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Top-down effects of semantic knowledge in visual search are modulated by cognitive but not perceptual load

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Moores, Laiti, and Chelazzi (2003) found semantic interference from associate competitors during visual object search, demonstrating the existence of top-down semantic influences on the deployment of attention to objects. We examined whether effects of semantically related competitors (same-category members or associates) interacted with the effects of perceptual or cognitive load. We failed to find any interaction between competitor effects and perceptual load. However, the competitor effects increased significantly when participants were asked to retain one or five digits in memory throughout the search task. Analyses of eye movements and viewing times showed that a cognitive load did not affect the initial allocation of attention but rather the time it took participants to accept or reject an object as the target. We discuss the implications of our findings for theories of conceptual short-term memory and visual attention.

Desimone and Duncan (1995) suggested that selective visual attention emerges from a biased competition among visual stimuli, moderated by both bottom-up saliency and top-down knowledge (e.g., stored object representations). Top-down control is assumed to be exerted from working memory (WM), where an object template is held that can guide the allocation of visual selective attention (see Chelazzi, Duncan, Miller, & Desimone, 1998; Chelazzi, Miller, Duncan, & Desimone, 1993; Duncan & Humphreys, 1989). Although numerous studies have focused on visual aspects of top-down influences on visual search (e.g., Downing, 2000; Soto, Heinke, Humphreys, & Blanco, 2005; Woodman, Vogel, & Luck, 2001), less is known about semantic influences on the deployment of visual selective attention.

Moores, Laiti, and Chelazzi (2003, Experiment 4) demonstrated the existence of top-down associative effects on the deployment of visual attention during visual search for objects. They gave participants a target prompt (e.g., "motorbike"), followed by a central fixation point and an object display of four objects. The display was flashed only briefly (73 msec on average; individually determined presentation times ranged from 47 to 97 msec). The authors compared participants' performance when an associate to the target (e.g., "motorbike helmet") was present with their performance when no such associate was present. They obtained no effect of the presence of an associate on target-present trials. However, on target-absent trials, participants were less accurate and responded more slowly when an associate was present (with 18% false "target-present" reports and a reaction time [RT] of 867 msec) compared with how they performed when no associate was present (with 10% false '"target-present" reports and an RT of 801 msec). The authors hypothesized that, following the establishment of a template for a target (Duncan & Humphreys, 1989), there is a spread of activation to templates of semantically related items. Related items then compete for selection and are more likely than are unrelated distractors present in the field to be selected.

The findings obtained by Moores et al. (2003) imply that participants were able to quickly activate and process conceptual information about objects in the visual field. This is in keeping with theories of early and rapid conceptual processing, such as Potter's (1976, 1993, 1999)

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conceptual short-term memory (CSTM) hypothesis. Potter proposed that the apparent effortlessness with which people process conceptual information when reading or attending a conversation requires a form of WM that allows for a rapid identification and initial conceptual processing of incoming information. CSTM differs from early stages of visual short-term memory in that it is associated with rapid access to conceptual information about fixated stimuli far beyond visual stimulus properties. With this information, semantic associations that exist in long-term memory (LTM) between momentarily active items become available as well. CSTM is distinct from LTM, as established, for instance, by the finding that information briefly activated in CSTM is, in most cases, forgotten immediately. This finding also supports a further distinction between CSTM and standard notions of short-term memory (STM) or WM (e.g., Baddeley, 1986, 2000). The time span for which information in CSTM remains activated is much shorter than the retention span assumed in standard notions of STM, provided that the information in CSTM is not otherwise consolidated and gains access to STM or LTM. Such a "fleeting" conceptual memory (see Potter, 1999) may play an essential role in natural scene perception, which requires viewers to identify rapidly the segments of the scene they perceive upon each fixation and at the same time integrate the conceptual information from successive fixations into a coherent conceptual representation of the scene (see also Dell'Acqua & Grainger, 1999; Potter, Staub, Rado, & O'Connor, 2002; VanRullen & Thorpe, 2001).

The experimental results reported by Moores et al. (2003) are compatible with Potter's CSTM hypothesis, and they have further implications: They provide evidence for semantic influences on the selection of stimuli for attention, which, according to the CSTM hypothesis, is a necessary condition for processing stimuli beyond CSTM (in STM or LTM). This is demonstrated most clearly in Experiment 5 of Moores et al., where they monitored participants' eye movements during search. On target-absent trials, participants were significantly more likely to look first to the associate than to any of the other objects. When the target was present, most initial saccades were directed to the target. However, the likelihood of first saccades being made to targets was reduced when there was also an associate in the display. These findings demonstrate that conceptual information from the objects in the display can be activated rapidly enough to influence the planning and execution of the first saccade to the objects present.

In the present experiments, we evaluated whether the top-down effects observed by Moores et al. (2003) were modulated by the relative perceptual load of the search displays (Experiments 1A and 1B) or by the cognitive load carried by participants (Experiment 2). Lavie, Hirst, de Fockert, and Viding (2004) argued that there should be contrasting effects of different types of processing load on search. High perceptual load, which we induced by presenting many rather than few distractor objects, should enforce a stronger, and arguably earlier, focusing of selective attention, thereby decreasing effects of distraction in search displays (Lavie et al., 2004; see also Biedermann, Blickle, Teitelbaum, & Klatsky, 1988). This should reduce any interference effects from distractors that are semantically related to the target (hereafter, "competitors"). As a result, we would expect an interaction of display size and competitor effects, with reduced competitor effects under conditions of high perceptual load. Specifically, there should be fewer first saccades toward competitors for large than for small display sizes. Alternatively, participants might be able to process the identity of the objects preattentively in parallel across the visual field (see Starreveld, Theeuwes, & Mortier, 2004), in which case we would expect no interaction between the variation of display size and competitor effects on the initial deployment of visual selective attention.

High cognitive load—for instance, when there is a substantial load on WM rather than a smaller or no load—should reduce the cognitive control capacities available for the top-down control of visual search by means of an object template held in WM. In addition, a high cognitive load is likely to affect the viewer's ability to suppress irrelevant information. As a result, participants might be less efficient in deciding whether an attended object is the target or not. A high cognitive load, then, should increase interference from competitors in search, relative to when little or no load is present. We therefore expected to find effects of cognitive load early on in the search process, as well as during the course of the search process (when irrelevant information must be suppressed).

Like Moores et al. (2003), we monitored the participants' eye movements while they explored the display. This allowed us to evaluate when and for how long participants looked at specific object locations. In particular, we assessed where participants directed their first fixation; we took this as a measure of the location to which selective attention was first directed. In addition to first fixation locations, we computed the viewing time (VT) for each object in the display (i.e., the time participants spent looking at each object during the course of the search process). We assumed that the VT for individual objects should reflect the time it took participants to evaluate whether the object they looked at (and attended to) was the target or not.

EXPERIMENTS 1A AND 1B

We examined the effects of perceptual load in two subexperiments, both contrasting performance with four and eight objects in the display. In both experiments, we assessed whether the influence of a competitor was modulated by the perceptual load of the other items in the display. In Experiment 1A, the target and the competitor could appear at each of four or eight locations in the field, so that participants should adopt a distributed attentional set, with all locations receiving equal priority. In Experiment 1B, the competitor always appeared in the same location (at the top of the display), and we investigated to what extent semantic interference effects were modulated by the perceptual load of the display, when the competitor's location was known and could be ignored.

Experiment 1A
Distributed Attention

Method

Participants. Thirty-two undergraduate students of the University of Birmingham, all native speakers of British English, were tested in exchange for payment or course credits. All had normal or corrected-to-normal vision.

Materials. Black-and-white line drawings of four sets of 16 objects were selected from Snodgrass and Vanderwart (1980) as the target objects (e.g., bird), associatively related competitors (e.g., feather), categorically related competitors (e.g., fish), and unrelated distractors (e.g., cloud), respectively. Experimental stimuli were created that included 1 item from each of these sets. Four additional sets of distractor objects were selected for creating the 8-object displays (see Appendix).

We extended the study of Moores et al. (2003) by including categorically related competitors (i.e., members of the same semantic category as the target) as well as associate competitors; we will refer to the categorically related competitors as *cohyponym competitors*. Rapid access to conceptual information about objects, specifically about their superordinate category (Barnard, Scott, Taylor, May, & Knightley, 2004; Dell'Acqua & Grainger, 1999; Maki, Frigen, & Paulsen, 1997; Potter, 1976; VanRullen & Koch, 2003; VanRullen & Thorpe, 2001), may lead to fellow category exemplars being particularly strong competitors to targets. Effects of associative relations between stimuli have been shown to differ from effects of same-category relations in word production and word perception tasks (e.g., Alario, Segui, & Ferrand, 2000; Perea & Rosa, 2002; Wheeldon & Monsell, 1994; see also Bar, 2004). By including cohyponym competitors and associate competitors, we assessed whether such differences impact search.

