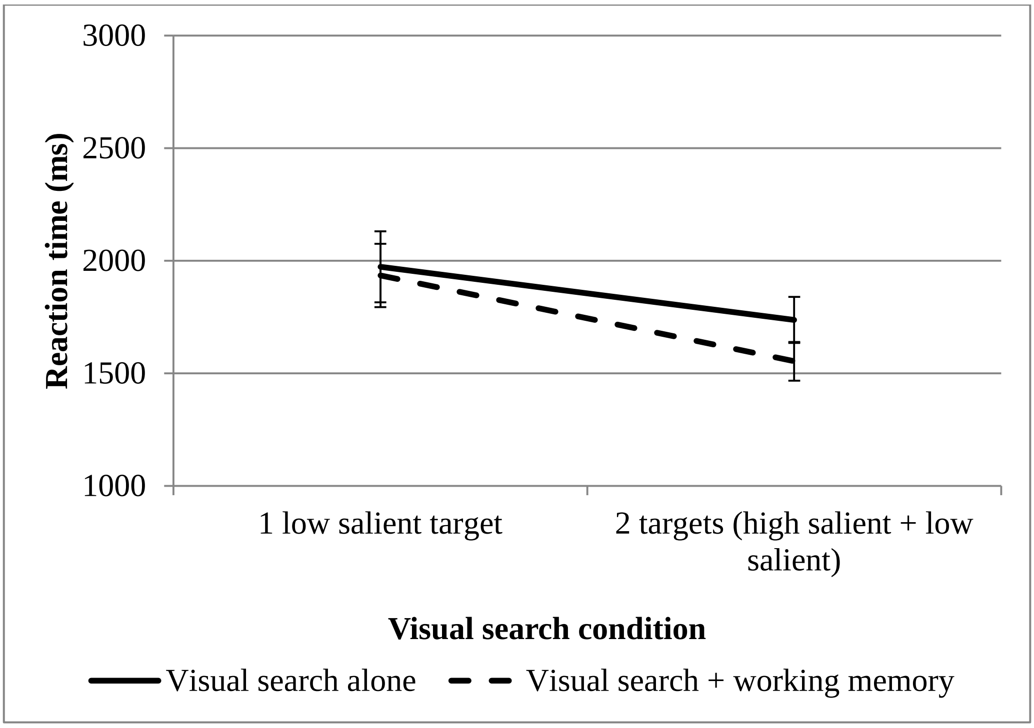

Fig. 5. The results of experiment 1 (RT of the second mouse click for visual search). Error bars represent standard error means.

Working memory

RmANOVA revealed the significant effect of condition, $F(2, 46) = 8.51$, $p = .002$, $\eta p^2 = 0.227$. But pairwise comparisons (Bonferroni corrected) did not reveal significant differences between the dual-target condition ($M = 76.92$, $SD = 15.04$) and the single low-salient target condition ($M = 76.33$, $SD = 15{,}07$), $p = .721$[6]. The results are presented in *Figure 6*.

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[6] The Bonferroni corrected alpha is .017 due to three comparisons conducted.

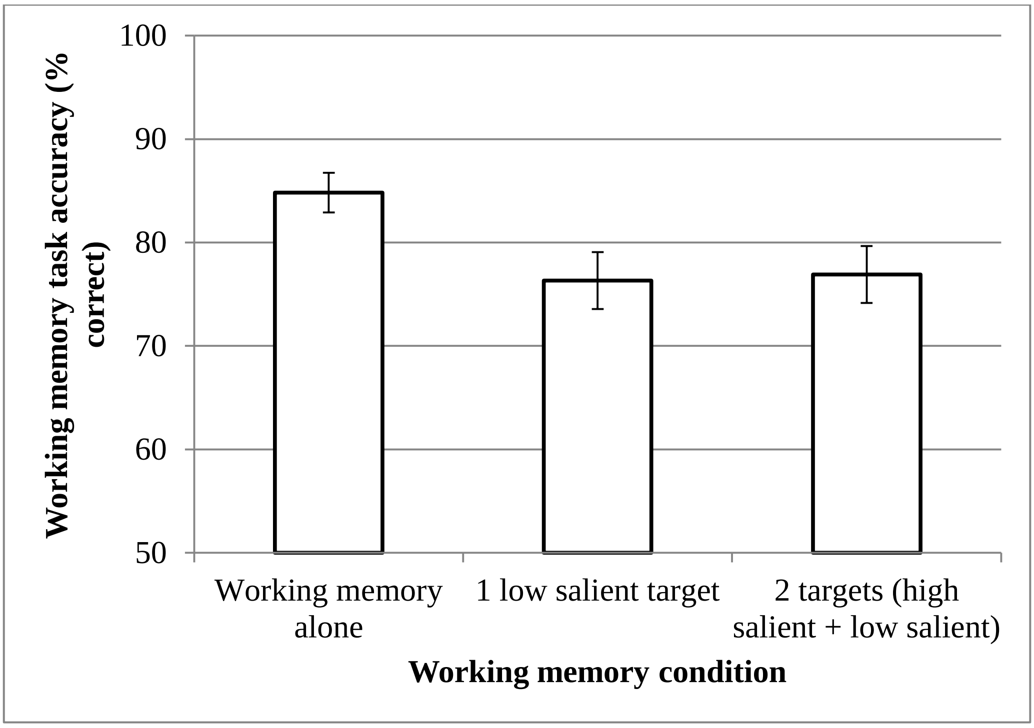

Fig. 6. The results of experiment 1 (working memory task). Error bars represent standard error means.

Discussion

Our results revealed a significant effect for the number of targets: the SSM effect (the decrease in accuracy in the detection of a second, low-salient, target after the first, high-salient, target was found) was present both for the VS condition and for the VS + WM condition. Additional WM load did not affect the visual search accuracy for either the single low-salient target condition or the dual-target condition. The WM task accuracy was also similar for the single low-salient target condition and the dual-target condition. This result is inconsistent with the predictions made by the resource depletion theory, which considers the object working memory as the resource. If the dual-target visual search and the color memorization task required the same recourses, interference would be observed, but no interference was observed in our experiment.

The RT of the first mouse click was lower for the dual-target condition compared to the single low-salient target condition. As the first target found in the dual-target condition was considered high-salient, this result is quite obvious: it takes less time to find a high-salient target than a low-salient target. There is a slight difference in the VS task and the VS + WM task for the dual-target condition, revealed by rmANOVA but not revealed by pairwise comparisons, supposing a longer RT for the VS + WM condition. This might be explained by the fact that the additional memory task requires more resources and thus extends the search time; this pattern is observed only for high-salient targets (as in the dual-target condition, the first target found is high-salient). A possible explanation may be the floor effect for a single low-salient target: it takes such a long time (4483.23 ms) to find the target and to make a mouse click in the VS condition that the additional memory load does not matter much. However, as the difference between the VS and the VS + WM conditions is not revealed by pairwise comparisons, this difference should be treated with caution.

The RT of the second mouse click (which was made on the low-salient target in the dual-target condition and on the OK button in the single low-salient target condition) was also shorter for the dual-target condition as compared to the single low-salient target condition. This result is consistent with our recent results on dual-target visual search where a similar paradigm was used (Gorbunova, 2017) and with the results from a visual search task with one target, where the RT increased in trials when the target was absent compared to trials when the target was present (e.g. Kwak, Dagenbach, & Egeth, 1991; Moraglia, 1989).

Overall, the results of this experiment contradict the idea that object working memory depletion is the reason for the SSM effect. Nevertheless, there might be a possibility for separate memory stores for individual, basic features of an object, such as size, color, and orientation (Alvarez & Cavanagh, 2004). For that reason, a color WM task would not affect a shape dual-target visual search. In Experiment 2, we address this issue.

Experiment 2

In this experiment, we changed the WM task paradigm. We considered that a shape memorization task would be more appropriate to reveal the role of the object working memory in a dual-target visual search with targets defined by shape.

Method

Participants

24 new volunteers, 3 male and 21 female, students of National Research University Higher School of Economics participated in the study. All of them were native Russian speakers with normal or corrected to normal vision. The age varied between 17 and 20 years (*M* = 19.00, *SD* = 0.90). All participants were naive to the experimental hypothesis.

The experiment included three conditions: a working memory (WM) task, a visual search (VS) task and a combined task for working memory and visual search (VS + WM). The order of presentation was counterbalanced across subjects. Articulatory suppression was used during the whole experiment to avoid the possibility of verbal coding.

Apparatus

The apparatus was the same as used in Experiment 1.

Working memory task

Stimuli

The stimuli had 6 varying shapes: pentagon, diamond, triangle, oval, cross and square. They were drawn with unfilled black lines. The stimuli size was 1.15° × 2.32°. The stimuli and an example of a WM task display are presented in *Figure 7*. The stimuli were presented on gray background (CIE *xy* = 0.273, 0.304; luminance = 40.897 cd/m^2). There were always 4 items per display.

