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ORIGINAL ARTICLE

Eye movements as a gatekeeper for memorization: evidence for the persistence of attentional sets in visual memory search

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Abstract Attention is known to serve multiple goals, including the selection of information for further perceptual analysis (selection for perception) and for goal-directed behavior (selection for action). Here, we study the role of overt attention (i.e., eye movements) as a gatekeeper for memorization processes (selection for memorization). Subjects memorized complex multidimensional stimulus displays and subsequently indicated whether a specific (probe) item was present. In Experiment 1 we utilized an incidental learning setting where in the beginning only a subset of display stimuli was relevant, whereas in a transfer block all stimuli were possible probe items. In Experiment 2, we used an explicit learning setting within a between-group design. Response times and gaze patterns indicated that subjects learned to ignore irrelevant stimuli while forming memory representations. The findings suggest that complex feature binding processes in peripheral vision may serve to guide overt selective attention, which eventually contributes to filtering out irrelevant information even in highly complex environments. Gaze patterns suggested that attentional control settings persisted even when they were no longer required.

Introduction

The amount of information provided by our environment forces us to select a subset of relevant information on the basis of our present goals, a phenomenon that has been termed "selective attention" (see Pashler, 1998). Selective attention encompasses a variety of phenomena and can be subdivided with respect to functional roles. For example, attention may serve to select information for further perceptual analysis (*selection for perception*; e.g., Broadbent, 1958; see Schneider & Deubel, 2002), or to select an appropriate action in the presence of response alternatives (*selection for action*; e.g., Allport, 1987, Van der Heijden, 1992). Here, we focus on eye movements (i.e., overt visual attention) as a gatekeeper for memorization, a functional role of attention that may be termed *selection for memorization*.

Both attention and memory are constructs encompassing a variety of dissociable mechanisms (see Awh, Vogel, & Oh, 2006). For example, selective attention ensures that limited working memory capacity is filled with relevant, as opposed to irrelevant information (e.g., Conway & Engle, 1994; Kane, Bleckley, Conway, & Engle, 2001). Since only few objects can be maintained in visual working memory (e.g., Cowan, 2001; Fougnie & Marois, 2006; Irwin & Andrews, 1996; Vogel, Woodman, & Luck, 2001), this calls for efficient mechanisms to control which information may occupy this limited resource.

Indeed, research on visuospatial processing demonstrated that attention can be selectively directed towards relevant stimuli. For example, it has been shown that location-specific target probabilities affect visual search and learning (e.g., Biederman, 1972; Brockmole, Castelhano, & Henderson, 2006; Chun, 2000; Chun & Jiang, 1998; Haider & Frensch, 1999; Hoffmann & Kunde, 1999; Kunde & Hoffmann, 2005). More importantly, a recent line of research provided direct evidence for covert attention as a gatekeeper for working memory in the visuospatial domain. Luck and Vogel (1997) used a paradigm in which an array of objects was briefly presented before a comparison array was shown. The participants' task was to

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indicate whether the array has changed, and the task became increasingly difficult when more than four objects were part of the array. Further research involving the presence of irrelevant distracters within the arrays revealed that working memory capacity was directly associated with the ability to filter out task-irrelevant information that would impose a burden on working-memory capacity (Vogel, Woodman, & Luck, 2005).

A complementary stream of research established that covert attention can be controlled by an incidentally learned set of relevant stimuli. Shiffrin and Schneider (1977) manipulated the amount of targets to search for (memory set size) and the amount of distracters within each search frame (frame size). Stimuli and responses were either related by a *consistent mapping* (i.e., if a stimulus was a target in one trial, it never appeared as a distracter) or by a *varied mapping* (i.e., the same stimulus could serve as both target and distracter over trials). Interestingly, in their Experiment 4d they investigated how consistent training in visual search for specific (relevant) items affected performance after a change in the target set. As a result, they found that former targets captured attention automatically, even though participants were instructed to ignore them. This finding can be interpreted as evidence for learned attention-based weighting mechanisms which persist over time even when they are no longer task-relevant (see also Kyllingsbaek, Schneider, & Bundesen, 2001), at least when the stimuli consist of relatively basic alphanumeric characters. However, according to the Theory of Visual Attention (Bundesen, 1990), attentional selection may not necessarily be based on simple physical features, but (at least theoretically) "intelligent selection is possible" (p. 527).