We assessed the associative strength of the target–competitor pairs in the word association norms available in the Edinburgh Association Thesaurus (www.eat.rl.ac.uk; Kiss, Armstrong, Milroy, & Piper, 1973), which provides the proportion of occurrence of words (adjectives, nouns, and verbs) as responses to a given target in a word-association task. On average, the names of the associate competitors were mentioned significantly more often in response to the target words we used in our experiment (23%) than were the names of the cohyponym competitors [3.2%; $t(15) = 3.37$, $p = .004$].

In a pretest of the materials, 14 participants were asked to rate the visual similarity of the target–associate and target–cohyponym pairs on a scale from 1 (*very dissimilar*) to 5 (*very similar*). The critical target–associate and targe–cohyponym pairs (16 pairs each; see Appendix) were interleaved with 48 filler pairs of semantically unrelated objects. Most of the filler pairs had been tested in a previous rating study and had been rated as being very dissimilar (24 filler pairs, e.g., *tie–swan*) or very similar (24 filler pairs, e.g., *pencil–needle*). The present ratings for the target–associate and target–cohyponym pairs were as low as those for visually dissimilar pairs (all medians = 1) and significantly different from the ratings for visually similar pairs (median rating: 4.25; $z = 3.34$, Wilcoxon signed rank tests by participants for pairs of targets and associatively related competitors vs. visually similar pairs; $z = 3.31$ for pairs of targets and categorically related competitors vs. visually similar pairs; both $ps = .001$).

The line drawings of all objects included in the experiment were scaled to fit within a 100 × 100 pixel area (4.6º × 4.6º at a viewing distance of 60 cm). All eight object sets were matched for visual complexity (measured as the proportion of black pixels in a black-and-white picture of 100 × 100 pixel size). Two versions of each object were created, showing the same object in different left–right orientations. Object displays consisted of circular arrangements of four or eight objects (see Figure 1). The distance between the midpoint of the screen and the midpoints of the objects was 7.4º (170 pixels).

Design. The 2 × 2 × 3 design comprised three within-participants factors: target status (absent, present), display size (four objects, eight objects), and competitor condition (associate competitor present, cohyponym competitor present, no related competitor present). Ninety-six object configurations were assembled from the four sets of targets, associates, cohyponyms, and unrelated distractors. Each display included one object from each set. Competitor condition and target status were manipulated by combining related or unrelated objects from these sets. For instance, in the target-present/associate-present condition, the target was combined with its associate competitor and two unrelated objects from the remaining sets (cohyponyms and unrelated distractors, respectively). Similarly, in the target-present/cohyponym-present condition, the target was combined with its cohyponym competitor and two unrelated objects from the remaining sets (associ-

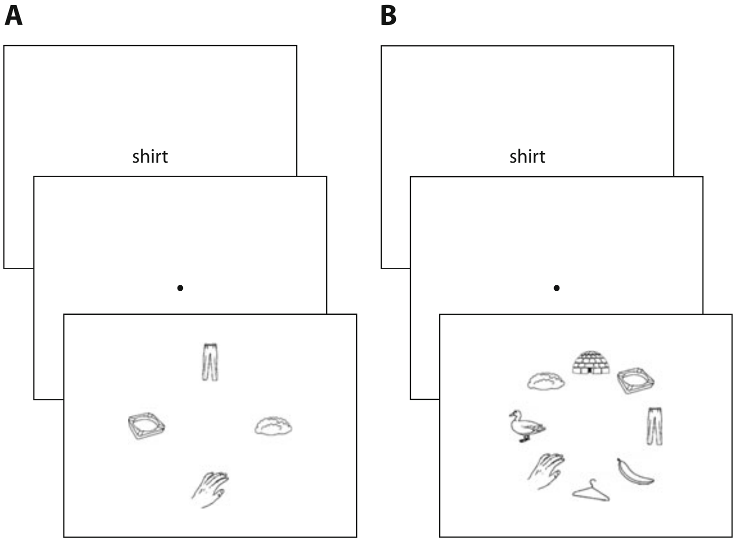

Figure 1. Trial structure and examples of displays used in Experiment 1 (target-absent/competitor-present condition).

ates and unrelated distractors, respectively). In the target-present/no-competitor-present condition, the target was combined with three unrelated objects, including one each from the sets of associates, cohyponyms, and unrelated distractors. Three parallel target-absent conditions were created by replacing the target with an unrelated foil from the targets set and combining it (1) with three unrelated objects from the other three sets (target-absent/no-competitor-present condition), (2) with the associate competitor and two unrelated objects from the cohyponyms and unrelated distractors sets (target-absent/associate-present condition), or (3) with the cohyponym and two unrelated objects from the associates set and the unrelated distractors set (target-absent/cohyponym-present condition). With this design, each object of each set featured once in each condition. For each condition, 16 configurations were assembled, corresponding to the 16 target cues (see Appendix). Figure 1A shows one of the displays used in the target-absent/cohyponym-present condition. This display includes one object each from the targets set (hand), the associates set (ashtray), the cohyponyms set (trousers), and the unrelated distractors set (cloud). Only the cohyponym (trousers) is semantically related to the target cue (shirt).

There were four experimental blocks of 96 object configurations per participant. Across the six conditions included in each block (three target-present and three target-absent conditions), the orientation of the objects was counterbalanced. Two blocks each were created from each orientation scheme. In one block, half of the object configurations were augmented by four additional unrelated distractor objects to create the eight-object displays (see Figure 1B and Appendix); in the other block, the complementary half of the configurations was augmented accordingly. The displays were generated by randomly assigning the objects to one of four (or eight) locations on the screen. One consequence of this was that the four objects included in both display sizes did not appear in the same locations. This is shown in Figures 1A and 1B, in which the four objects that appear in both displays (hand, ashtray, trousers, cloud) appear in different locations in display sizes 4 and 8. The displays were presented in a random order within a block, and the order of experimental blocks was counterbalanced across participants.

Apparatus. The experiment was controlled by a Pentium IV 1.5-GHz computer. Stimuli were presented on a Trinitron Multiscan G240 17-in. monitor, using a screen resolution of 600 × 800 pixels. Eye movements were recorded using a head-mounted eyetracker (SMI Eyelink V2.04; SR Research Ltd.) with a sampling rate of 250 Hz. Responses were registered using a response buttonbox (SR Research).

Procedure. Participants received written instructions and studied a picture booklet presenting all objects included in the experiment. The eyetracker was mounted and the system was calibrated. Each experimental block lasted approximately 10 min, with short breaks between blocks. After the experiment, participants were debriefed.

Prior to each trial, a drift correction was performed. Subsequently, the target name was presented for 1 sec, followed by a central fixation cross for 600 msec and the presentation of the object display until participants had responded.

Data analysis. During the experiment, response latencies and the accuracy of the responses were recorded, as were details on the locations and the onset and offset times of saccades and fixations. RTs, error rates, and eye movement measures were obtained using DataViewer 1.2.33 (SR Research). Square areas of interest of 108 × 108 pixels were defined for each object location, and a circular area of interest with a radius of 24 pixels was defined for the center. The analysis of the eyetracking data was restricted to the time between display onset and the participant's response on a given trial, which corresponded to the total presentation time of the object display. The location of each fixation was extracted, as was information on whether it was registered in one of the areas of interest. In addition, the nearest area of interest was computed for all fixations that had been registered close to one of the areas of interest (40.1% of all fixations). These fixations were allocated to the interest area at the center of the screen when they had been registered within a radius of 44 pixels around the midpoint of the display (corresponding to approximately 1.9º of visual angle when seen from a distance of 60 cm); otherwise they were allocated to the object region nearest to them.

Gazes were defined as a series of successive fixations within an object. Their total duration was computed as the time between the onset of the first fixation and the offset of the last fixation (Meyer, Sleiderink, & Levelt, 1998). The VT on an object was computed as the summed duration of all gazes to the object (in 97.1% of all cases, the VT corresponded to the first gaze duration).

The first five trials were excluded as practice trials. Trials were discarded when participants had not looked at the center of the screen at display onset (5.5% of the trials), or when they had blinked during display inspection (1.9%). Responses were excluded when participants had pressed the incorrect button (3.4%) or when no RT could be registered for technical reasons (0.8%). Of the remaining responses, trials with RTs deviating more than three standard deviations from a participant's mean were excluded, leaving 86.9% of the original data for statistical analyses.

