Do the Contents of Working Memory Capture Attention?
Yes, But Cognitive Control Matters

Suk Won Han
Vanderbilt University

Min-Shik Kim
Yonsei University

There has been a controversy on whether working memory can guide attentional selection. Some researchers have reported that the contents of working memory guide attention automatically in visual search (D. Soto, D. Heinke, G. W. Humphreys, & M. J. Blanco, 2005). On the other hand, G.F. Woodman and S. J. Luck (2007) reported that they could not find any evidence of attentional capture by working memory. In the present study, we tried to find an integrative explanation for the different sets of results. We report evidence for attentional capture by working memory, but this effect was eliminated when search was perceptually demanding or the onset of the search was delayed long enough for cognitive control of search to be implemented under particular conditions. We suggest that perceptual difficulty and the time course of cognitive control as important factors that determine when information in working memory influences attention.

Keywords: working memory, attention, visual search, cognitive control

The human cognitive system cannot process every input it receives because of its limited capacity. Selective attention plays a critical role in human information processing, preventing information overload by allocating limited resource to the most critical and relevant aspect of information. A large body of research has investigated which factors would be important to determine what is attended. Studies using visual search have suggested that salient stimuli or newly appearing objects are prioritized for selection in a bottom-up manner, winning any competition for attention in relation to other competitors (Theeuwes, 1992, 2004; Yantis & Jonides, 1984). On the other hand, other authors have shown that top-down strategies or task relevancy can also be critical for attentional orienting (Bacon & Egeth, 1994; Leber & Egeth, 2006; Yantis & Jonides, 1990). In addition, a classical study by Duncan and Humphreys (1989) suggested that the activation of a template for the target, stored in memory, could guide attention through top-down control.

In accordance with Duncan and Humphreys (1989) and Desimone and Duncan (1995), working memory has also been suggested as one of factors that influence attentional selection. Numerous researchers have reported that visual information is maintained in working memory via the allocation of attention to that information. In addition, studies have shown that both visuo-spatial working memory and executive working memory load influence attentional effects on visual processing, suggesting a functional overlapping or sharing of resources between working memory and attention (Awh & Jonides, 2001; Awh, Jonides, & Reuter-Lorenz, 1998; Han & Kim, 2004; Oh & Kim, 2004; Woodman & Luck, 2004). Based upon the close interaction between working memory and attention, Downing (2000) showed that not only could attention determine what is stored in working memory, but the contents of information in working memory also influenced what is attended in the visual scene. Since this initial study, the effects of working memory on attention have been subject to considerable debate. Consistent with Downing’s (2000) study, Soto, Heinke, Humphreys, and Blanco (2005) showed that features or objects maintained in working memory could guide spatial attention and saccades in an involuntary manner. On the other hand, Woodman and Luck (2007) suggested that working memory did not guide spatial attention automatically, but rather, its contents could be used in a flexible manner for a more efficient search. The goal of the current study is to find an integrative explanation for these conflicting arguments.

In Downing’s (2000) study, participants were required to memorize a face (memory face). After the memory face disappeared, two faces were briefly presented. One was identical to the memory face, whereas the other was novel. The offset of the two-face presentation was followed by the brief presentation of a spatial probe either at the location of the memory face or at the location of the novel one. The responses to the spatial probe were faster when it was presented at the location of the memory face than when it was at the location of the novel face. Based upon these results, Downing suggested that the item maintained in working memory could guide spatial attention automatically.

However, Lee and Kim (2002) and Woodman and Luck (2007) provided an alternative account for the results obtained by Down-
ing (2000). According to these authors, participants could have attended the memory-matching face strategically to refresh their memory representations, reducing the load of the working memory task. Downing’s results might not reflect automatic attentional capture by working memory, but instead reveal strategic deployment of attention to the memory-matching stimulus to reduce cognitive load.