Previous studies on attentional filtering in memory-based search tasks did not examine whether eye movements might play an important role as a gatekeeper for visual working memory, especially in more complex scenes with presentation durations allowing for eye movements to occur. However, many studies demonstrated the usefulness of eye movement recordings as an indicator of attention processes during search on a more general level. For example, several studies already showed that gaze patterns may vary as a function of the task goal (display memorization vs. item search), and that memory performance for objects is closely related to spatial and temporal fixation patterns during encoding (e.g., Castelhano, Mack, & Henderson, 2009; Friedman, 1979; Loftus, 1972; Nelson & Loftus, 1980). Therefore, eye movements might be the most natural means to direct visuospatial attention to relevant information (e.g., Deubel & Schneider, 1996; Findlay & Gilchrist, 2003; Maioli, Benaglio, Siri, Sosta, & Cappa, 2001; Zelinsky & Sheinberg, 1996). However, up to now there is a lack of empirical data on the role of eye movements during attentional filtering in memory-based search tasks.

The present study aims at investigating eye movements in a memory-based search task more closely. More specifically, we asked what eye movements can tell us about the mechanisms of transferring relevant (vs. irrelevant) stimuli into memory (selection for memorization). Since the study of eye movements appears especially interesting within complex visual environments, we utilized complex stimuli. Stimulus complexity was introduced on two levels. First, we used multidimensionally coded items consisting of letters, objects, and colors. We reasoned that these complex stimuli are closer to the complexity of our daily environment than, for example, alphanumeric symbols or basic shapes used in previous studies (e.g., Shiffrin & Schneider, 1977). Second, display set size exceeded working-memory capacity. We reasoned that if subjects were able to store all information, there would be no need for filtering. Additionally, eye movements should be especially important in large search arrays, where information cannot be processed at a single glance.

Experiment 1

Here, we utilized a within-subjects incidental-learning design. During two learning blocks of trials, subjects were presented with displays containing nine stimuli. After a brief interval, a single probe stimulus appeared at a randomized screen position. Participants indicated whether the probe appeared in the previous display. Crucially, and not explicitly mentioned by the experimenter, only a limited number of (six) stimuli were possible probe stimuli (the "reference set"). If subjects incidentally learned the reference set, they could use this information to selectively enhance performance by focussing on the relevant items.

Critically, in a final negative transfer block, the procedure essentially remained the same, but *all* display items were potential probe stimuli. This procedural change was not mentioned to the participants. If participants indeed learn to filter out irrelevant information in complex stimulus arrays one would expect worse memory performance in the negative transfer block, because focussing attention (and eye movements) mainly on items of the reference set would be dysfunctional. If eye movements play an important role during filtering, one would also expect more fixations on relevant (vs. irrelevant) items in the learning blocks.

To study how filtering abilities are modulated by current memory demands, we additionally varied the amount of items from the reference set (one vs. four) presented within each display. If participants learn to use the reference set during memorization, one would expect better performance for displays with low memory load (only one relevant item), since it should be easier to store and/or process one item as opposed to four items.

Method

Participants

Sixteen university students (mean age 24 years, range 20–36 years, ten female) participated. They gave informed consent and received credits for participation.

Material

We used multidimensional colored stimuli which resembled rectangular juice packages and consisted of a four-letter pronounceable pseudo brand name in the upper part and the picture of a fruit in the lower part. Altogether, three brand names, six fruits, and nine stimulus colors were used. From all 162 possible combinations, a set of eighteen different items was randomly sampled to serve as an item pool for the experiment. Six of these eighteen items were randomly selected as members of the reference set, which was the same for all participants. In sum, 252 displays consisting of nine items each were constructed. Displays either contained one or four items from the reference set. Stimulus positions in the displays were randomized. The size of each item on the display was 4 × 5.5 cm (equivalent to 3.4° × 4.7° visual angle). The display size was 14° × 20° visual angle.

Apparatus

Participants were seated 67 cm in front of a 21 in. cathode ray monitor (temporal resolution: 100 Hz, spatial resolution: 1,240 × 1,068). The spacebar of a keyboard was used during calibrations, and mouse buttons were used as response keys. Eye movements of the right eye were registered using an Eyelink I infrared reflection system (SR Research, Canada) with a temporal resolution of 250 Hz. A chin rest was used to minimize head movements. The spatial measurement accuracy of the eye tracking system easily allowed to determine the fixated object within the search array.