To analyze the initial allocation of attention, the location of the first object fixation was evaluated for trials where a first fixation toward one of the object areas occurred within the first 500 msec after display onset (89.2% of all valid trials).[1] Due to the increased number of objects in the large displays, the percentages of fixations registered for individual objects were reduced, relative to the small displays. To take account of this, we limited the analyses of percentages of first fixations to those four objects that were presented in both display sizes (one object each from the targets, associates, cohyponyms, and unrelated distractors sets). We computed the percentage of first fixations to each of these objects in relation to the sum of all first fixations to these four objects, excluding fixations to the objects that only featured in the large object displays (21.7% of all valid first fixations). With this procedure, the chance level of fixating a given object was 25% for both display sizes.

When analyzing whether related objects were fixated first more often on related than on unrelated trials, we compared the percentage of first fixations to a related object (associate or cohyponym) to the percentage of fixations to the foil replacing the associate or cohyponym on unrelated trials. This was possible because all displays included one object from each of the four basic sets (targets, associates, cohyponyms, unrelated distractors) and the conditions with no competitor (target-present/no-competitor-present and target-absent/no-competitor-present) included unrelated objects (foils) from the associates and the cohyponyms sets. In the same fashion, we compared the percentage of fixations to the target in target-present trials with the percentage of fixations to the foil replacing it in target-absent trials.

In our analyses, we did not obtain any substantial differences between the effects of associate and cohyponym competitors and will therefore report the results of comparisons of both types of competitors (averaging across trials with associate and cohyponym competitors) with unrelated distractors (averaging across the trials with associate foils and competitor foils). For each dependent variable, an ANOVA was conducted including the within-participants factors target status (present, absent), display size (four, eight), and competitor condition (competitor, foil). In subsequent ANOVAs, we analyzed target-absent and target-present trials separately.

Results

Error rates. Overall, error rates were low (3.6%). They were significantly lower when the target was absent (1.2%) than when it was present [6.1%; $F(1,31) = 46.35$, $p = .001$, $CI = 2.08\%$, $\eta_p^2 = .599$]. Error rates were higher in large displays (4.2%) than in small displays [3.1%; $F(1,31) = 9.82$, $p = .004$, $CI = 1.07\%$, $\eta_p^2 = .241$], but they were unaffected by competitor condition. There were no interactions between the independent variables.

RTs. The mean RTs are shown in Figure 2A. As expected, RTs were significantly shorter on target-present than on target-absent trials [by 288 msec; $F(1,31) = 205.09, p = .001$, $CI = 58$ msec, $\eta_p^2 = .869$], and they were shorter for four-object than for eight-object displays [by 223 msec; $F(1,31) = 297.78$, $p = .001$, $CI = 37$ msec, $\eta_p^2 = .906$]. The effect of display size was larger on target-absent trials (293 msec) than on target-present trials [153 msec; $F(1,31) = 63.12, p = .001$, $CI = 25$ msec, $\eta_p^2 = .671$, for the interaction of target status and display size]. On average, participants took 24 msec longer to respond when a competitor was present than when it was absent [$F(1,31) = 19.61, p = .001, CI = 16$ msec, $\eta_p^2 = .388$]. The effect of the competitor was substantially more pronounced on target-absent trials [38 msec; $t(31) = 5.12$, $p = .001$] than on target-present trials [10 msec; $t(31) = 1.21$, n.s.], yielding a significant interaction of target status and competitor condition [$F(1,31) = 5.48$, $p = .026$, $CI = 17$ msec, $\eta_p^2 = .150$]. Importantly, there was no interaction between the display size and the competitor condition, for target-present or for target-absent trials (both Fs < 1).

Location of first object fixation. On 52.4% of the target-present trials, the first fixation was directed at the target. This percentage was not significantly modulated by the presence of a competitor (53.1% without competitor present vs. 51.8% with competitor present; $F < 1$). The percentage of first fixations to the target was higher for small display sizes (54.2%) than for large display sizes [50.6%; $F(1,31) = 4.09, p = .052, CI = 3.63\%$, $\eta_p^2 = .117$].

Figure 2B presents the percentage of first fixations to the competitor and its foil as a function of target status and display size. There were more first fixations to the competitor and its foil when the target was absent (28.8%) than when it was present [18.7%; $F(1,31) = 80.75$, $p = .001$, $CI = 3.23\%$, $\eta_p^2 = .723$], and more first fixations were directed to the competitor than to its foil [26.7% vs. 20.8%; $F(1,31) = 75.58$, $p = .001$, $CI = 1.98\%$, $\eta_p^2 = .709$]. There was no effect of display size, and there were no significant interactions of target status, competitor condition, and display size (all Fs < 1).

VTs. VTs to the target were analyzed in the target-present condition only. Target VTs were shorter with small display sizes (381 msec) relative to large display sizes [403 msec; $F(1,31) = 14.69$, $p = .001$, $CI = 12$ msec, $\eta_p^2 = .322$], but they were unaffected by the presence or absence of a competitor ($F < 1$ for competitor condition and its interaction with display size).

Figure 2C shows the VTs to the competitor and its foil broken down by target status and display size. The VTs were significantly longer on target-absent trials (212 msec) than on target-present trials [179 msec; $F(1,31) = 43.77$, $p = .001, CI = 14$ msec, $\eta_p^2 = .585$]. There was no significant main effect of display size, but there was a significant interaction of display size and target status [$F(1,31) = 7.24$, $p = .011$, $CI = 14$ msec, $\eta_p^2 = .189$]. Display size only affected VTs in target-absent trials, where VTs to competitors and their foils were longer with small than with large display sizes [by 17 msec; $t(31) = 3.14$, $p = .004$]. On average, competitors were viewed 13 msec longer than were their foils [$F(1,31) = 10.83, p = .003, CI = 12$ msec, $\eta_p^2 = .259$]. There were no interactions of competitor condition with display size or target status.

Discussion

Our results largely replicate those of Moores et al. (2003, Experiment 5). We obtained interference effects on target search from the semantically related competitors (cohyponyms and associates) in the analyses of RTs, percentages of first fixation, and competitor VTs, though for RTs our effects were largely confined to trials where the target was absent. The interference effects were not moderated by variations of perceptual load (the number of objects in the display), even though the display size had a substantial effect on RTs. The effects of display size on RTs were of the order of those commonly found in difficult search tasks (search rates of approximately 38 msec/item and 69 msec/item on target-present and target-absent trials, respectively; cf. Duncan & Humphreys, 1989), which shows that the load manipulation was effective. Despite this, the top-down effects on search were equally effective across the two display sizes.

It might be argued that this finding was a result of the long display presentation times. Participants may have covertly and serially attended to all four (or eight) objects in the display prior to making the first fixation. However, analyses of the onset latency of the first saccade occurring within 80 to 500 msec after display onset (Trottier & Pratt, 2005) suggest that this was not the case: Had the stimuli been covertly attended to prior to the first fixation, we would expect the first saccade to occur later in eight-object display trials than in four-object display trials. However, saccadic onset latencies differed by only 2 msec between display size conditions (small displays, $M = 201$ msec; large displays, $M = 203$ msec; $F < 1$) in both target-present and target-absent trials. The main effect of target status and its interaction with display size were also nonsignificant (both Fs < 1).

Another possible reason why display size did not interact with competitor effects might be that the design of Experiment 1A differed from the design used in previous studies of perceptual load effects on competitor processing. In many of these studies, the competitor appeared at a fixed location in the periphery of the search displays, away from where the target could appear (e.g., Lavie, 1995). With the competitor in a fixed location, which is always irrelevant, the perceptual load may have a greater impact. For example, there may be more processing of this always-to-be-ignored location (and item) at the small display size than at the large display size. In essence, keeping the competitor at a fixed location should maximize the chances that an increasing perceptual load will decrease competitor processing.

Using the object search task employed in the present experiments, we tested the effects of competitors that were not part of the primary search display. In Experiment 1B, which was parallel to Experiment 1A in all aspects except for the allocation of the objects on the screen, we always positioned the competitor (and its foil) in the location at the top of the display and allocated all other objects randomly to the remaining three or seven locations. To discourage participants from looking at the competitor, we instructed them that the target would never appear in the location at the top of the display.