Several other studies were also concerned with the interaction between working memory and attentional selection. Soto et al. (2005) showed top-down guidance of spatial attention from working memory using a visual search paradigm. In their experiments, a colored shape was presented as a memory prime, followed by a visual search display. In the search display, there was a left or right tilted line among three vertical lines. Participants had to report the orientation of the tilted line. Each search item was inside colored-shape placeholders, one of which was identical in color and/or shape to the memory prime. The placeholder with the identical feature to the memory prime contained a target on a valid trial or a distractor on an invalid trial. On neutral trials, the feature of the memory prime was absent from the search display. Reaction times (RTs) in the search task were faster in valid than in neutral trials and invalid trials, indicating that the contents of working memory guided spatial attention.

Soto et al. (2005) also tested the possibility that information held in working memory guided attention in an involuntary manner. In their fourth experiment, in which there were only neutral and invalid trials, RTs were slower for invalid than for neutral trials even though participants knew that the item with the feature maintained in working memory would never be a target. This result suggests that working memory guided spatial attention in an involuntary manner. In Soto et al.’s experiment, the working memory task was to memorize a simple object. In contrast with Downing (2000), limited types of simple objects were repeatedly presented within the whole experiment, making them highly familiar. This memory task would not have been demanding enough to necessitate strategic perceptual resampling because the capacity limit of visual working memory, especially with simple stimuli, is about four objects (Alvarez & Cavanagh, 2004; Vogel, Luck, & Woodman, 2001). Furthermore, participants could have had an incentive not to attend the memory-matching stimulus because they were already instructed that the memory-matching item would never be a target. In another recent study, Soto, Humphreys, and Heinke (2006) also showed that the memory-matching distractor could be prioritized even in the presence of a pop-out target in the visual search task, whereas Olivers, Meijer, and Theeuwes (2006) found that a singleton in the search display that matched the stimulus in working memory induced a larger attentional capture effect. These studies provide evidence of attentional capture by working memory, circumventing the perceptual resampling account.

On the other hand, Woodman and Luck (2007) designed similar experiments to those of Soto et al. (2005), but with different results. A colored square was presented for memorizing, followed by a search display. Search items were colored Landolt squares. On half of the trials, one of the distractors could match the memory item in color or both in color and shape (invalid trials). In the other half, there was no memory-matching distractor (neutral trials). Woodman and Luck also noted that their design eliminated the possibility of strategic deployment of attention to the memory-matching stimulus because participants knew the memory-matching stimulus would never be a target. Woodman and Luck reported that they could not find any evidence that working memory contents captured attention. Furthermore, in their third experiment, Woodman and Luck reported that spatial attention could be deviated away from the location of the memory-matching distractor to make search efficient on invalid trials. Woodman and Luck suggested that working memory contents did not capture attention automatically, but the cognitive control setting could form a “template for rejection.” This “template for rejection” could be used to filter out the distractor matching the memory item, resulting in faster responses for invalid trials.

In summary, there is currently mixed evidence on whether the contents of working memory influence attention, and if they do, under what circumstances. In the present study, we sought to replicate attentional capture by working memory, whereas also demonstrating top-down modulation on the effect of memory-driven attentional capture, using the same task. The important point to be considered here is that it would take some time for cognitive control of the irrelevant information in working memory to come into effect (Badre & Wagner, 2006; Humphreys, Stalmann, & Olivers, 2004; Kim & Cave, 2001). To enable cognitive control based upon top-down knowledge to come into effect, we manipulated the perceptual difficulty of visual search in Experiments 1 and 2, and we delayed the onset of the visual search task in Experiment 4. We hypothesized that the search item matching the feature maintained in working memory would be prioritized by default. As shown in Figure 1, perceptual processing in an easy search task could be completed early and the search task finished before any cognitive control could be put into effect. In this case, although it was known that the memory color would always be

![Figure 1](image-url)
associated with the distractor, top-down control would not be able to override the default prioritization of the memory-matching item because cognitive control would not be fully established. This prioritization would be revealed by increased RTs on invalid trials (when the memory item matched a distractor) compared with neutral trials (the memory item did not reappear in the search display). In contrast, when search is perceptually difficult, perceptual processing may be extended long enough for cognitive control to be implemented. When cognitive control based on top-down knowledge is fully established, the initial prioritization by the memory color should diminish. In addition, when there is sufficient time for cognitive control to be implemented even with an easy search task (e.g., giving a long interval between the memory item and the search display), the effect of memory-driven attentional capture should be diminished.