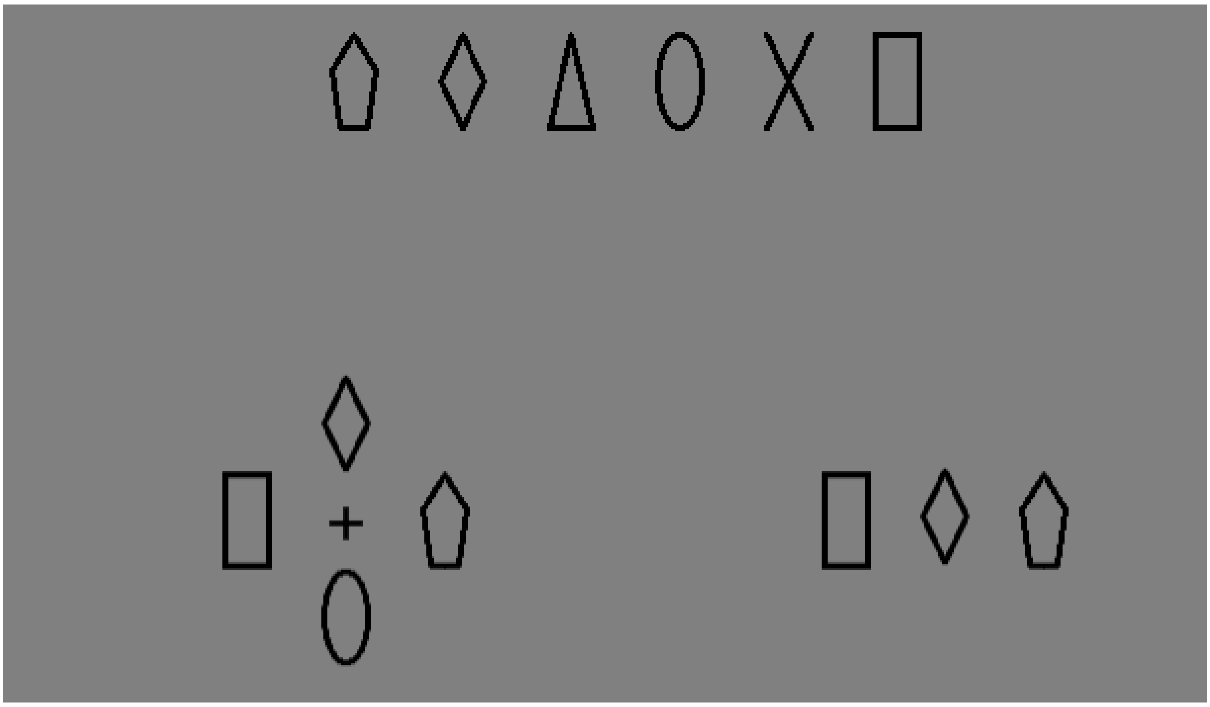

Fig. 7. The stimuli used in Experiments 2 and 3 (at the top) and the example of the working memory task display of Experiment 2 (at the bottom, on the left) and Experiment 3 (at the bottom, on the right).

Procedure

The procedure was similar to Experiment 1, except the task of the participants was to memorize the shapes of the stimuli rather than the color. The participant's task was to remember the initial shapes of the figures of the sample array and to report if the test array is the same as the sample array or not. In 50% trials, the sample array was the same as the test array, in the other 50% trials, one of the shapes was changed.

Visual search task

The stimuli and the procedure were the same as in Experiment 1.

Visual search + working memory task

The stimuli and the procedure were similar to Experiment 1, except the task of participant was to memorize the shapes of stimuli rather than the color (as in the WM task from this experiment).

Results

The apparatus and methods of data analysis were the same as in Experiment 1. The data for the one high-salient target condition and the no-target condition was not used in the statistical analysis but is reported in *Table 2*.

Visual search

Accuracy

RmANOVA revealed a significant effect for the number of targets, *F*(1, 23) = 15.70, *p* = .001, ηp^2 = 0.406. The effect of the WM load is also significant, *F*(1, 23) = 8.01, *p* = .009, ηp^2 = 0.258. The interaction is not significant, *F*(1, 23) = 0.23, *p* = .638, ηp^2 = 0.010. The results are presented in *Figure 8*.

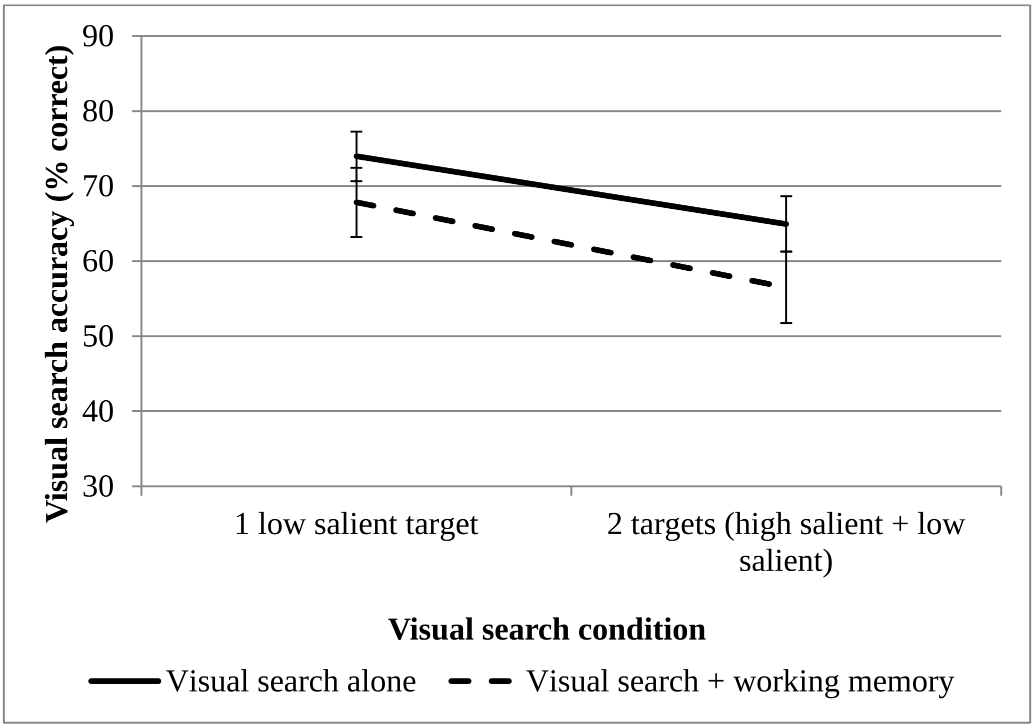

Fig. 8. The results of experiment 2 (accuracy data for visual search). Error bars represent standard error means.

Reaction time

For the first mouse click, rmANOVA revealed a significant effect for the number of targets, *F*(1, 21[7]) = 61.69, *p* = .000, ηp^2 = 0.746. The effect of the WM load is significant, *F*(1, 21) = 6.08, *p* = .022, ηp^2 = 0.224. The interaction is not significant, *F*(1, 21) = 2.72, *p* = .114, ηp^2 = 0.115.

For the second mouse click, rmANOVA revealed a significant effect for the number of targets, *F*(1, 22) = 40.08, *p* = .000, ηp^2 = 0.646. The effect of the WM load is not significant, *F*(1, 22) = 0.27, *p* = .611, ηp^2 = 0.012. The interaction is not significant, *F*(1, 22) = 0.15, *p* = .705, ηp^2 = 0.007.

The results are presented in *Figure 9* and *Figure 10*.

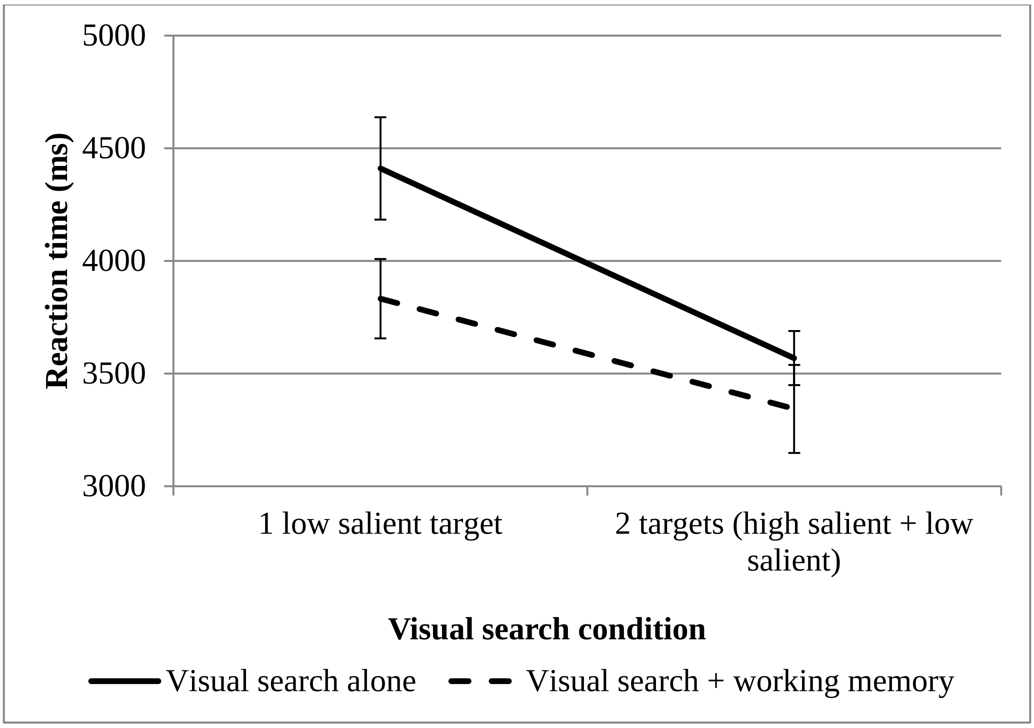

Fig. 9. The results of experiment 2 (RT of the first mouse click for visual search). Error bars represent standard error means.