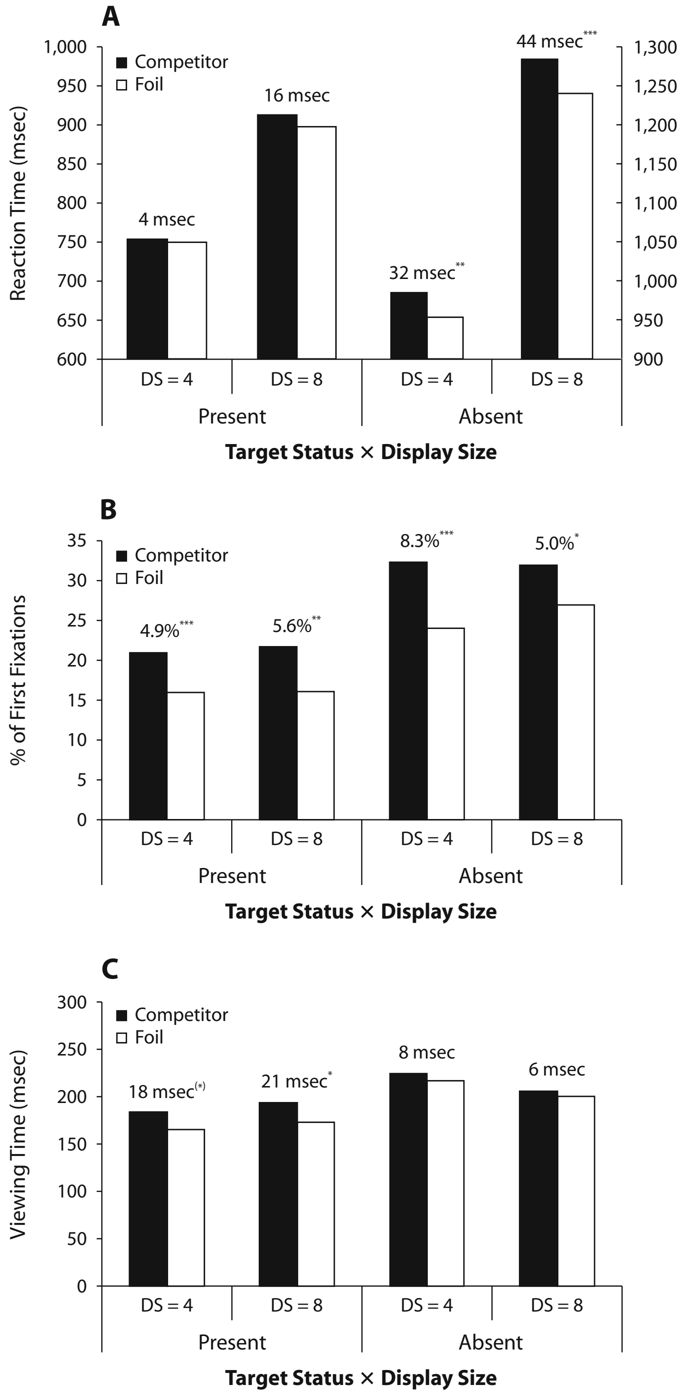

Figure 2. Experiment 1A: (A) Reaction times, (B) percentages of first fixations to the competitor and its foil, and (C) viewing times of the competitor and its foil (subject means) by target status, display size (DS), and competitor condition. In Figure 2A, the left scale applies to the target-present condition and the right one to the target-absent condition. Figures in the graphs represent the differences between the competitor conditions (competitor, foil), broken down by target status and WM load, and their levels of significance (paired *t* tests; $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$; $^{(*)}p < .1$).

Experiment 1B
Fixed Competitor Location

Method

Participants. Twenty-four undergraduate students of the University of Birmingham participated in exchange for course credits. All had normal or corrected-to-normal vision.

Materials. The search displays used in Experiment 1B included the same objects as the displays used in Experiment 1A. However, the competitors (and their unrelated foils) now always appeared at the top of the display.

Apparatus, Design, and Procedure. The same apparatus and design were used as in Experiment 1A. The trial timing was the same as before. In addition to the instructions given in Experiment 1A, participants were explicitly instructed that the target would never appear in the location at the top of the display but only in one of the remaining locations.

Data analysis. Two participants had to be excluded after testing, one because she was not a native speaker of English and one because of technical problems during the recording of the eye movements. Trials were discarded when participants had not looked at the center of the screen at display onset (6.2%), had blinked during display inspection (2.4%), or had pressed the incorrect button (3.3%). After exclusion of outliers, 86.6% of the original data remained for statistical analyses. As in the analyses of Experiment 1A, the location of the first object fixation was evaluated when it occurred within the first 500 msec after display onset (84.0% of all valid trials). The nearest area of interest was computed for all fixations that had been registered close to one of the areas of interest (34.4% of all valid first fixations). As before, we limited the analyses of percentages of first fixations to those four objects that were presented in both display size conditions, and computed the percentage of first fixations to one of those four objects in relation to the sum of all first fixations to these four objects, excluding fixations to the objects that only featured in the large object displays (22.9% of all valid first fixations).

Results

Error rates. As in Experiment 1A, error rates were low (3.4%), and they were significantly lower when the target was absent (1.2%) than when it was present [5.6%; $F(1,21) = 75.97$, $p = .001$, $CI = 1.65\%$, $\eta_p^2 = .783$]. When the target was present, error rates were higher in large display sizes (7.1%) than in small display sizes [4.8%; $F(1,21) = 7.26$, $p = .014$, $CI = 1.78\%$, $\eta_p^2 = .257$]. There was no parallel effect of display size on target-absent trials ($F < 1$), yielding a significant interaction of target status and display size [$F(1,21) = 9.08$, $p = .007$, $CI = 2.15\%$, $\eta_p^2 = .302$].

RTs. The mean RTs are shown in Figure 3A. RTs were significantly shorter on target-present than on target-absent trials [by 287 msec; $F(1,21) = 108.65$, $p = .001$, $CI = 80$ msec, $\eta_p^2 = .838$], and they were longer for eight-object than for four-object displays [by 231 msec; $F(1,21) = 210.50$, $p = .001$, $CI = 47$ msec, $\eta_p^2 = .909$]. The effect of display size was greater in target-absent trials (294 msec) than in target-present trials [169 msec; $F(1,21) = 17.72$, $p = .001$, $CI = 29$ msec, $\eta_p^2 = .458$ for the interaction]. There was no significant main effect of competitor condition, but there was a significant interaction of target status and competitor condition [$F(1,21) = 8.64$, $p = .008$, $CI = 15$ msec, $\eta_p^2 = .291$]. The competitor effect was confined to target-absent trials [25 msec; $F(1,21) = 8.93$, $p = .007$, $CI = 17$ msec, $\eta_p^2 = .298$; see Figure 3A]. Importantly, these competitor effects did not interact significantly with display size ($F < 1$).

Location of first object fixation. When the target was present, participants fixated the target first on 58.9% of the trials. This percentage was significantly higher in small display sizes (61.0%) than in large display sizes [56.6%; $F(1,21) = 4.71$, $p = .042$, $CI = 4.02\%$, $\eta_p^2 = .183$], but there were no significant effects of competitor condition or its interaction with display size.

As expected, the percentage of first fixations to the competitor and its foil at the top of the display was low (9.7%), because participants had been discouraged from searching for the target in this location. The percentages of first fixations to this location are shown in Figure 3B, broken down by target status, display size, and competitor condition (competitor vs. foil). They were not significantly affected by target status (target present, 8.8%; target absent, 10.6%). There were more first fixations to the competitor or its foil in displays with four objects (11.7%) than in displays with eight objects [7.7%; $F(1,21) = 18.17$, $p = .001$, $CI = 2.76\%$, $\eta_p^2 = .464$], and the competitor was fixated more often (11.2%) than its foil [8.2%; $F(1,21) = 17.43$, $p = .001$, $CI = 2.09\%$, $\eta_p^2 = .454$]. As in Experiment 1A, neither the interaction of display size and competitor condition nor any other interaction was significant.

Saccadic onset latencies. As discussed in Experiment 1A, it is conceivable that participants covertly and serially attended to all four (or eight) objects in the display prior to making the first fixation. As in Experiment 1A, we did not find any evidence for this hypothesis in the analyses of saccadic onset latencies. Saccadic onset latencies differed only minimally between display conditions (small displays, $M = 210$ msec; large displays, $M = 211$ msec; $F < 1$) in both target-present and target-absent trials. The main effect of target status and its interaction with display size were also nonsignificant.

VTs. When present, the target was viewed for 401 msec on average. The target VTs were unaffected by display size and competitor condition.

The VTs of the competitor and its foil are displayed in Figure 3C. They were longer when the target was absent (209 msec) than when it was present [177 msec; $F(1,21) = 25.65$, $p = .001$, $CI = 19$ msec, $\eta_p^2 = .550$]. They were unaffected by any of the other variables. Most likely this was due to a lack of power: As reported above, only 9.7% of all first gazes were directed to the competitor and its foil at the top of the display. When considering not only the first but all gazes to the competitor and its foil, the percentage of gazes to the competitor and its foil was only slightly higher (15% of all trials). As a result, the analyses of the VTs of the competitor and its foil were based on a limited number of observations.