Procedure

The experiment consisted of three blocks of 84 trials each. In the first two blocks (learning blocks), only items from the reference set were used as probe items, whereas in the third block (negative transfer block), all items served as potential probes. Twenty practice trials (in which items from the reference set were already used as probes) preceded the experiment. In each trial, one of the displays was presented for 5,000 ms. After display presentation, a 100-ms blank screen was introduced, followed by the presentation of a single probe item at a randomized screen position (see Fig. 1). Even though a 100-ms retention interval may principally result in performance benefits through iconic memory traces, we reasoned that this issue should play only a minor role given the complexity of the stimulus array. Additionally, this potential advantage was not confounded with any of the experimental conditions. Subjects were instructed to memorize the display to judge whether the subsequently presented probe was present in the display or not. Half of the trials were "target present" trials (requiring a right mouse key press); the remainder consisted of "target absent" trials (requiring a left mouse key press). Note that this procedure is similar to the varied mapping conditions of Shiffrin and Schneider (1977), since the same probe item could be associated with a "target present" response as well as with a "target absent" response. At the end of the experiment, subjects were involved in a counting backwards task (from 100 in steps of 13) for half a minute and were then (after debriefing) asked to select the six reference set stimuli among 18 items altogether. Calibrations of the Eyelink system (nine-point calibration routine) were repeated after each twenty trials. Participants received no specific instructions with respect to eye movements.

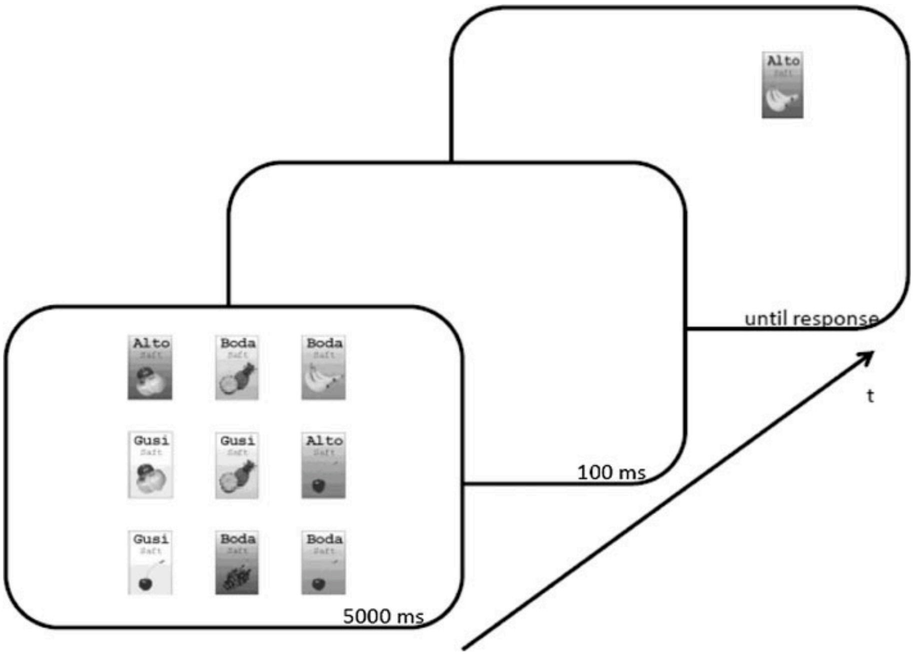
Design

For the analysis of accuracy as a dependent variable, we conducted a 2 × 2 ANOVA with the independent variables acquisition phase (learning vs. negative transfer) and load (1 vs. 4 relevant items within each display). Note that we only used data from the second block for the learning condition.

To assess whether the eyes were specifically guided towards the relevant stimuli we analyzed the mean number of fixations per stimulus as a function of acquisition phase and item type (reference set items vs. non-reference set items). Additionally, we analyzed refixations and initial gaze destinations (i.e., how soon the gaze was directed towards the different item types).

To further specify the impact of stimulus relevance information on global eye movement control, we conducted 2 × 2 ANOVAs with the independent variables acquisition phase and load to analyze how the number of fixations within each display, fixation durations, and saccade amplitudes were altered by the crucial stimulus relevance manipulation.

Fig. 1 Schematic trial sequence



Results and discussion

Accuracy

Figure 2 (upper panel) depicts mean accuracy (% correct responses to the probe items) across all three blocks. The 2 × 2 ANOVA indicated that performance decreased from the learning block (Block 2: 62%) to the negative transfer block (Block 3: 55%), $F(1, 15) = 13.90$, $p = 0.002$, $\eta_p^2 = 0.48$, showing that participants were able to process stimulus relevance to enhance performance. There was also a significant main effect of load, with better performance for displays including one relevant item (60%) as compared to displays containing four relevant items (56%), $F(1, 15) = 13.06$, $p = 0.003$, $\eta_p^2 = 0.47$, indicating that it was either easier to transfer one (vs. four) items into working memory, or that retrieval/comparison processes were more efficient. There was no significant interaction, $F < 1$. Additional one-sample *t* tests indicated that performance was significantly above chance level in all individual conditions depicted in Fig. 2 (upper panel), all $p < 0.05$, except for a marginally above chance level performance in the four relevant items condition in the transfer block, $p = 0.09$.