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[7] The df for RT data is less than 23 because some of the participants failed to find any targets in some conditions, that's why the dataset for RT contained less measurements.

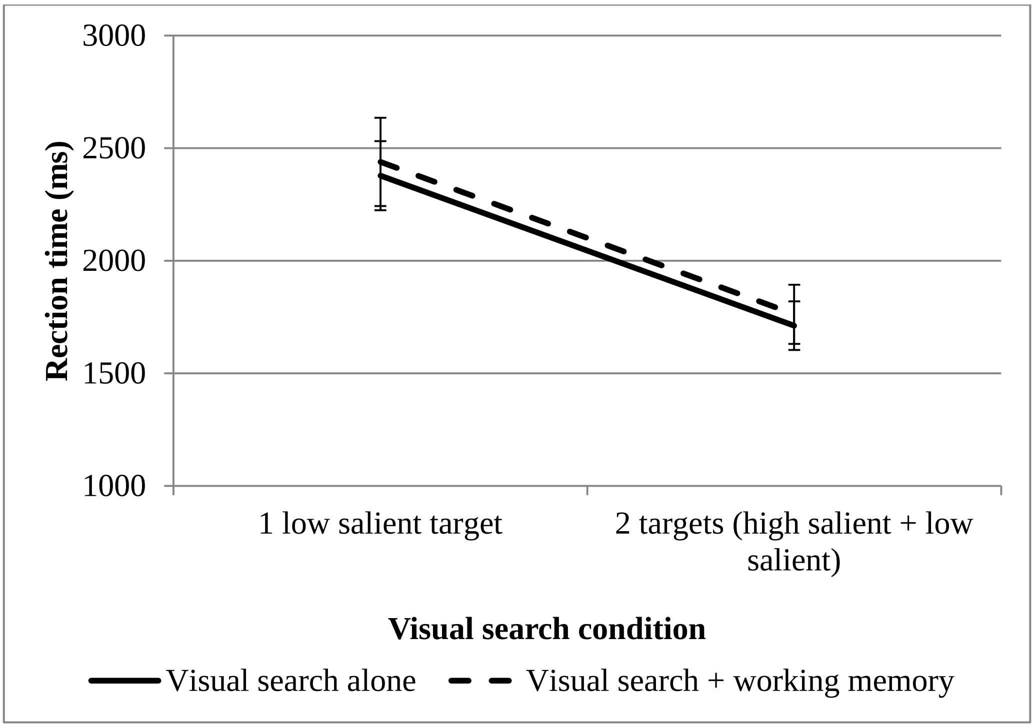

Fig. 10. The results of experiment 2 (RT of the second mouse click for visual search). Error bars represent standard error means.

Working memory

RmANOVA revealed a significant effect condition, *F*(2, 46) = 10.86, *p* = .002, ηp^2 = 0.321. Pairwise comparisons (Bonferroni corrected) revealed significant differences between the dual-target condition (*M* = 61.04, *SD* = 10.96) and the single low-salient target condition (*M* = 67.29, *SD* = 12.16), *p* = .008[8] and between the dual-target condition (*M* = 61.04, *SD* = 10.96) and the WM condition (*M* = 71.25, *SD* = 7.46), *p* = .000. The differences between the WM condition (*M* = 71.25, *SD* = 7.46) and the single low-salient target condition (*M* = 67.29, *SD* = 12.16) are not significant, *p* = .105. The results are presented in *Figure 11*.

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[8] The Bonferroni corrected alpha is .017 due to three comparisons conducted.

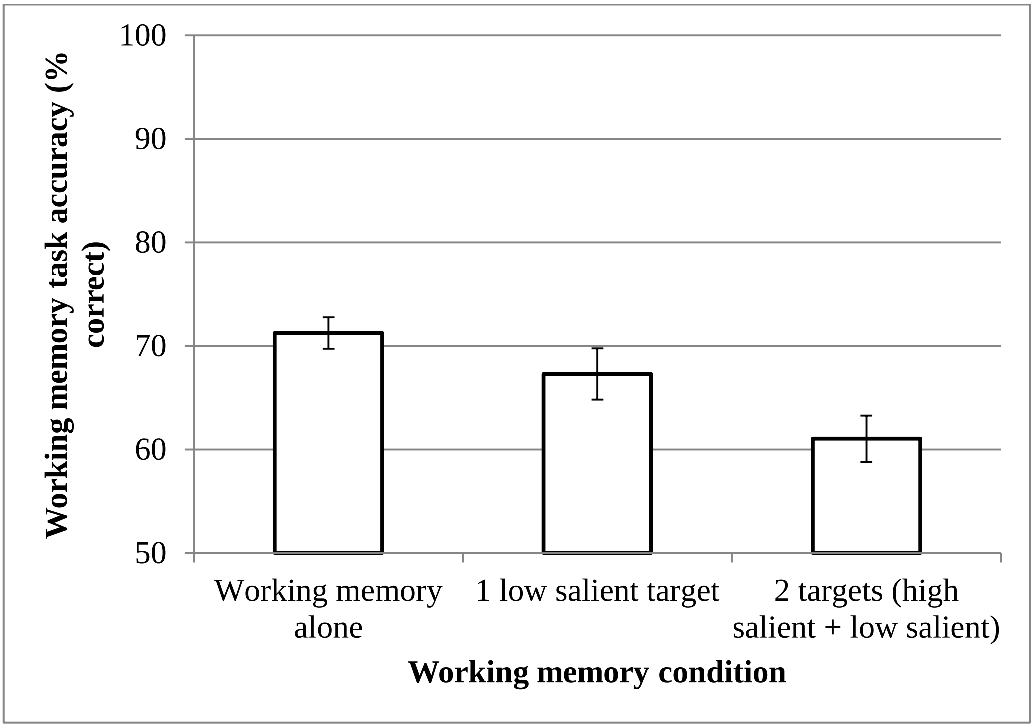

Fig. 11. The results of experiment 2 (working memory task). Error bars represent standard error means.

Discussion

As in Experiment 1, this experiment revealed a significant effect for the number of targets: SSM was present both for the VS condition and for the VS + WM condition. The role of the WM load was significant: the accuracy decreased in the VS + WM condition compared to the VS condition both for the single and the dual-target conditions. Nevertheless, the accuracy decreased with the additional WM load equally for the single and the dual-target conditions. This may indicate the general interference between the WM and the VS tasks, but no specific interference in the dual-target search condition. However, this specific interference is revealed in the WM task: the accuracy for the WM task decreased for the dual-target condition compared to the WM and the VS + WM single-target condition.

These results indicate that the dual-target search and the shape memorization task share a common resource. However, this is not a clear argument for the object memory resource depletion theory, assuming that the representation of the first target is loaded in the working memory system, depleting its resources and causing the second target omission. The additional

WM task had no specific influence on the dual-target search, but the additional VS task decreased the WM task accuracy. This could mean that the representations of the first and the second target are loaded in the working memory system and inhibit the working memory recall of the previously encoded stimuli. The single-target trials do not cause this violation because the WM capacity is big enough to hold the representations of shapes for memorization and the first target identity, whereas the second target representation causes WM overload and the decrease in the accuracy of WM recall. The second target omission is not related to working memory resource depletion, at least in a direct way.

The RT for the first mouse click is surprisingly lower for the VS + WM condition compared to the VS condition. This pattern is similar for both the single- and the dual-target condition. This might reflect the tendency of participants to make a mouse click as fast as possible in the VS + WM condition in order not to lose the items held in the working memory during the VS trial, as well as a speed-accuracy trade off.

The RT of the first mouse click was lower for the dual-target condition compared to the single low-salient target condition. The RT of the second mouse click was also lower for the dual-target condition compared to the single low-salient target condition. These results are the same as the findings of Experiment 1.