Discussion

The present results demonstrate that placing the competitors and their foils in a fixed location in the search display, and instructing participants that the target never appeared in that location, did not alter the pattern of results obtained in Experiment 1A. Importantly, we did not obtain any significant interaction of competitor condition and display size for any of the dependent variables.

As expected, the instruction that the target would never appear in the location at the top of the display led to lower percentages of first fixations to the competitor and its foil

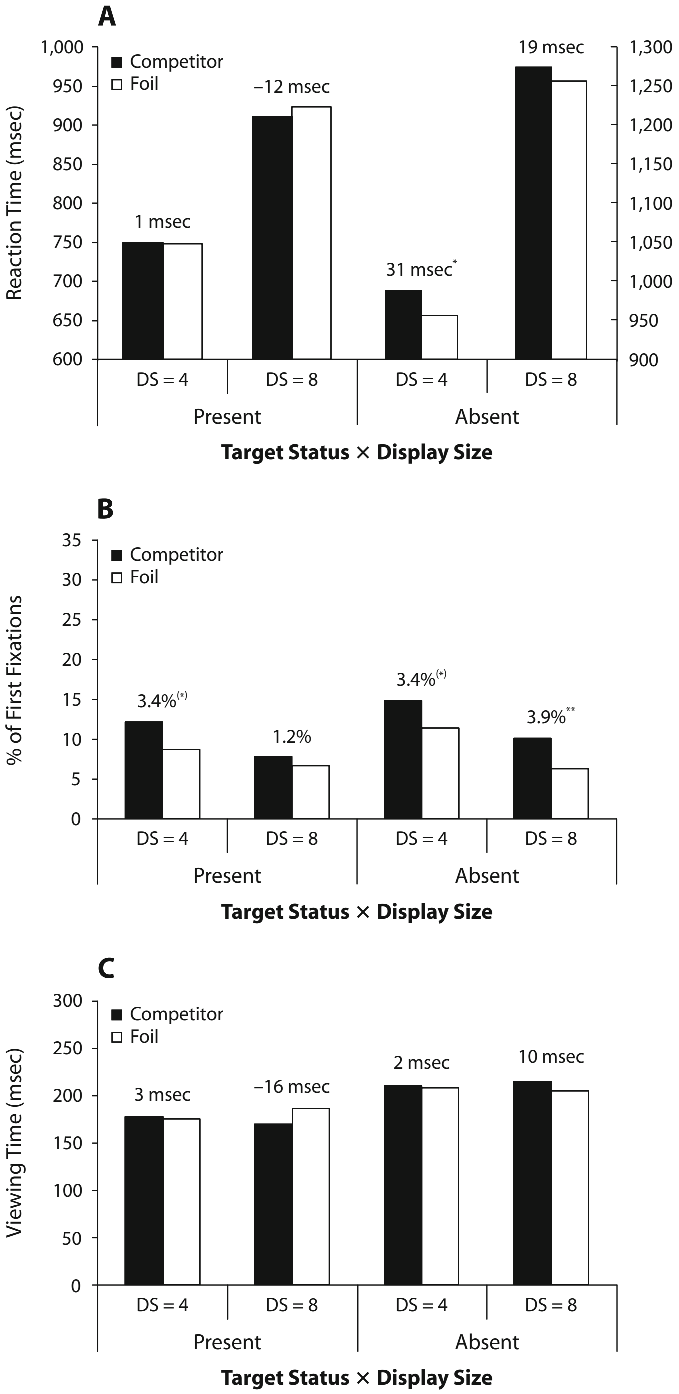

Figure 3. Experiment 1B: (A) Reaction times, (B) percentages of first fixations to the competitor and its foil, and (C) viewing times of the competitor and its foil (subject means) by target status, display size (DS), and competitor condition. In Figure 3A, the left scale applies to the target-present condition and the right one to the target-absent condition. Figures in the graphs represent the differences between the competitor conditions (competitor, foil), broken down by target status and WM load, and their levels of significance (paired *t* tests; $^{*}p < .05$; $^{**}p < .01$; $^{(*)}p < .1$).

and to shorter VTs of the competitor and its foil in Experiment 1B than in Experiment 1A (see Figures 2 and 3). Interestingly, RTs appeared to be largely unaffected by the altered instructions. Indeed, in a joint analysis of the RTs from Experiments 1A and 1B, we obtained no main effect of the between-participants factor experiment ($F < 1$), and experiment did not interact with any of the other variables. The competitor tended to have a weaker effect overall in Experiment 1B (fixed location) than in Experiment 1A (random location), specifically at display size eight (see Figures 2A and 3A). However, the interaction of competitor condition and experiment did not reach significance [$F(1,52) = 2.68, p = .107, CI = 12$ msec, $\eta_p^2 = .049$], nor did the three-way interaction of competitor condition, display size, and experiment [$F(1,52) = 1.47, p = .231, CI = 14$ msec, $\eta_p^2 = .027$].[2] There was, therefore, no evidence that increasing the perceptual load modulated the effects of the competitor on RTs, even when the competitor appeared in a fixed location in the displays (Experiment 1B).

Taken together, the results from Experiments 1A and 1B suggest that top-down guidance of selective visual attention is not strongly constrained by the numbers of objects present, at least up to the limits examined in this study. We will discuss the implications of this finding in more detail in the General Discussion, along with the results of Experiment 2.

EXPERIMENT 2

In Experiment 2, we tested the effects of WM load on the top-down guidance of search by combining the visual search task with a digit retention task. In this experiment, all displays consisted of four objects, and WM load was varied through the number of digits to be retained during the search task (one vs. five).

Method

Unless otherwise mentioned, the method was the same as in Experiment 1A. Thirty-two undergraduate students of the University of Birmingham (native speakers of English) participated, all with normal or corrected-to-normal vision. The same object sets were used as in Experiment 1A (targets, associates, cohyponyms, unrelated distractors), excluding the sets of additional distractor objects that had been used to create eight-object displays in Experiment 1. A $2 \times 2 \times 3$ design was used, including three within-participants factors (target status, WM load, and competitor condition). As in Experiments 1A and 1B, we did not obtain any substantial differences between the effects of associate and cohyponym competitors and will therefore report the results of comparisons of related (associate or cohyponym) competitors with their unrelated foils.

Two experimental blocks were created: Those configurations that had been augmented to large displays in Experiment 1A were now combined with a five-digit retention task; the remaining stimuli were combined with a one-digit retention task. The object displays were created in the same way as in Experiment 1A. The digit(-string) was presented at the beginning of each trial and was prompted at the end. Note that, contrary to other visual search experiments incorporating a similar WM load manipulation, the potential targets were not specified at the beginning of the experiment (e.g., *z* or *x* in a letter-search task), but the target was specified on a trial-by-trial basis. Therefore, each trial included a target-encoding and a search phase. In order to prevent the encoding of the digit(-string) from interfering with the encoding of the target name, we presented the digit(-string) for a relatively long time. During each trial, after successful drift correction, the digit(-string) to be retained across the duration of the search task was presented for 2,500 msec, followed by the target name for 1 sec, a central fixation cross for 600 msec, and the presentation of the object display. As soon as participants had pressed a button, the objects disappeared and participants were prompted to name the digit(-string) they had encoded at the beginning of the trial (see Figure 4). Each experimental block lasted approximately 25 min, with short breaks between blocks. After the experiment, participants were debriefed.

Data analysis. Trials were discarded when participants had not looked at the center of the screen at display onset (4.4%), had blinked during display inspection (5.7%), or had pressed the incorrect button (3.3%). On 1.1% of the trials, no response could be registered for tech-

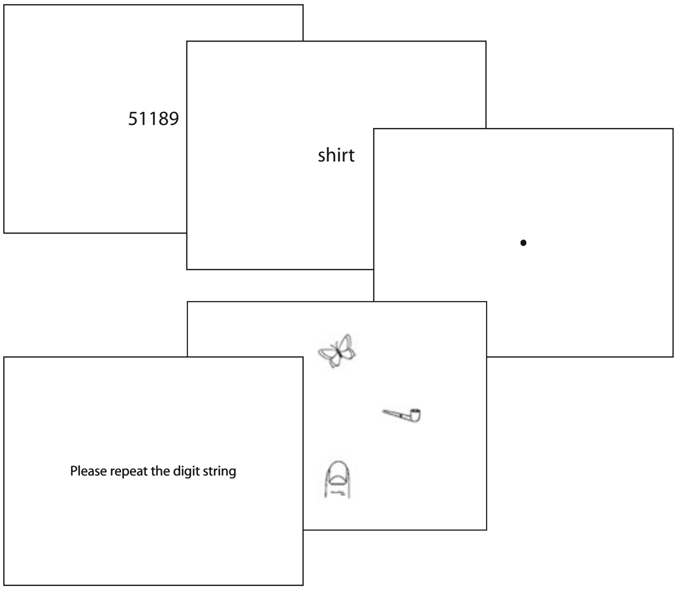

Figure 4. Trial structure used in Experiment 2.

nical reasons. After exclusion of RT outliers, 83.7% of the original data remained for statistical analyses. As before, in the analyses of first fixation locations, the nearest object area was computed for all fixations that did not land directly in one of the areas of interest (30.9% of all valid first fixations). We identified those trials where a first fixation toward one of the object areas occurred within the first 500 msec after display onset (corresponding to 91.9% of all valid first fixations).