Eye movements

Figure 2 (lower panel) depicts the *mean number of fixations* on reference set and non-reference set stimuli. The ANOVA comparing performance in Block 2 and 3 yielded

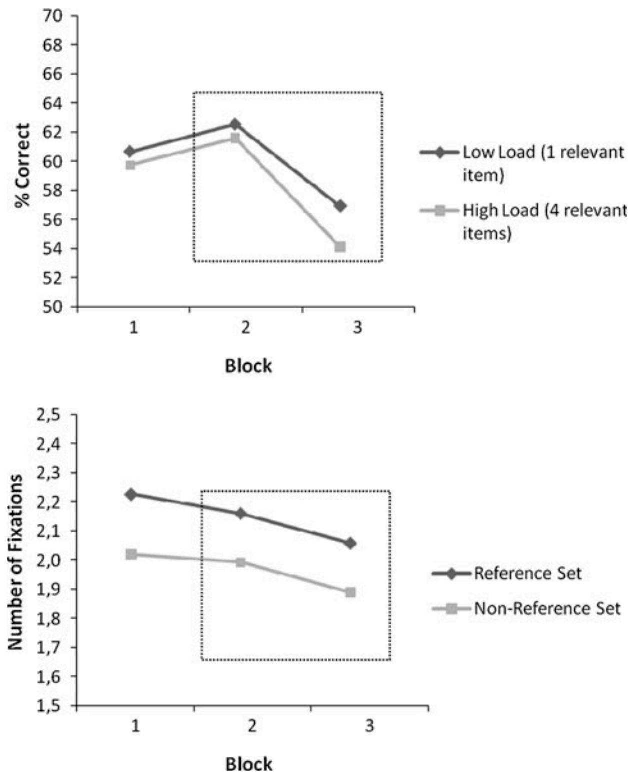


Fig. 2 Percentage of correctly remembered items (*upper panel*) and number of fixations on reference set items versus non-reference set items (*lower panel*) as a function of block, separately depicted for conditions with low versus high load (1 vs. 4 relevant items in the display) in Experiment 1. Note that the analyses reported in the "Results" section are based on the data highlighted by the *rectangle*

a significant main effect of acquisition phase, $F(1, 15) = 12.36$, $p = 0.003$, $\eta_p^2 = 0.45$, indicating that there were generally fewer fixations on the stimuli in the negative transfer block ($M = 1.94$) compared with the learning block ($M = 2.05$). Furthermore, stimuli from the reference set received more fixations ($M = 2.08$) than stimuli that were not part of the reference set ($M = 1.89$), $F(1, 15) = 19.07$, $p = 0.001$, $\eta_p^2 = 0.56$. There was no significant interaction of item type and block, $F < 1$, suggesting that stimuli from the reference set attracted attention in the negative transfer block even though they were no longer more relevant than the other stimuli. This finding can be interpreted as evidence for the persistence of attentional control settings even though they were no longer required.

Table 1 depicts an overview of the *global eye movement data*. There were more fixations ($M = 18.9$) and shorter mean fixation durations ($M = 241$ ms) in the learning block compared with the negative transfer block ($M = 17.6$ fixations with a mean duration of 261 ms), $F(1, 15) = 11.88$, $p = 0.004$, $\eta_p^2 = 0.46$, and $F(1, 15) = 8.01$, $p = 0.013$, $\eta_p^2 = 0.37$, respectively. There were no main effects of the number of relevant items and no significant interactions, all $p > 0.05$. Saccade amplitudes were also not significantly affected: all $p > 0.05$.

During each inspection of a display, several items were revisited after receiving their first gaze (refixations). We computed the mean *refixation probability* per item separately for reference set versus non-reference set items. The ANOVA revealed a significant main effect of acquisition phase, $F(1, 15) = 5.96$, $p = 0.028$, $\eta_p^2 = 0.28$, indicating overall fewer refixations in the negative transfer block ($M = 34.2\%$) versus the learning block ($M = 37.7\%$). Additionally, there was a main effect of item type, $F(1, 15) = 32.61$, $p < .001$, $\eta_p^2 = 0.69$ ($M = 38.0\%$ for items from the reference set vs. $M = 33.9\%$ for non-reference set items), but no significant interaction, $F < 1$.