Overall, the results of this experiment revealed interference between the WM and the VS tasks. Yet, the overall pattern of results shows a speed-accuracy trade off: the VS condition had better accuracy and a faster first mouse click compared to the combined condition. Another point is the lower working memory alone accuracy in the working memory alone condition compared to Experiment 1, and greater task complexity as reported by the subjects. For that reason, another experiment was conducted.

Experiment 3

The procedure of this experiment was similar to Experiment 2. The only difference is that the WM task included three objects, instead of four, for memorization. This manipulation was conducted in order to reduce overall task complexity.

Method

Participants

24 new volunteers, 5 male and 19 female, students of National Research University Higher School of Economics participated in the study. All of them were native Russian speakers with normal or corrected to normal vision. The age varied between 19 and 22 years (*M* = 20.17, *SD* = 0.76). All participants were naive to the experimental hypothesis.

The experiment included three conditions: a working memory (WM) task, a visual search (VS) task and a combined task for working memory and visual search (VS + WM). The order of presentation was counterbalanced across subjects. Articulatory suppression was used during the whole experiment to avoid the possibility of verbal coding.

Apparatus

The apparatus was the same as used in Experiments 1 and 2.

Working memory task

Stimuli

The stimuli were the same as in Experiment 2, except on each trial three (instead of four) shapes were displayed. The stimuli and an example of the WM task display are presented in *Figure 7.*

Procedure

The procedure was the same as in Experiment 2.

Visual search task

The stimuli and the procedure were the same as in Experiments 1 and 2.

Visual search + working memory task

The stimuli and the procedure were similar to Experiment 2, except the task of participant was to memorize three shapes instead of four.

Results

The apparatus and methods of data analysis were the same used in Experiments 1 and 2. The data for the one high-salient target condition and the no-target condition were not used in the statistical analysis but are reported in *Table 3*.

Visual search

Accuracy

RmANOVA revealed a significant effect for the number of targets, $F(1, 23) = 6.96$, $p = .015$, $\eta p^2 = 0.232$. The effect of the WM load is not significant, $F(1, 23) = 0.01$, $p = .910$, $\eta p^2 = 0.001$. The interaction is not significant, $F(1, 23) = 0.62$, $p = .441$, $\eta p^2 = 0.026$. The results are presented in *Figure 12*.

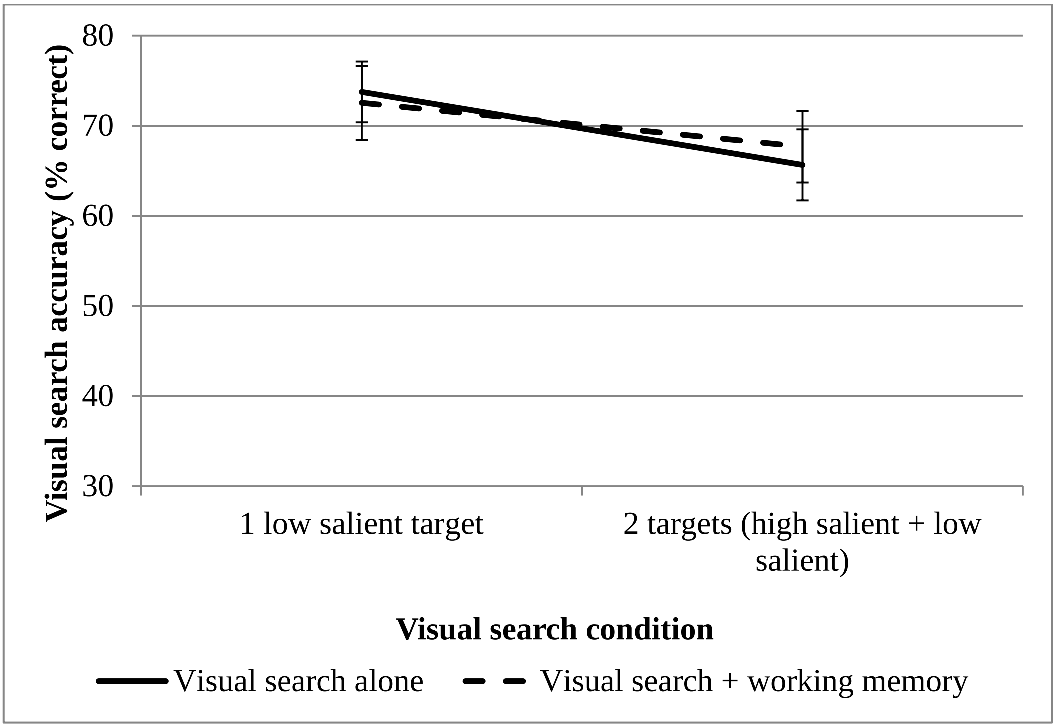

Fig. 12. The results of experiment 3 (accuracy data for visual search). Error bars represent standard error means.

Reaction time

For the first mouse click, rmANOVA revealed a significant effect for the number of targets, $F(1, 23) = 33.87$, $p = .000$, $\eta p^2 = 0.596$. The effect of the WM load is not significant, $F(1, 23) = 0.03$, $p = .866$, $\eta p^2 = 0.001$. The interaction is significant, $F(1, 23) = 5.29$, $p = .031$, $\eta p^2 = 0.187$. Pairwise comparisons revealed no significant differences between different levels of load (the VS task compared to the VS + WM task) both for the single low-salient target condition, $p = .277$ and for the dual-target condition, $p = .347$.

For the second mouse click, rmANOVA revealed a significant effect for the number of targets, $F(1, 23) = 32.46$, $p = .000$, $\eta p^2 = 0.585$. The effect of the WM load is not significant, $F(1, 23) = 1.35$, $p = .257$, $\eta p^2 = 0.055$. The interaction is significant, $F(1, 23) = 5.34$, $p = .030$, $\eta p^2 = 0.188$. Pairwise comparisons revealed no significant differences between different levels of load (the VS task compared to the VS + WM task) both for the single low-salient target condition, $p = .080$ and for the dual-target condition, $p = .608$.

The results are presented in *Figure 13* and *Figure 14*.

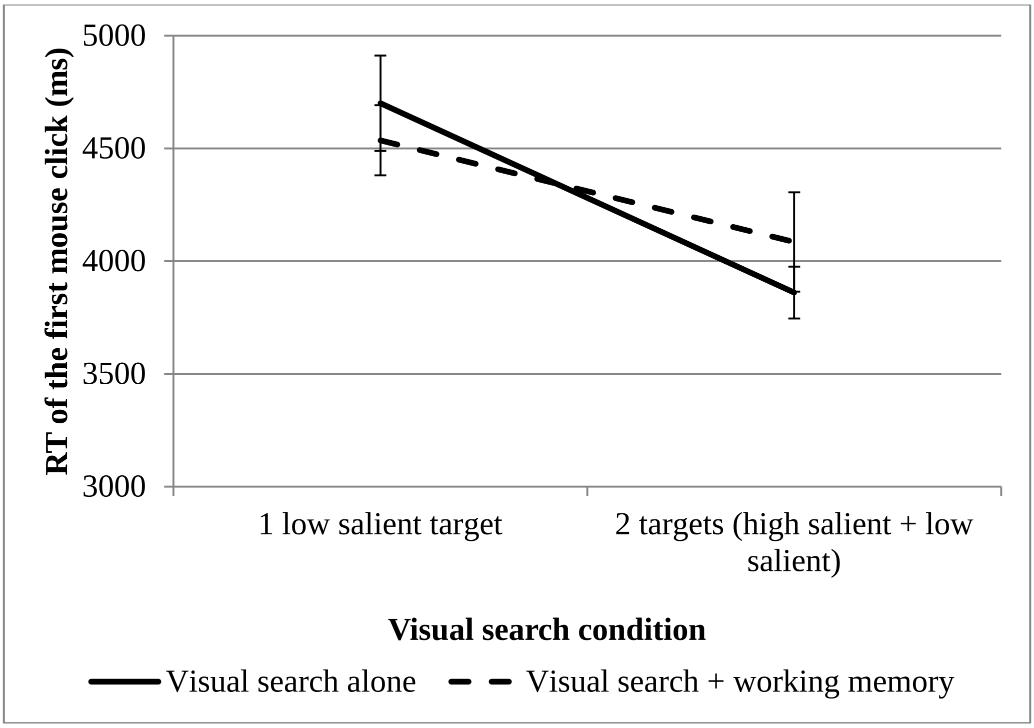

Fig. 13. The results of experiment 3 (RT of the first mouse click for visual search). Error bars represent standard error means.