Results

Accuracy of recall. On average, participants made fewer errors in the low WM load condition ($M = 1.07\%$) than in the high WM load condition [$M = 6.54\%$; $t(31) = 4.81$, $p = .001$], suggesting that the difficulty of the memory task increased in the high WM load condition.

Error rates and RTs. Participants made more errors on target-present trials (4.6%) than on target-absent trials [2.0%; $F(1,31) = 15.66$, $p = .001$, $CI = 1.88\%$, $\eta_p^2 = .336$]. Error rates were unaffected by any of the other variables or their interactions.

Mean RTs by target status, WM load, and competitor condition are presented in Figure 5A. RTs were significantly shorter in target-present trials (856 msec) than in target-absent trials [1,048 msec; $F(1,31) = 107.61$, $p = .001$, $CI = 54$ msec, $\eta_p^2 = .776$]. There was a main effect of competitor condition [39 msec; $F(1,31) = 24.6$, $p = .001$, $CI = 23$ msec, $\eta_p^2 = .442$], which was largely confined to the target-absent trials, yielding a significant interaction of competitor condition and target status [$F(1,31) = 39.94$, $p = .001$, $CI = 21$ msec, $\eta_p^2 = .563$]: On target-absent trials, RTs were significantly longer when there was a competitor in the display (1,091 msec) than when there was no competitor [1,006 msec; $F(1,31) = 47.20$, $p = .001$, $CI = 25$ msec, $\eta_p^2 = .604$]. There was no significant main effect of WM load ($F < 1$), and WM load did not interact with any of the other variables.

Location of first object fixation. In target-present trials, 53.2% of the first fixations were directed at the target. Compared with the target-present/no-competitor-present condition (52.8%), this percentage was not significantly modulated by the presence of a competitor (53.8%; $F < 1$), and it was unaffected by WM load ($F < 1$).

As would be expected, first fixations to the competitor and its foil were registered more often when the target was absent (29.1%) than when it was present [17.5%; $F(1,31) = 103.53$, $p = .001$, $CI = 3.30\%$, $\eta_p^2 = .770$; see Figure 5B]. Across both target status conditions, there was a significant main effect of competitor condition, with the competitor being fixated significantly more often (25.6%) than its foil [21.1%; $F(1,31) = 21.57$, $p = .001$, $CI = 2.79\%$, $\eta_p^2 = .410$]. When the target was absent, the competitor effect was similar in size at high and at low WM load (see Figure 5B; $F < 1$ for the interaction of competitor condition and WM load). When the target was present, the competitor effects were substantially more pronounced at low than at high WM load (see Figure 5B) [6.2% vs. 1.0%; $F(1,31) = 3.82$, $p = .060$, $CI = 2.73\%$, $\eta_p^2 = .110$ for the interaction]. In the analyses across both target status conditions, this pattern of results yielded a significant three-way interaction of target status, WM load, and competitor condition [$F(1,31) = 4.27$, $p = .047$, $CI = 2.55\%$, $\eta_p^2 = .121$].

VTs. When the target was present, it was inspected for 463 msec, on average. Target VTs were unaffected by competitor condition and WM load or their interaction. Figure 5C displays the VTs of the competitors and their foils across experimental conditions. Competitors were viewed significantly longer (234 msec) than their foils were [200 msec; $F(1,31) = 23.65$, $p = .001$, $CI = 20$ msec, $\eta_p^2 = .433$]. The VTs of the competitor and its foil were significantly longer in target-absent trials (245 msec) than in target-present trials [188 msec; $F(1,31) = 46.61$, $p = .001$, $CI = 24$ msec, $\eta_p^2 = .601$], but did not differ across WM load conditions ($F < 1$). The competitor effects were smaller in target-present than in target-absent trials [$F(1,31) = 3.09$, $p = .088$, $CI = 19$ msec, $\eta_p^2 = .091$ for the interaction], but they were reliable in both target status conditions [target present, 22 msec, $F(1,31) = 5.79$, $p = .022$, $CI = 18$ msec, $\eta_p^2 = .157$; target absent, 45 msec, $F(1,31) = 19.74$, $p = .001$, $CI = 21$ msec, $\eta_p^2 = .389$; see Figure 5C].

Discussion

Experiment 2 replicated the effects of semantically related competitors on RTs, VTs, and percentages of first fixations. As in Experiment 1A, the competitor effects were largely confined to target-absent trials. Contrary to our expectation, there were no significant main effects of WM load on processing times or percentages of first fixations, suggesting that our load manipulation was ineffective. One possible explanation for this is that the relatively long exposure time of the digits (2.5 sec) rendered the encoding and retention of five digits as easy as that of one digit. In a review of the early studies on the effects of concurrent load on attention to cognitive tasks, Logan (1978) found that only memory loads of "seven items or more produce interference in proportion to load. . . . Loads of less than five items have been shown to produce interference when the array for the visual task is presented less than 1 sec after the memory load" (p. 36). The exposure time we used in the present experiment was considerably longer (2.5 sec). The inefficiency of our WM load manipulation (one vs. five digits) may therefore have been caused by the specific timing of the presentation of the digit(-string). This latter explanation would predict relatively high levels of accuracy in the WM load task, which we observed in the present experiment (the accuracy in the WM load task was above 90% in both load conditions). Other authors who have crossed a selective attention task with a WM load task have varied the encoding and retention time provided for one versus several digits. For instance, Lavie et al. (2004, Experiment 1) presented one-digit stimuli for 500 msec, followed by a mask for 750 msec, and six-digit stimuli for 2 sec, followed by a mask for 2.5 sec, yielding much longer encoding and retention times for long than for short digit strings. They, too, obtained levels of accuracy in the WM load task above 90% (95% and 92% for low and high WM load conditions, respectively; $p = .10$ for the difference between error rates). They obtained parallel results with less discrepant presentation times between load conditions (Experiment 2; low load, 750-msec stimulus presentation time, plus 1,250-msec mask; high load, 1.5-sec presen-