To analyze *initial gaze destinations* (i.e., how soon the gaze was directed towards each item type), we eliminated data points in which the gaze was already located on a reference set item (or on a non-reference set item, respectively) at the moment of display onset. The ANOVA revealed no significant main effect of acquisition phase, $F < 1$, but a significant effect of item type, $F(1, 15) = 76.58$, $p < 0.001$, $\eta_p^2 = 0.84$ ($M = 621$ ms for non-reference set items, $M = 1{,}310$ ms for reference set items). More interestingly, however, there was a significant interaction between item type and block, $F(1, 15) = 4.95$, $p = 0.042$, $\eta_p^2 = 0.25$, indicating a smaller difference between reference set items and non-reference set items in the learning block (633 ms) than in the negative transfer block (746 ms). This finding can be interpreted as a relative advantage for reference-set items in the learning block as compared with the negative transfer block. This result may indicate that during learning, item relevance is already processed (to some extent) parafoveally (i.e., prior to the first fixation of an item from the reference set).

Table 1 Eye movement parameters during display inspection as a function of acquisition phase in Experiment 1

	Acquisition phase	
	Learning	Negative transfer
Fixations (*N*)	18.9 (0.8)	17.6 (1.0)
Fixation duration (ms)	241 (9.1)	261 (14.2)
Saccade amplitude (°)	6.58 (0.20)	6.54 (0.23)

In the negative transfer block all stimuli were task-relevant

The values represent means (SE in parentheses)

Recognition scores

The recognition test, in which a fixed amount of six stimuli (namely, the reference set) should be chosen among 18 stimuli altogether, resulted in a mean of 3.31 correctly chosen items. This mean significantly differed from guessing rate (two items), $t(15) = 4.87$, $p < 0.01$, indicating that subjects gained some (but far from perfect) explicit knowledge regarding the reference set.

Experiment 2

In Experiment 2, we utilized a between-subjects design using the same stimulus material. In one group (baseline group, $n = 20$, equivalent to the negative transfer condition in the present experiment), all display items served as probes, whereas in the other group (reference set group, $n = 20$, equivalent to the learning condition in Experiment 1) only reference set items were used as probes. Thus, unlike in the negative transfer phase of Experiment 1, items from the reference set were not associated with a previous learning history in the baseline group of Experiment 2. Both groups saw the same displays in the same order.

Unlike in Experiment 1, we focussed on *explicit* knowledge about item relevance. To this end, we introduced a learning session in which the reference set group learned all reference set items prior to the experiment. Participants were explicitly told that only these items are relevant throughout the experiment for a successful completion of the task, since only reference set items were used as probes. In the baseline group, all items of each display served as potential probes, and no learning session prior to the experiment was implemented.

To determine the extent to which relevant information is processed, we additionally varied the display set size in both groups in Experiment 2. If participants use information about item relevance perfectly in the reference set group, an increase of display set size (independent from the amount of relevant items) should not lead to a decrease in performance. In the baseline group, working memory capacity is presumably exceeded in both display set size conditions, because all nine or twelve items in each display were relevant for a perfect completion of the task. Therefore, increasing display set size would probably also not affect performance in this group.

In Experiment 2, we chose to either present two or five items from the reference set in each display. Unlike in Experiment 1 (where the corresponding load manipulation included 1 vs. 4 items), this allows for testing the flexibility of the cognitive system in this task. If the strategy of the participants is to store all relevant items presented in each display, performance should be worse in the condition with five relevant items compared with the condition with two relevant items, since it should be more difficult to process more information (similar to the results in Experiment 1). However, it is also possible that in the five items condition participants do not store all five items, but rather only the missing item from the reference set. This rather flexible cognitive strategy would predict the opposite data pattern, namely a performance advantage for displays containing five relevant items.

Method

Participants

Forty new students with normal or corrected-to-normal sight took part in this experiment, 25 females and 15 males. Mean age was 25 years, ranging from 22 to 31. They gave informed consent and received credits for participation.

Material and apparatus

The basic stimuli and apparatus were the same as in Experiment 1. However, we here utilized 168 stimulus displays. Half of the displays contained nine, the other half 12 items (display size). Furthermore, the displays either contained two or five items from the reference set. The positions of stimuli in the displays were randomized.