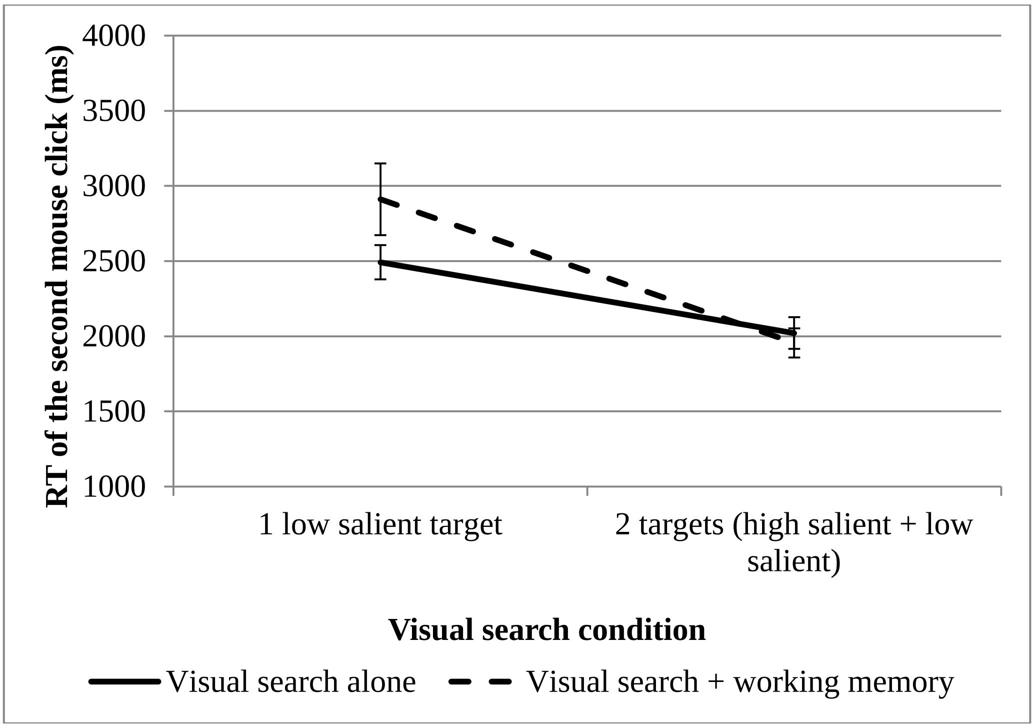

Fig. 14. The results of experiment 3 (RT of the second mouse click for visual search). Error bars represent standard error means.

Working memory

RmANOVA revealed a significant effect for the condition, *F*(2, 37) = 14.61, *p* = .000, ηp^2 = 0.388. Pairwise comparisons (Bonferroni corrected) revealed significant differences between the dual-target condition (*M* = 75.21, *SD* = 15.62) and the single low-salient target condition (*M* = 79.38, *SD* = 13.64), *p* = .010[9] and between the dual-target condition (*M* = 75.21, *SD* = 15.62) and the WM condition (*M* = 85.79, *SD* = 9.54), *p* = .000. The differences between the WM condition (*M* = 85.79, *SD* = 9.54) and the single low-salient target condition (*M* = 79.38, *SD* = 13.64) are also significant, *p* = .003. The results are presented in *Figure 15*.

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[9] The Bonferroni corrected alpha is .017 due to three comparisons conducted.

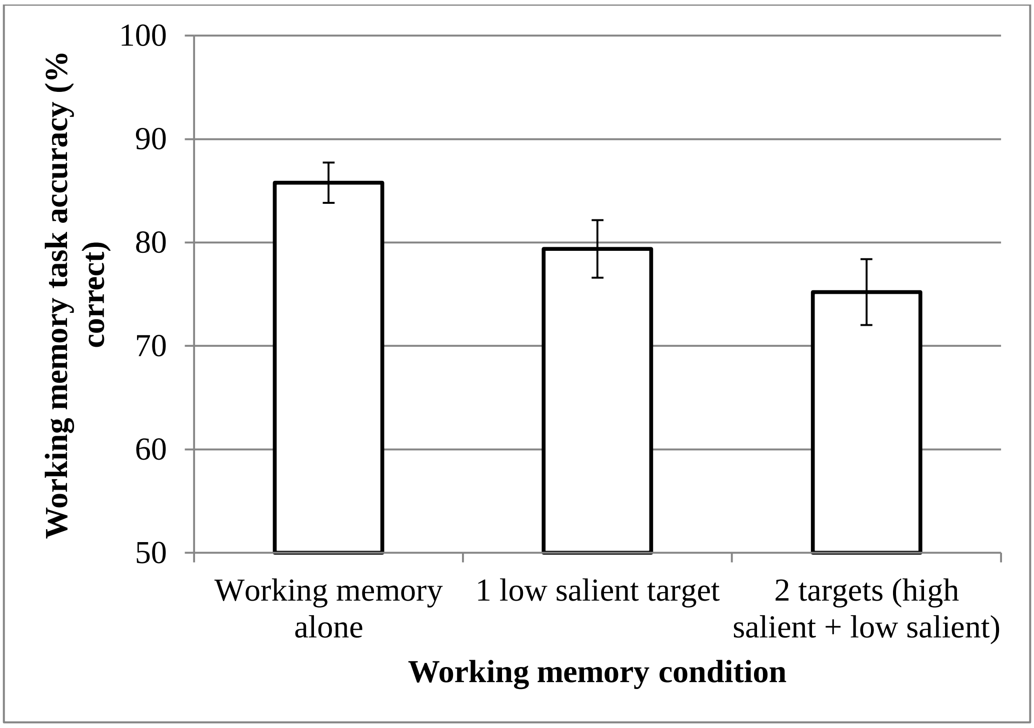

Fig. 15. The results of experiment 3 (working memory task). Error bars represent standard error means.

Discussion

As Experiments 1 and 2, this experiment revealed a significant effect for the number of targets: SSM was present both for the VS condition and for the VS + WM condition. The results of this experiment are the same as for Experiment 2 for the WM task, where the accuracy of the WM task decreased with the number of targets in the VS task, revealing interference between the dual-target search task and the WM task. This is consistent with the idea of interference between the WM and VS tasks. The WM task accuracy is comparable with Experiment 1, indicating similar task complexity.

The results of this experiment differ from Experiment 2 for the visual search task: in this experiment, no difference in accuracy was found for the VS condition and the VS+WM condition. The effect of the WM load is also not significant for the first and second mouse clicks. This reflects the absence of a speed-accuracy trade-off, observed in the previous experiment.

In this experiment, we also replicated the results for RT data from Experiments 1 and 2: The RT of the first and the second mouse click was lower for the dual-target condition compared to the single low-salient target condition. The difference between Experiment 1 and Experiment 2 is the interaction between the WM load factor and the number of targets: the VS + WM task assumes a slight increase of the RT for the single low-salient target condition, however, this was not detected by pairwise comparisons. This might be a sign that an increased WM load extends the time required to report the target absence.

Overall, this experiment replicated the results of Experiment 2 in the part related to the shape WM task and the dual-target visual search interference, with comparable results to Experiment 1 for the WM task accuracy and without a speed-accuracy trade-off for the VS task, observed in Experiment 2. In this way, the results of this experiment revealed a violation of the WM task with the additional dual-target VS task but not a violation of the dual-target VS task with the additional WM task.

Given the important role of spatial working memory in visual search (Oh & Kim, 2004; Woodman & Luck, 2004) there is a possibility that the locations of the first-found targets are encoded in the working memory and cause resource depletion. For that reason, Experiment 4 was conducted.

Experiment 4

In this experiment, we used a spatial working memory task to test whether the locations of the first-found target encoded in the working memory serve as the mechanism of subsequent search misses. We used the spatial WM task from Woodman & Luck (2004).

Method

Participants

30 new volunteers, 10 male and 20 female, students of National Research University Higher School of Economics participated in the study. All of them were native Russian speakers with normal or corrected to normal vision. The age varied between 17 and 25 years (*M* = 18.70, *SD* = 1.51). All participants were naive to the experimental hypothesis.

The experiment included three conditions: a working memory (WM) task, a visual search (VS) task and a combined task for working memory and visual search (VS + WM). The order of presentation was counterbalanced across subjects. Articulatory suppression was used during the whole experiment to avoid the possibility of verbal coding.

Apparatus

The apparatus was the same as used in Experiments 1-3.

Working memory task

Stimuli

Two black dots were displayed sequentially on opposite sides of a cross located in the center of the screen. The stimuli were presented in order not to overlap with the stimuli for visual search task. The size of the each dot was 0.41° × 0.41°.

Procedure

In the memory-only condition, the participants performed a location change detection task. Each trial began with the sequential presentation of two black dots that were used to indicate the to-be-remembered locations. Each dot was presented for 500 ms, and the two dots were separated by a 500 ms blank period. Subjects had to remember the positions of two dots and keep this information in working memory. The dots were presented sequentially to discourage subjects from forming a shape-based configural representation of the two locations (e.g., a line of a certain orientation). After the presentation of the two dots there was a blank interval (5000 ms), and then two dots appeared on the screen at the same time.