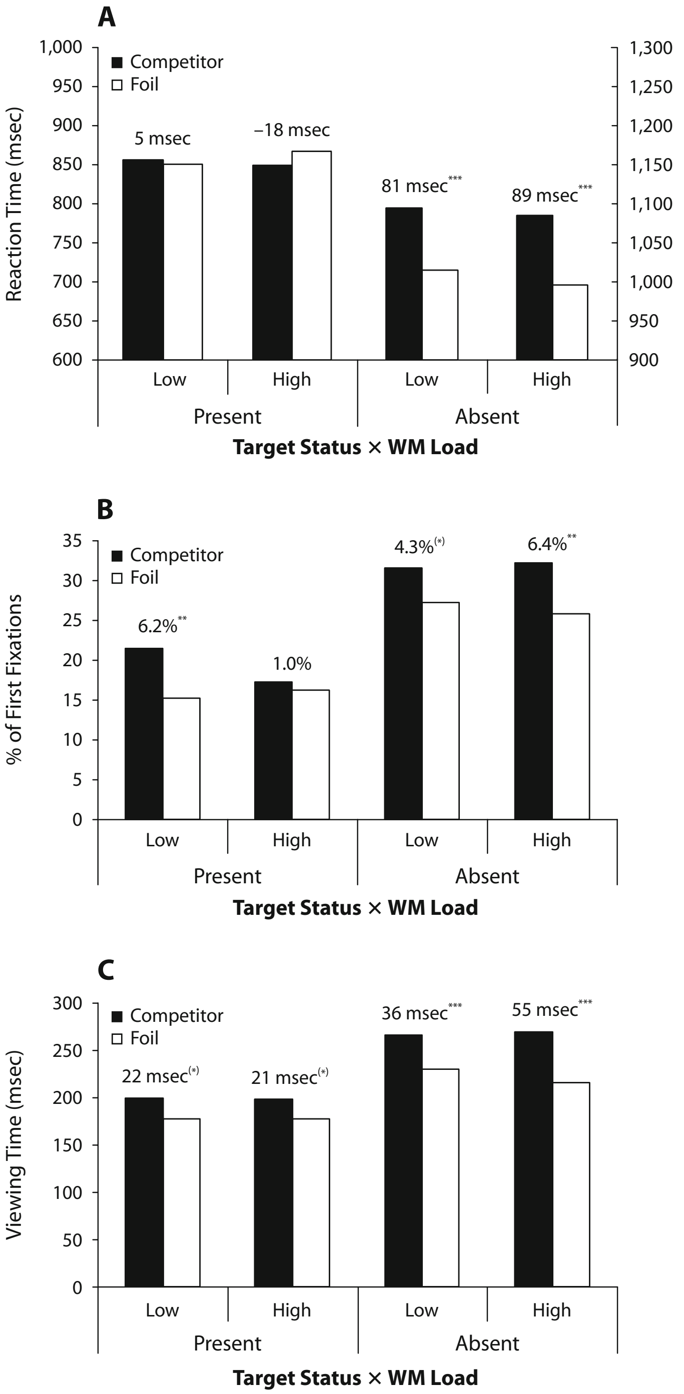

Figure 5. Experiment 2: (A) Reaction times, (B) percentages of first fixations to the competitor and its foil, and (C) viewing times of the competitor and its foil (subject means) by target status, WM load, and competitor condition. In Figure 5A, the left scale applies to the target-present condition and the right one to the target-absent condition. Figures in the graphs represent the differences between the competitor conditions (competitor, foil), broken down by target status and WM load, and their levels of significance (paired *t* tests; $^{**}p < .01$; $^{***}p < .001$; $^{(*)}p < .1$).

tation time, plus 1,250-msec mask). In both experiments there were significant interactions between the competitor effect and the WM load. With an equal encoding time for small and large loads, we should, if anything, have found exacerbated effects.

However, an important difference between the present experiment and the experiments reported by Lavie et al. (2004) is that Lavie and colleagues tested the WM load conditions in a blocked fashion, whereas we mixed low and high WM load trials. Lavie et al. "suspected that intermixing trials of different memory load in one block would result in a general increase in load on cognitive control . . . and hence reduce the potency of the manipulation" (p. 344, note 5). If this hypothesis is correct, we should find a difference between a no-load condition (as assessed in Experiment 1A) and a load condition (as assessed in Experiment 2). Indeed, the effects of competitors on RTs were larger in Experiment 2 (more than 70 msec on target-absent trials) than in Experiment 1A (less than 40 msec on target-absent trials), even when participants only memorized one digit (see Figures 2 and 5).

We compared the size of the competitor effects on the RTs, VTs, and percentages of first fixations to competitors and their foils in Experiment 1A (at display size four) and Experiment 2 (collapsing over both memory load conditions). ANOVAs included the within-participants factors target status (present, absent) and competitor condition (competitor, foil) and the between-participants factor WM load (present, absent). The results of the analyses of RTs are presented in Table 1. As established in the analyses of each experiment reported above, participants responded significantly faster when the target was present than when it was absent. The presence of a competitor significantly slowed RTs (main effect of competitor condition), especially when the target itself was absent (interaction of competitor condition and target status). The interaction of competitor condition and WM load approached significance ($p = .054$) in the overall analyses across both target-present and target-absent conditions. It was more pronounced in target-absent trials [$F(1,62) = 11.11, p = .001, CI = 11$ msec, $\eta^2_{\mathrm{p}} = .152$] than in target-present trials ($F < 1$), yielding a significant three-way interaction of competitor condition, WM load, and target status in the overall analyses (see Table 1).

Table 1 also presents the results of the analyses of the VTs of the competitor and its foil. There were significant main effects of target status and competitor condition, and the effect of WM load approached significance. WM load interacted significantly with competitor condition. As seen in the analyses of the RTs, this interaction was confined to target-absent trials [$F(1,62) = 9.28, p = .003$, CI = 9 msec, $\eta^2_{\mathrm{p}} = .130$], yielding a significant three-way interaction of target status, competitor condition, and WM load (see Table 1).

Percentages of first fixations to the competitor and its foil were significantly higher when the target was absent than when it was present [$F(1,62) = 147.59, p = .001, CI = 1.76\%, \eta^2_{\mathrm{p}} = .704$], and they were higher to the competitor than to its foil [$F(1,62) = 86.59, p = .001, CI = 1.20, \eta^2_{\mathrm{p}} = .583$]. This competitor condition effect was significant not only for target-absent trials [$F(1,62) = 48.44, p = .001, CI = 1.40\%, \eta^2_{\mathrm{p}} = .439$] but also for target-present trials [$F(1,62) = 20.51, p = .001, CI = 1.34\%, \eta^2_{\mathrm{p}} = .249$]. The interaction of target status and competitor condition did not reach significance. There was no main effect of WM load on percentages of first fixations and no significant interaction of WM load and competitor condition. The percentage of first fixations to the target in the target-present condition was unaffected by competitor condition, WM load, or their interaction.

These results suggest that search was less effective when participants carried some WM load. Apparently, though, this effect occurred because the load affected the time taken to reject a competitor; WM load had no detrimental effect on the initial deployment of attention, as would have been shown by an increased effect of the competitor condition on the number of first fixations to the competitor and its foil under load compared with no-load conditions. We suggest, therefore, that the effects of WM load and its interaction with competitor condition seen in the analyses of RTs and competitor VTs (in target-absent trials) were primarily carried by the (increased) processing times for rejecting a competitor during search. In line with this interpretation, *accepting* a target (on target-present trials) was associated with significantly longer VTs under a high WM load ($M = 463$ msec) than under no WM load [$M = 381$ msec; $F(1,62) = 8.92, p = .004, CI = 27$ msec, $\eta^2_{\mathrm{p}} = .126$].

GENERAL DISCUSSION

Our experiments confirmed that, during search for a prespecified object, semantic knowledge about the target

Table 1
Results of Statistical Analyses of the Reaction Times and the Viewing Times of the Competitor and Its Foil Observed in Experiment 1A (Display Size = 4) and Experiment 2

	Reaction Times				Distractor Viewing Times			
	$F(1,62)$	p	CI (msec)	η^2_{p}	$F(1,62)$	p	CI (msec)	η^2_{p}
Target status	281.48^{***}	.001	24	.819	99.99^{***}	.001	10	.617
Target status × WM load	0.97	.329	24	.015	1.20	.277	10	.019
Competitor condition	26.36^{***}	.001	11	.298	24.74^{***}	.001	9	.285
Competitor condition × WM load	$3.84^{(*)}$	.054	11	.058	4.59^{*}	.036	9	.069
Target status × competitor condition	36.30^{***}	.001	10	.369	0.88	.353	8	.014
Target status × competitor condition × WM load	10.02^{**}	.002	10	.139	4.29^{*}	.043	8	.065
WM load	$3.62^{(*)}$	.062	68	.055	$3.68^{(*)}$	.060	14	.056

Note—Analyses involved target status (present, absent) and competitor condition (competitor, foil) as within-participants variables and WM load (present in Experiment 2, absent in Experiment 1A) as a between-participants variable. $^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$. $^{(*)}p < .1$.

is activated and modulates visual selection. We found no interaction of these semantic effects with perceptual load (Experiments 1A and 1B). However, the presence of a WM load increased the interference effect of a competitor in the display relative to the absence of a WM load (in Experiment 1A). WM load did not affect the initial deployment of attention (as assessed by first fixation locations) but the time taken to reject the competitor, once selected (as assessed by VTs). This is in line with evidence from fMRI studies showing increased competitor-related activity in the visual cortex under high as opposed to low WM load conditions (de Fockert, Rees, Frith, & Lavie, 2001), but our eye movement data suggest that the effects of cognitive load affect processes subsequent to visual selection and not the selection process itself. A related observation was reported by Stolz (1996): She found that in a spatial cuing task involving words at fixation and words as spatial cues, the semantic relatedness between the fixation word and the cue word influenced the effectiveness of the cue word as spatial cue. The cuing effect was significantly more pronounced when the cues were semantically related to the fixation word than when they were unrelated. This effect was restricted to invalid cues, suggesting that the semantic relatedness of the cue did not influence the time to move attention to a cued location, but substantially affected participants' efficiency in moving away from an invalid cue to the target location.