Procedure

Participants were randomly assigned to either of two groups. In the reference set group, participants took part in the reference set learning session prior to the experiment. Pictures of the six items were presented several times until participants recalled all items correctly. They were informed that only these items were relevant for a successful completion of the task. Then, 20 practice trials were administered. Afterwards, participants again freely recalled recall the reference set, before the main experiment started. In each of the 168 trials, a stimulus display was presented for 8,000 ms (due to the larger display sizes). After display presentation, a 100-ms blank screen was introduced, followed by the presentation of a single probe item at a randomized position on the screen. Participants indicated whether the probe was present in the previous display. Half of the trials required a “present” response. At the end of the experiment, participants counted backwards from 100 in steps of 13 for about half a minute, before they were asked to freely recall the reference set again.

In the baseline group, no learning session or recall tests were administered. Here, all items (and not only items from the reference set) served as potential probes. Participants were told that all items in the display are relevant for a successful completion of the task. Again, half of the trials required a “present” response. The identity and sequence of the displays were identical to those in the reference set group.

Results and discussion

All participants from the reference set group successfully completed the learning session in a short time. After that, all of them were able to correctly recall the items after both the practice trials and the main experiment.

Accuracy

For the group comparison on accuracy data, means from the “two relevant” and “five relevant” items conditions in the reference set group were pooled, and a 2 × 2 ANOVA with the independent variables group (reference set vs. baseline) and display size (9 vs. 12) was conducted. The influence of the amount of relevant items was analyzed in detail by reporting a separate 2 × 2 ANOVA for the reference set group, using the amount of relevant items (2 vs. 5) and display set size (9 vs. 12) as independent variables.

Participants in the reference set group remembered more items ($M = 70.3\%$) compared to the baseline group ($M = 59.1\%$), $F(1, 38) = 30.72$, $p < 0.001$. This finding replicates the main results from Experiment 1, suggesting that participants in the reference set group were successful in selectively transferring relevant information into working memory. Additionally, memory performance was better for smaller ($M = 66.9\%$) compared with larger displays ($M = 62.5\%$), $F(1, 38) = 16.98$, $p < 0.001$. The interaction between group and display size was significant, too, $F(1, 38) = 10.09$, $p = 0.003$. A separate test in the baseline group revealed no significant effect of display set size, $t(19) = 0.79$, $p = 0.44$, whereas this effect was clearly present in the reference set group, $p < 0.001$.

The 2 × 2 ANOVA in the reference set group with the amount of relevant items (2 vs. 5) and display size (9 vs. 12) as independent variables revealed that increasing display size negatively affected performance, $F(1, 19) = 20.60$, $p < 0.001$, suggesting that the selection process was not perfect: If selection was perfect, one would have expected that display size has no influence on performance in the reference set group, since the amount of relevant information did not covary with display size. However, the amount of correctly remembered items was significantly lower for larger displays in this group, indicating that the increasing amount of distractors negatively affected memory performance. This might be due to interference from distractors on the memorization of the relevant items, especially given the overall similarity of all items. However, display size did not affect performance in the baseline group, which might be an effect of overall task difficulty: Given that all display items had to be remembered, STM capacity is clearly exceeded in both display size conditions, leading to essentially the same performance.

Interestingly, accuracy was higher for displays containing five relevant items ($M = 73\%$) compared with displays containing only two relevant items ($M = 67.6\%$), $F(1, 19) = 10.51$, $p = 0.004$ (see Fig. 3), representing a reversed pattern as compared with Experiment 1. This finding is in line with a more flexible view of the participants' cognitive abilities, indicating that in the five-item-condition, only one item (i.e., the missing one from the reference set) was stored/processed in memory.

Eye movements

Due to the between-group design, we were not able to address the issue of a potential persistence of attentional sets in Experiment 2. Thus, here we only present a condensed report of eye movement parameters. Table 2 presents an overview of general parameters comparable to the corresponding report from Experiment 1. Most importantly, in the reference set group relevant items were fixated more often ($M = 3.04$ fixations) compared with irrelevant items ($M = 2.74$ fixations), $t(19) = 5.42$, $p < 0.001$. This finding is in line with the corresponding result in Experiment 1 and provides further evidence for the role of eye movements as a gatekeeper for the selective transfer of relevant information into working memory.