The working memory task consisted of 100 trials. In the half of the trials, two dots appeared at the same locations that they were presented at the first time. On the other half of the trials, one of the dots was shown at another location. Thus, the task was to make a two-alternative response to indicate whether a location change was detected. In this task, the subject used the keyboard to answer. If the answer was positive (the same location), subject pressed “Z” button. In the case of a negative response observer pressed “V” button. The order of presentation was random.

Visual search task

Stimuli

There were two types of stimuli in the visual search task: the target stimuli, which were T-letters, and the distractor stimuli, which were L-letters. The letters could have various orientations: 0°, 90°, 180°, 270°. In total, there were 20 stimuli in the trial display. The targets could be high-salient and low-salient, the distracters could have high, medium or low salience (the luminance was the same as in Experiments 1-3). On each trial, there could be one, two or no targets. For two targets, one was always high-salient and the other was low-salient. The stimuli size was 1.40° ×1.40°. There were 2 buttons ("NO" and "OK") at the bottom of the screen, used for participant responses. Size of each button was 6.85° × 4.32°. The example of the VS trial is displayed in Figure 1.

Procedure

The procedure was the same as in Experiments 1-3. This experimental condition consisted of 100 trials. 25% of displays had no targets, 25% had a single low-salience target, and 25% of trials had a single high-salience target, while remaining 25% had a low-salience and a high-salience target. The sequence of presentation was random.

Visual search + working memory task

Stimuli

The stimuli were the same as the stimuli from the VS alone and the WM alone conditions.

Procedure

In this task the subject had to perform both tasks for working memory and visual search simultaneously. At the beginning of the trial, two dots were displayed for 500 ms each separated by a 500 ms ISI. After the presentation of two dots the stimuli for the visual search task appeared on the display. After the subject made a second mouse click in the VS task, two dots appeared on the screen and participant had to make a two-alternative response for the WM change location task.

This task consisted of 100 trials. In 25 trials, no target was present. In 25 trials, a single low-salient target was present. In 25 trials, a single high-salient target was present. 25 trials had both a low-salience and a high-salience target. The memory change-present and change-absent trials were distributed almost equally across the conditions. The order of presentation was randomized.

Results

The apparatus and methods of data analysis were the same as in Experiments 1-3. The data for the one high-salient target condition and the no-target condition was not used in the statistical analysis but is reported in *Table 4*.

Visual search

Accuracy

RmANOVA revealed a significant effect for the number of targets, $F(1, 29) = 9.31$, $p = .005$, $\eta p^2 = 0.243$. The effect of the WM load is not significant, $F(1, 29) = 0.03$, $p = .872$, $\eta p^2 = 0.001$. The interaction is not significant, $F(1, 29) = 1.01$, $p = .324$, $\eta p^2 = 0.034$. The results are presented in *Figure 16*.

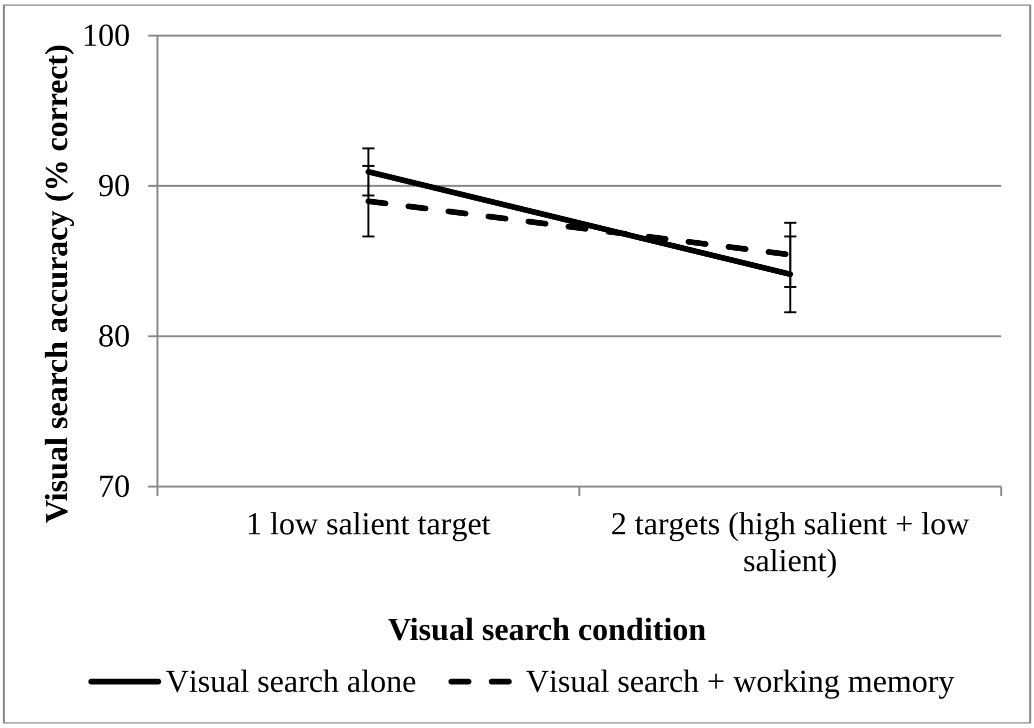

Fig. 16. The results of experiment 4 (accuracy data for visual search). Error bars represent standard error means.

Reaction time

For the first mouse click, rmANOVA revealed a significant effect for the number of targets, *F*(1, 29) = 134.90, *p* = .000, ηp^2 = 0.823. The effect of the WM load is also significant, *F*(1, 29) = 6.85, *p* = .014, ηp^2 = 0.191. The interaction is not significant, *F*(1, 29) = 0.54, *p* = .468, ηp^2 = 0.018.

For the second mouse click, rmANOVA revealed a significant effect for the number of targets, *F*(1, 29) = 40.06, *p* = .000, ηp^2 = 0.580. The effect of the WM load is not significant, *F*(1, 29) = 1.24, *p* = .275, ηp^2 = 0.041. The interaction is not significant, *F*(1, 29) = 0.61, *p* = .441, ηp^2 = 0.021.

The results are presented in *Figure 17* and *Figure 18*.

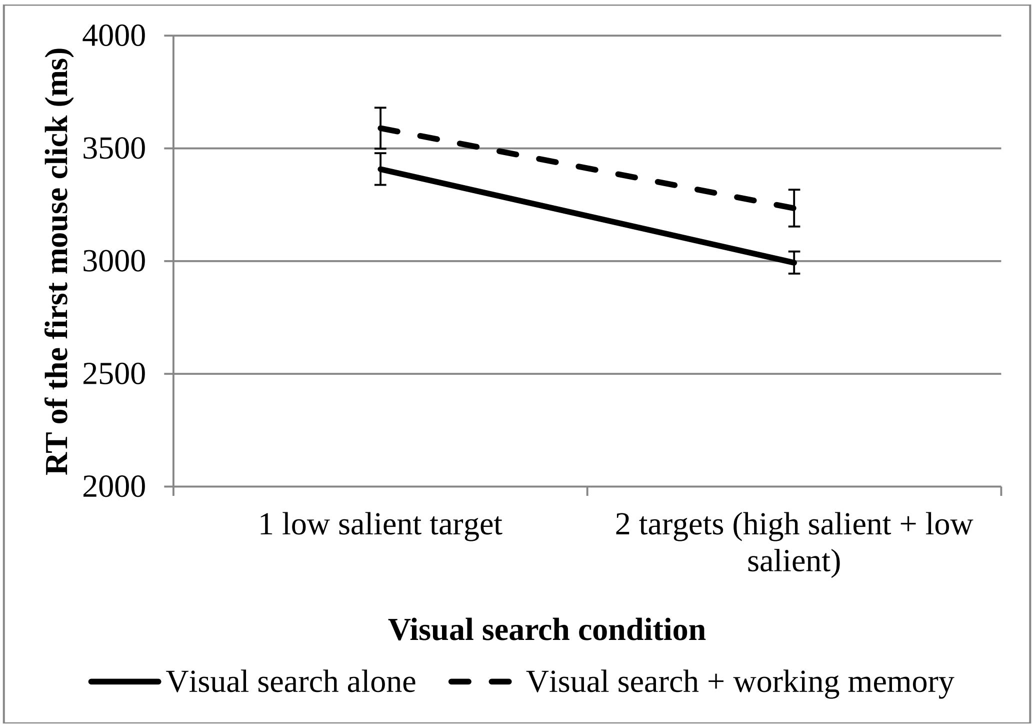

Fig. 17. The results of experiment 4 (RT of the first mouse click for visual search). Error bars represent standard error means.