The competitor effects on first-fixation locations, found on target-absent trials in both Experiments 1 and 2, indicate that semantic properties of stimuli can guide visual attention (Desimone & Duncan, 1995; Duncan & Humphreys, 1989). Interestingly, this semantic effect on selection was not itself affected by varying the perceptual load of the display (from four to eight items), even though there were strong effects of the display size on RTs. This, in turn, suggests that semantic guidance of search is not limited by this increase in the display size, though the increased perceptual load affects the efficiency of search. For example, top-down activation may be applied in parallel across the items present, augmenting competition from stimuli related to targets, while the overall level of competition increases with the display size. Alternative explanations of the nonsignificant interaction of competitor and display size effects, suggesting that participants attended to all four or eight objects covertly and serially prior to making the first fixation, were ruled out by analyses of saccadic onset latencies. The first saccade after display onset occurred at around 200 msec after display onset, irrespective of the number of objects in the display.

The joint analysis of Experiments 1A and 2, however, suggests that the processing of semantic distractors is limited by cognitive load, although the effect emerges late in search (e.g., it affects VTs, reflecting factors influencing performance after the stimulus has been selected). When participants carried a cognitive load, they found it more difficult to reject selected competitors that were semantically related to the target. It may be that, under low load conditions, the target template is assigned greater weight when being matched to a selected item (see Bundesen, 1990), relative to any other templates that are activated (e.g., those for competitors)—after all, participants do respond to targets rather than to competitors. As the cognitive load increases, though, any differential weighting may decrease, leading to greater semantic interference on rejecting selected distractors. Interestingly, very similar results have been reported by Soto, Humphreys, and Heinke (2006) in a study of effects of WM on search in patients with frontal lobe lesions. Soto et al. (2006) had participants hold an irrelevant item in WM and examined whether this item influenced a subsequent search task (e.g., when the WM item reappeared in the search display). The data showed that frontal patients were more strongly affected by the item in WM than control participants were. This emerged as an effect on the efficiency with which they rejected the item held in WM if it was selected in search. However, there was no difference between patients and control participants in terms of the likelihood of first selecting the WM item in search. There are grounds for arguing that the effects of cognitive load are modulated through the frontal lobes (de Fockert et al., 2001). Thus, when there is an increased cognitive load, or when there is a frontal lobe lesion, competitors become hard to reject following their selection. This is consistent with the differential weighting of a template for the target being contingent on frontal lobe structures (see also Badre, Poldrack, Paré-Blagoev, Insler, & Wagner, 2005; Miller & Cohen, 2001).

Implications for the Early-/Late-Selection Debate

The argument that there can be parallel processing of semantic information for up to eight items in picture displays also speaks to the long-standing debate about the relations between early and late attentional selection (cf. Broadbent, 1958; Deutsch & Deutsch, 1963; Lachter, Forster, & Ruthruff, 2004). According to early selection accounts, we might suppose that there is only relatively superficial processing of the physical properties of stimuli until they are selected. The present results, however, are more consistent with there being parallel processing of items to a semantic level, with the semantic information influencing selection. Subsequent to this, there is a process of matching the selected item against a template in order to verify that the correct target stimulus is present. Semantic effects also emerge in this process of matching to a template, due to competition between the target's template and those of semantically related competitors (see Bundesen, 1990, for a discussion of a possible mechanism). Interestingly, other recent work in our laboratory has shown that not only semantic information, but even the names of objects, may be derived in parallel: Meyer, Belke, Telling, and Humphreys (2007) showed that performance in a search task is affected by the presence or absence of a competitor with a homophonous name to the target (e.g., *animal–baseball bat*). The limits on the level of processing that operates in parallel across displays with multiple objects remain an issue for future research.

To conclude, our data suggest that in visual search, top-down lexical and semantic object knowledge can guide visual selective attention, and that this guidance is largely based on parallel processing of the stimuli in the display. When an object is attended to, the processes involved in matching it against the target template are capacity limited. As a result, effects of top-down semantic knowledge in visual search are modulated by cognitive, but not perceptual, load.

Further Implications: CSTM

The present findings support the CSTM hypothesis put forward by Potter (1976, 1993, 1999), according to which viewers are able to quickly activate and process conceptual information about objects they briefly look at. On average, participants in the present experiments looked at an object for approximately 200 msec during the course of the visual search process; that is, they searched the display at an average looking rate of 4–5 objects/sec. Potter (1976, Experiment 1) showed that participants provided with a written description of a scene—for instance, "a road with cars"—were able to detect the scene in a rapidly presented series of pictures at presentation times as short as 167 msec (six pictures/sec) or 250 msec per picture (four pictures/sec), with rates of correct detection responses as high as 74% (at 167 msec/picture) and 87% (at 250 msec/picture). These relatively high detection rates were accompanied by poor recognition rates of the briefly presented pictures (15% at six pictures/sec and 27% at four pictures/sec).

The original motivation of the rapid sequential presentation of multiple stimuli as in Potter (1976) was, according to Potter (1999), "to simulate normal visual perception, in which the eye fixates briefly on a succession of points and thus processes a continuous sequence of snapshots" (p. 18). This approximation of natural visual exploration behavior presupposes that conceptual information only becomes activated once an object has been fixated. The results from the present study suggest that conceptual information influences visual search prior to the first fixation, during the stage of planning the first saccade to one of the objects. It appears that such top-down information can be applied to the objects in a display in parallel, even prior to selection for attention. Our findings therefore extend Potter's CSTM hypothesis, by suggesting that there is parallel conceptual processing of visual stimuli prior to the first selection for attention (as assessed by the first fixation location in the present experiments). This possibility has been discussed before with regard to related evidence concerning semantic equivalents of the attentional blink and negative priming effects, which had previously been reported primarily in experiments involving purely visual tasks (cf. Barnard et al., 2004; Maki et al., 1997; see also Luck, Vogel, & Shapiro, 1996).

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NOTES

1. Moores et al. (2003) evaluated first saccade landing points rather than first fixation locations as a measure of the initial deployment of visual attention. In the present experiments, the first saccade landing point coincided with the location of the first fixation for more than 95% of all cases in each of the three experiments. In the few cases showing diverging first saccade landing points and first fixation locations, either the analysis software could not provide a location for the first saccade landing point, or the landing point was within the area pertaining to the central fixation point and was followed by a saccade to the first fixation location. We elected to use first fixation locations as the dependent variable, which provided us with slightly more valid cases. Analyses of first saccade landing points yielded virtually identical results to analyses of first fixation locations.

2. As in the individual analyses of each experiment, the joint analysis of RTs yielded significant main effects of target status [$F(1,52) = 298.26$, $p = .001$, $CI = 47$ msec, $\eta_p^2 = .852$], display size [$F(1,52) = 494.15$, $p = .001$, $CI = 29$ msec, $\eta_p^2 = .905$], and competitor condition [$F(1,52) = 15.40$, $p = .001$, $CI = 12$ msec, $\eta_p^2 = .229$], as well as significant interactions of target status and display size [$F(1,52) = 66.58$, $p = .001$, $CI = 23$ msec, $\eta_p^2 = .561$] and target status and competitor condition [$F(1,52) = 12.02$, $p = .001$, $CI = 12$ msec, $\eta_p^2 = .188$]. None of the other interactions reached significance; specifically, the interaction of competitor condition and display size was not significant ($F < 1$).

APPENDIX
Object Sets Used in Experiments 1 and 2

					Additional Unrelated Distractors Used in Experiments 1A and 1B			
	Set 1 (Targets)	Set 2 (Associates)	Set 3 (Cohyponyms)	Set 4 (Unrelated Distractors)	Set 5	Set 6	Set 7	Set 8
1	hand	finger	foot	torch	anchor	glasses	snowman	plug
2	shirt	button	trousers	swan	ant	grapes	scissors	ruler
3	plane	propeller	ship	tie	banana	guitar	leaf	mitten
4	bird	feather	fish	lollypop	purse	hanger	snake	mushroom
5	crown	king	sceptre	pear	thermometer	hat	whistle	rabbit
6	nose	face	eye	bell	candle	flag	wheel	igloo
7	saddle	horse	horseshoe	cloud	chair	necklace	saw	tree
8	organ	church	horn	football	clock	umbrella	duck	envelope
9	hammer	nail	drill	card				
10	comb	hair	brush	mouse				
11	lock	key	hinge	plaster				
12	racket	shuttle	bat	flower				
13	cigarette	ashtray	pipe	weight				
14	screw	nut	hook	belt				
15	thread	needle	rope	butterfly				
16	arrow	bow	bullet	broom				

Note—One object each of Sets 1–4 appeared in each display. To create eight-object displays in Experiment 1, four additional objects were selected from Sets 5 to 8.

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