Generally, participants scanned larger displays with significantly more fixations ($M = 28.6$) compared with the smaller displays ($M = 27.9$), $F(1, 38) = 38.85$, $p < 0.001$. Mean fixation durations were shorter for displays containing twelve items ($M = 231$ ms) than for displays containing nine items ($M = 237$ ms), $F(1, 38) = 41.24$, $p < 0.001$. Saccade amplitudes were larger in the displays containing twelve items ($M = 6.37°$) compared with displays containing only nine items ($M = 6.22°$), $F(1, 38) = 6.78$, $p = 0.013$. There were no significant group differences with respect to the number of fixations, fixation durations, and saccade amplitudes, all $ps > 0.10$. The amount of targets present in the display in the reference set group hardly affected eye movement behavior. Only a slight tendency towards larger saccade amplitudes was found for displays containing two relevant items ($M = 6.21°$) versus five relevant items ($M = 6.16°$), $F(1, 19) = 3.28$, $p = 0.086$. Taken together, these analyses mainly reveal an adaptation of the scanning strategy to the display size, with more fixations and larger saccade amplitudes for larger displays. Since the display presentation times were fixed, this went hand in hand with decreased mean fixation durations. An interesting observation is that saccade amplitudes tended to be larger in displays with two (vs. five) relevant items in the reference set group. A reason for this could be that in displays with only two relevant items, the mean distance between these items should be larger compared with displays with five relevant items, in turn leading to larger saccade amplitudes.

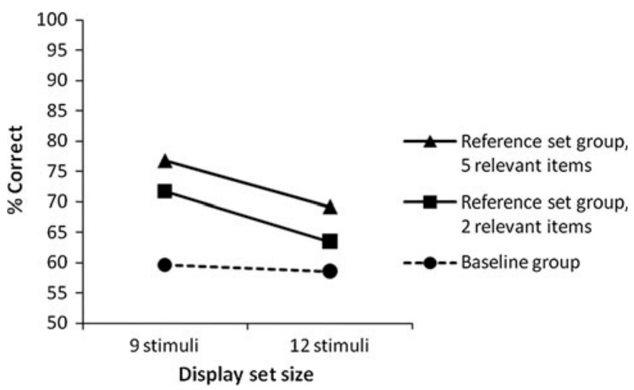


Fig. 3 Percentage of correctly remembered items as a function of display set size for the baseline group and for the reference set group in Experiment 2, separately depicted for conditions with 2 versus 5 relevant items in the displays

General discussion

In the present study, we investigated the role of eye movements in the acquisition and persistence of attentional control settings within a memory-based search task. In Experiment 1, we utilized an incidental learning design in which participants learned to focus attention on a subset of relevant stimuli for memorization purposes. Then, in a negative transfer block all stimuli were task-relevant, and focussing on the previously relevant stimuli became dysfunctional. As a main result, we found that participants selectively directed their eyes towards relevant stimuli during learning, which was reflected in better memory

Table 2 Eye movement parameters during display inspection as a function of group in Experiment 2

	Group	
	Reference set	Baseline
Fixations (*N*)	29.3 (0.8)	27.1 (1.10)
Fixation duration (ms)	225 (9.1)	241 (9.0)
Saccade amplitude (°)	6.16 (0.12)	6.37 (0.18)

Note that values represent means averaged across display set size conditions to enable direct comparisons with Experiment 1

In the baseline group all stimuli were task-relevant

The values represent means (SE in parentheses)

accuracy when compared with the negative transfer block. However, during negative transfer participants' gaze still prioritized stimuli that were previously relevant, suggesting that eye movement control contributes to the persistence of attentional control settings. In Experiment 2, we replicated the main finding, i.e., the effective prioritization of relevant (vs. irrelevant) stimuli, in an explicit learning setting within a between-group design.

Subjects are known to be able to focus on relevant (vs. irrelevant) information (e.g., Biederman, 1972; Chun, 2000; Kunde & Hoffmann, 2005), which may serve to select specific information for further perceptual analysis (*selection for perception*; e.g., Broadbent, 1958; see Schneider & Deubel, 2002), or to execute an appropriate action in the presence of behavioral alternatives (*selection for action*; e.g., Allport, 1987; Van der Heijden, 1992). The present experiments showed that performance in a memory search task was better when only a subset of stimuli in a display was relevant as compared with conditions in which all stimuli were relevant. This benefit indicates that participants learned to tell relevant from irrelevant items during memorization (*selection for memorization*). Thus, a longer-lasting representation of a category (relevant items) has been incidentally (Experiment 1) or explicitly (Experiment 2) acquired and stored in long-term memory.