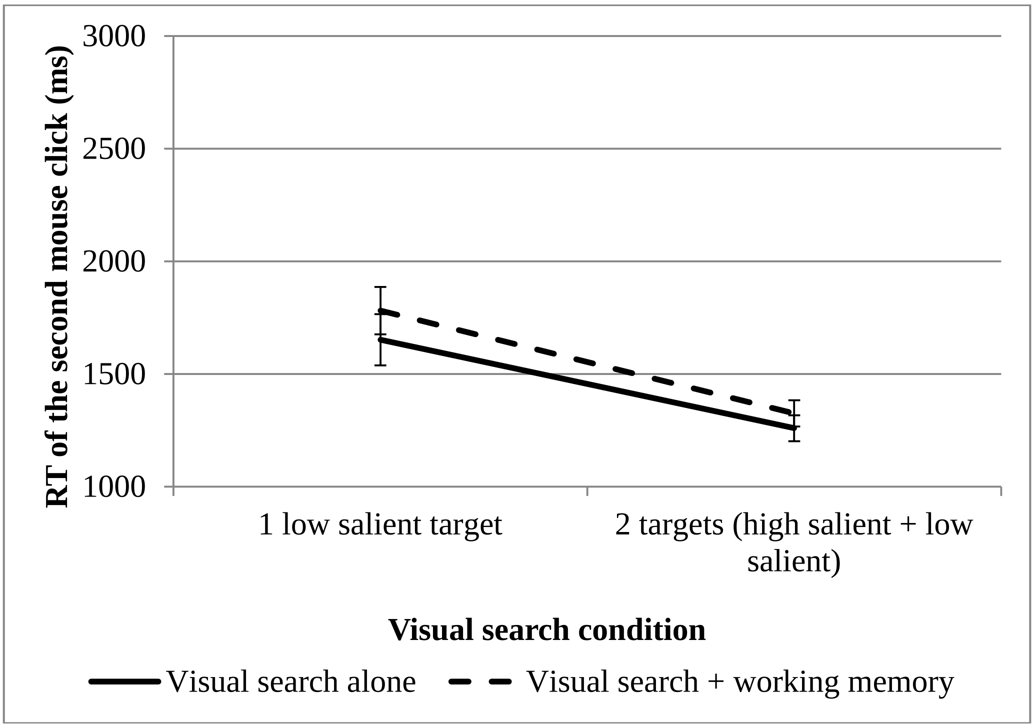

Fig. 18. The results of experiment 4 (RT of the second mouse click for visual search). Error bars represent standard error means.

Working memory

RmANOVA revealed a significant effect of condition, $F(2, 46) = 5.31$, $p = .013$, $\eta p^2 = 0.155$. But pairwise comparisons (Bonferroni corrected) did not reveal significant differences between the dual-target condition ($M = 74.93$, $SD = 15.96$) and the single low-salient target condition ($M = 73.60$, $SD = 19.58$), $p = .524$[10]. The results are presented in *Figure 19*.

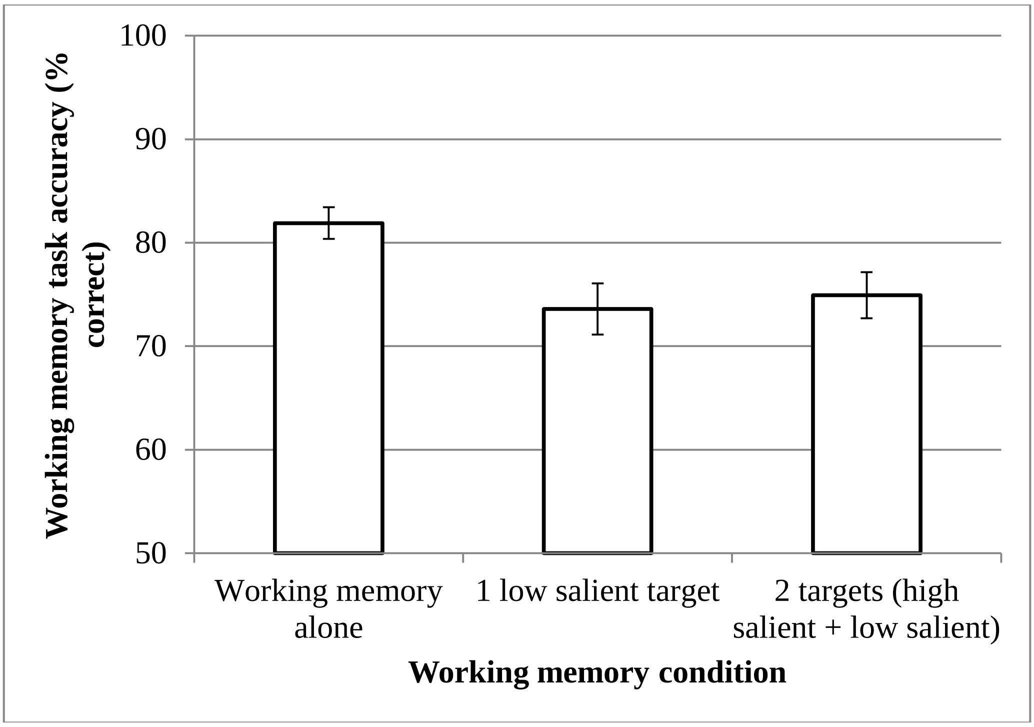

Fig. 19. The results of experiment 4 (working memory task). Error bars represent standard error means.

Discussion

As in Experiments 1-3, this experiment revealed a significant effect for the number of targets: SSM errors were present both for the VS condition and for the VS + WM condition. The effect of the working memory load is not significant for SSM errors: the visual search accuracy does not decrease with an additional spatial working memory load, and no significant differences were revealed in the WM task accuracy for the single low-salient and the dual-target conditions in the VS + WM task.

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[10] The Bonferroni corrected alpha is .017 due to three comparisons conducted.

Nevertheless, the RT of the first mouse click decreased with an additional spatial working memory load. This pattern is present both for the single low-salient target and the dual-target trials. This might be an indicator of general interference for the spatial working memory and visual search tasks: visual search requires spatial working memory to memorize the observed locations. For that reason, the visual search is slowed with an additional spatial working memory load. This result is consistent with the previous findings (Oh & Kim, 2004; Woodman & Luck, 2004). As this effect is not present for second mouse click, there is no reason to assume the special role of spatial working memory overload in SSM errors.

The RT of the first mouse click and the RT of the second mouse click are slower for the single low-salient target condition compared to the dual-target condition. These results are the same as in Experiments 1-3.

Overall, the results of this experiment revealed no impact of an additional spatial working memory load in SSM errors. This is an argument for SSM errors not being related to spatial working memory overload.

General discussion

Four experiments were conducted to reveal the role of a working memory deficit in SSM errors. The first experiment investigated the role of object working memory using a classical color change detection task. In the second and the third experiment, a modified change detection task was applied, using shape as the relevant feature. In the fourth experiment, a spatial working memory task was used to reveal the role of spatial working memory in SSM errors. The second and third experiments revealed significant interference between the working memory and visual search tasks, whereas the first and the fourth experiments did not reveal this pattern.

A dual-target visual search interferes with the object working memory task when the features used in the WM task are the same features that define the VS task: the interference is observed for the shape-based WM task and the shape-based VS task, but not for the shape-based VS task and the color-based WM task. This is an argument for separate storage of different features in working memory.

Overall, an additional dual-target VS task decreases WM task performance, but an additional WM task does not decrease dual-target VS task performance. This is the argument for WM recall being inhibited by VS stimuli and for the idea of general VS and WM task interference. But this cannot be assumed as an argument for the WM resource depletion theory as the second target omission probability does not increase with an additional WM load.

Although our experiments were conducted in the frame of working memory resource depletion theory as the explanation of SSM errors, the relation to perceptual similarity theory should be discussed as well. According to that theory, the first-found target creates a representation (similar to “an attentional template” (e.g. Carlisle et al., 2011)), which is responsible for creating a perceptual bias. The subject tends to search for perceptually similar targets and to miss perceptually dissimilar targets. This explanation is not necessarily contradictory to the resource depletion account: an attentional template can both cause resource overload and create perceptual bias. After the first-found target is encoded in the working memory, an attentional template is created. This attentional template might be stored in the working memory and guide the subsequent visual search. From this point of view, it is still possible to discuss the role of working memory as the relevant explanation of SSM errors. Thus, new experiments should be conducted, including the manipulation of both WM load and the perceptual similarity in dual-target visual searches. Another manipulation could use different stimuli for the WM task, more similar to the VS task stimuli.

Previous experiments using a single-target visual search revealed the role of spatial working memory, assuming that the observed locations are encoded during the visual search task. These locations are expected to be encoded during the dual-target visual search as well. After the first target is found, its location is encoded in spatial working memory, but this representation does not interfere with the subsequent search. This is an argument for the idea of functionally separable spatial and object working memory subsystems.

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Table 1. The results of Experiment 1.