These findings are in line with previous data indicating that subjects are able to selectively transfer relevant information into working memory (Conway & Engle, 1994; Kane et al., 2001; Shiffrin & Schneider, 1977; Vogel et al., 2005). However, these previous studies on filtering mechanisms mainly utilized brief display presentations to avoid the occurrence of eye movements, although it has repeatedly been argued that eye movements may represent the most natural and default means for selecting visual information (e.g., Findlay & Gilchrist, 2003; Maioli et al., 2001; Zelinsky & Sheinberg, 1996). In line with this claim, the present eye movement analyses revealed that relevant stimuli received more fixations than did irrelevant stimuli. In this way, overt attention served as a gatekeeper to working memory, which may be especially important in complex, more natural scenes.

Gaze patterns in the negative transfer condition of Experiment 1 revealed that even though stimuli from the reference set were no longer more relevant than other stimuli, they still received more fixations. Additionally, there was an accuracy advantage for displays containing one (vs. four) items from the reference set. Most likely, subjects were unable to get rid of the tendency to prioritize items that were relevant in the learning blocks, so that the presence of four previously relevant items distracted from the encoding of other items, eventually limiting performance compared with a condition when only one distracting stimulus was present in the display. Taken together, this suggests that attentional control settings (e.g., Pratt, Sekuler, & McAuliffe, 2001) exhibited a tendency to persist even when they were no longer required.

This observed attentional persistence indicates that a major portion of information about stimulus relevance was learned implicitly, since implicit knowledge is known to persist longer compared with explicit knowledge (e.g., Tunney, 2003). Note that also previous studies indicated that consistent training in search for specific items affected performance after a change in the target set, so that former targets automatically captured attention (Kyllingsbaek et al., 2001; Shiffrin & Schneider, 1977, Experiment 4d). However, the present study extends these findings by showing (a) that selection can be based on complex, multidimensional categorization processes and (b) that eye movements play a major role within this complex selection process.

Note that in both experiments relevant items received more fixations than irrelevant items, indicating that display inspection was not conducted in a random-like item-by-item fashion (e.g., as according to the concept of "serial search" in Treisman & Gelade, 1980). Rather, participants seemed to prioritize relevant items. From the perspective of visual search theories (which were designed to explain search in more classic search tasks), the ability to search for multidimensionally defined stimuli among highly similar distracters is not readily explained, since most of these theories are build upon the assumption of attentional guidance on the basis of salient perceptual features (e.g., color) or feature differences (e.g., Duncan & Humphreys, 1989; Wolfe, 1994). In our memory search task, however, a perceptual pre-processing of a salient stimulus dimension would not suffice to explain how attention was selectively directed to relevant stimuli. Instead, the present data rather suggest that filtering can also be based on attentional weighting mechanisms which involve multiple stimulus dimensions (see Bundesen, 1990).

A further inspection of the eye movement data in Experiment 1 reveals a more detailed picture. Although the time interval between display onset and the first fixation on either a reference set item or a non-reference set item generally revealed an expected overall advantage for non-reference set items (due to a greater overall number of non-reference set items), the data suggested a relative advantage for reference set items during learning (compared with negative transfer), which may indicate that during display inspection, subjects were to some extent able to process whole objects in peripheral vision, necessitating peripheral feature binding processes (Mordkoff & Halterman, 2008) in order to selectively direct the eyes towards relevant information.

The preference for relevant information was also reflected in a greater number of refixations for reference set items (vs. non-reference set items), which at least partly may have occurred in order to refresh relevant information in working memory. However, it should also be noted that participants were not able to completely ignore irrelevant information, as indicated by the frequent occurrence of fixations on irrelevant items in both experiments. This is probably due to interference based on the high similarity between all items within a display as well as due to inter-trial interference based on visual similarity across displays. The overall increase of fixation durations in the negative transfer condition in Experiment 1, where all items were relevant for memorization, are in line with previous studies showing increased fixation durations resulting from greater working memory load (Peterson, Beck, & Wong, 2008).

As noted earlier, our stimuli were quite complex (configurations of colors, words, and pictures) so that several working memory systems (e.g., verbal and visual) may have interacted to push processing capacity to its limits. This is reflected in the maximum performance level of 62% in Experiment 1 (see Fig. 2). Thus, we assume that stimuli which are less complex and visually more distinct (e.g., alphanumeric symbols) should optimize the effects of target category acquisition (see Shiffrin & Schneider, 1977), but the present study indicates that filtering processes come into play even under conditions which are closer to the complexity of our daily environment.

In sum, the study extends previous research on filtering processes during memorization by showing that selection can be based on complex, multidimensional categorization processes, and by suggesting that eye movements may serve as a gatekeeper for visual working memory (see Awh et al., 2006).

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