Task	Condition	Index	Mean	SD
WM alone task	WM alone	WM accuracy	84.83333	10.47849
VS+WM task	WM+VS, no targets	WM accuracy	75.5	12.35956
	WM+VS, 1 high salient target	WM accuracy	74.91667	14.16472
	WM+VS, 1 low salient target	WM accuracy	76.33333	15.06785
	WM+VS, 2 targets	WM accuracy	76.91667	15.0385
VS alone task	VS alone, no targets	VS accuracy	92.08333	7.134283
	VS alone, 1 high salient target	VS accuracy	70.75	16.50692
	VS alone, 1 low salient target	VS accuracy	65.25	19.76533
	VS alone, 2 targets	VS accuracy	49.55986	22.73461
VS+WM task	VS+WM, no targets	VS accuracy	81.21532	15.49733
	VS+WM, 1 high salient target	VS accuracy	68.03649	19.51811
	VS+WM, 1 low salient target	VS accuracy	61.44893	23.58185
	VS+WM, 2 targets	VS accuracy	49.16633	27.96119
VS alone task	VS alone, no targets	1st click RT	5997.324	1019.468
	VS alone, 1 high salient target	1st click RT	4289.653	621.4847
	VS alone, 1 low salient target	1st click RT	4483.227	541.9617
	VS alone, 2 targets	1st click RT	3710.432	507.5245
VS+WM task	VS+WM, no targets	1st click RT	5759.598	1604.003
	VS+WM, 1 high salient target	1st click RT	4409.7	1389.292
	VS+WM, 1 low salient target	1st click RT	4508.816	1423.27
	VS+WM, 2 targets	1st click RT	3991.881	1213.851
VS alone task	VS alone, no targets	2nd click RT	238.8392	102.7953
	VS alone, 1 high salient target	2nd click RT	2048.843	777.2456
	VS alone, 1 low salient target	2nd click RT	1972.681	863.3099
	VS alone, 2 targets	2nd click RT	1736.784	559.3306
VS+WM task	VS+WM, no targets	2nd click RT	341.2473	291.4473
	VS+WM, 1 high salient target	2nd click RT	1867.157	751.7514
	VS+WM, 1 low salient target	2nd click RT	1934.086	770.3868
	VS+WM, 2 targets	2nd click RT	1553.204	472.4248

Table 2. The results of Experiment 2.

Task	Condition	Index	Mean	SD
WM alone task	WM alone	WM accuracy	71.25	7.461495
VS+WM task	WM+VS, no targets	WM accuracy	61.14583	12.06818
	WM+VS, 1 high salient target	WM accuracy	65.83333	14.66411
	WM+VS, 1 low salient target	WM accuracy	67.29167	12.15651
	WM+VS, 2 targets	WM accuracy	61.04167	10.95734
VS alone task	VS alone, no targets	VS accuracy	89.47917	10.63166
	VS alone, 1 high salient target	VS accuracy	71.97917	14.72537
	VS alone, 1 low salient target	VS accuracy	73.95833	16.23397
	VS alone, 2 targets	VS accuracy	64.9556	18.12575
VS+WM task	VS+WM, no targets	VS accuracy	85.59743	10.1687
	VS+WM, 1 high salient target	VS accuracy	67.88471	23.20995
	VS+WM, 1 low salient target	VS accuracy	67.83489	22.60844
	VS+WM, 2 targets	VS accuracy	56.49726	23.45048
VS alone task	VS alone, no targets	1st click RT	6327.325	1114.74
	VS alone, 1 high salient target	1st click RT	4203.567	587.7411
	VS alone, 1 low salient target	1st click RT	4410.755	595.8506
	VS alone, 2 targets	1st click RT	3568.186	614.8761
VS+WM task	VS+WM, no targets	1st click RT	5869.324	1229.589
	VS+WM, 1 high salient target	1st click RT	3741.486	996.5714
	VS+WM, 1 low salient target	1st click RT	3832.158	860.5495
	VS+WM, 2 targets	1st click RT	3342.801	955.3507
VS alone task	VS alone, no targets	2nd click RT	252.8139	105.7471
	VS alone, 1 high salient target	2nd click RT	2456.233	801.5538
	VS alone, 1 low salient target	2nd click RT	2377.864	750.0756
	VS alone, 2 targets	2nd click RT	1711.848	527.4701
VS+WM task	VS+WM, no targets	2nd click RT	291.3616	154.9606
	VS+WM, 1 high salient target	2nd click RT	2451.511	798.2391
	VS+WM, 1 low salient target	2nd click RT	2439.095	962.506
	VS+WM, 2 targets	2nd click RT	1761.982	646.4998

Table 3. The results of Experiment 3.

Task	Condition	Index	Mean	SD
WM alone task	WM alone	WM accuracy	85.79167	9.541576
VS+WM task	WM+VS, no targets	WM accuracy	78.54167	13.24757
	WM+VS, 1 high salient target	WM accuracy	81.5625	15.05086
	WM+VS, 1 low salient target	WM accuracy	79.375	13.63838
	WM+VS, 2 targets	WM accuracy	75.20833	15.61975
VS alone task	VS alone, no targets	VS accuracy	90.625	8.573531
	VS alone, 1 high salient target	VS accuracy	76.25	14.81773
	VS alone, 1 low salient target	VS accuracy	73.75	18.38596
	VS alone, 2 targets	VS accuracy	65.65467	21.67495
VS+WM task	VS+WM, no targets	VS accuracy	78.72762	17.56911
	VS+WM, 1 high salient target	VS accuracy	74.40494	13.84429
	VS+WM, 1 low salient target	VS accuracy	72.53367	22.44321
	VS+WM, 2 targets	VS accuracy	67.6629	21.71855
VS alone task	VS alone, no targets	1st click RT	6389.581	1159.015
	VS alone, 1 high salient target	1st click RT	4419.412	630.7079
	VS alone, 1 low salient target	1st click RT	4699.97	710.591
	VS alone, 2 targets	1st click RT	3860.571	667.3049
VS+WM task	VS+WM, no targets	1st click RT	6448.968	1168.982
	VS+WM, 1 high salient target	1st click RT	4387.281	890.1741
	VS+WM, 1 low salient target	1st click RT	4536.122	850.2184
	VS+WM, 2 targets	1st click RT	4084.631	1206.384
VS alone task	VS alone, no targets	2nd click RT	286.0606	167.6711
	VS alone, 1 high salient target	2nd click RT	2518.67	759.3444
	VS alone, 1 low salient target	2nd click RT	2491.664	623.4778
	VS alone, 2 targets	2nd click RT	2020.995	578.9655
VS+WM task	VS+WM, no targets	2nd click RT	400.4899	262.2409
	VS+WM, 1 high salient target	2nd click RT	2830.399	1226.713
	VS+WM, 1 low salient target	2nd click RT	2911.086	1312.184
	VS+WM, 2 targets	2nd click RT	1955.551	533.6348

Table 4. The results of Experiment 4.

Task	Condition	Index	Mean	SD
WM alone task	WM alone	WM accuracy	81.9	11.17679
VS+WM task	WM+VS, no targets	WM accuracy	74.53333	16.2899
	WM+VS, 1 high salient target	WM accuracy	74.13333	17.663
	WM+VS, 1 low salient target	WM accuracy	73.6	19.58465
	WM+VS, 2 targets	WM accuracy	74.93333	15.96318
VS alone task	VS alone, no targets	VS accuracy	89.33333	25.30549
	VS alone, 1 high salient target	VS accuracy	91.46667	6.94676
	VS alone, 1 low salient target	VS accuracy	90.93333	8.529597
	VS alone, 2 targets	VS accuracy	84.1161	13.85828
VS+WM task	VS+WM, no targets	VS accuracy	95.60352	6.357103
	VS+WM, 1 high salient target	VS accuracy	88.60622	14.38312
	VS+WM, 1 low salient target	VS accuracy	88.98366	12.79662
	VS+WM, 2 targets	VS accuracy	85.419	11.74775
VS alone task	VS alone, no targets	1st click RT	4286.337	685.7649
	VS alone, 1 high salient target	1st click RT	3363.349	451.3003
	VS alone, 1 low salient target	1st click RT	3408.209	388.0314
	VS alone, 2 targets	1st click RT	2993.211	266.1247
VS+WM task	VS+WM, no targets	1st click RT	4692.04	766.9928
	VS+WM, 1 high salient target	1st click RT	3597.154	543.3548
	VS+WM, 1 low salient target	1st click RT	3589.975	497.0616
	VS+WM, 2 targets	1st click RT	3234.58	446.7008
VS alone task	VS alone, no targets	2nd click RT	262.4448	293.0899
	VS alone, 1 high salient target	2nd click RT	1665.43	690.5949
	VS alone, 1 low salient target	2nd click RT	1651.424	622.7486
	VS alone, 2 targets	2nd click RT	1259.174	316.5572
VS+WM task	VS+WM, no targets	2nd click RT	321.917	183.7295
	VS+WM, 1 high salient target	2nd click RT	1824.913	547.741
	VS+WM, 1 low salient target	2nd click RT	1780.597	576.4525
	VS+WM, 2 targets	2nd click RT	1324.938	318.4111

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