The reason why Woodman and Luck (2007) failed to find evidence of attentional capture by working memory could be because their search task was perceptually demanding, and so it allowed time for cognitive control mechanisms to come into play. On the other hand, Soto et al.’s (2005) easier search task may have enabled the memory item to influence search before cognitive control was established. However, the experimental tasks and stimuli of Woodman and Luck and Soto et al. were different, so it is impossible to compare their results directly. In the present study, we tried to reconcile the conflicting results by systematically varying experimental parameters within the same task. Perceptual difficulty was varied systematically by manipulating target-distractor similarity in separate experiments (Duncan & Humphreys, 1989). Furthermore, in our final experiment, the onset of the visual search was delayed long enough for cognitive control to reset the prioritization of the search items. We asked whether this would change the effects of working memory on search.

Experiment 1

Experiment 1 was designed to investigate whether or not working memory contents could guide attention involuntarily when the concurrent visual search task was perceptually demanding. When search was perceptually demanding, there would be sufficient time for cognitive control to take place, modulating memory-based attentional capture. We also examined whether the effectiveness of cognitive control would depend on search speed.

Method

Participants. Twenty-five undergraduate students at Yonsei University participated for course credits. All of them had normal or corrected-to-normal vision and were naïve as to the purpose of the experiment. Informed consents were obtained from all of the participants.

Stimuli and apparatus. The stimuli were presented on a 17-inch CRT monitor with a black background. The monitor refresh rate was 75 Hz and the resolution was set to 1,024 × 768 pixels. The experiment was programmed using MATLAB equipped with psychophysics toolbox (Brainard, 1997), and was run on a PC with Pentium 4 processor. Viewing distance was set to 57 cm and an adjustable chin rest was used. Participants were required to fixate on a small gray cross (0.5° × 0.5° of visual angle). The memory sample was a colored square (each 0.71° × 0.71°) presented 1.0° above fixation. The color of the memory sample was chosen randomly among a selection of seven colors (red, green, blue, yellow, pink, cyan, and white). Each color was produced by RGB permutations. The distractors were three colored squares (1.29° × 1.29°) with a gap (0.07° × 0.29°) on the left and the right side of the square, with a line thickness of 0.07°. The target had a slightly larger gap (0.07° × 0.43°) on either the left or the right side. The search items were presented at four locations of equal distance among 20 locations evenly spaced on an imaginary circle with the radius of 6.5°. The overall shape of the search array could vary, but the distance between items was constant. The target with the larger left side gap and with the larger right side gap appeared equally often in randomized order. Two thirds of the total trials were invalid trials, in which there was a distractor with the same color as that of the memory sample. The remaining trials were neutral trials, in which the color of the memory sample did not match any color in the search display. Participants were instructed that the item with the memory-matching color would never be a target.

Procedure and design. A sample trial sequence is shown in Figure 2. At the beginning of each trial, “ABCD” was presented at the center of the screen for 506 ms, which prompted participants to begin a verbal rehearsal, repeating ABCD. A fixation cross was present continuously throughout the whole experiment. After a subsequent 506-ms interval, a 506-ms presentation of the memory sample followed. The participants were required to memorize the

![Figure 2](https://example.com/figure2.png)

An example of an invalid trial. In the visual search array, there was a distractor with a color matching the memory sample.
color of the memory sample. After a 506-ms interval, the visual search display was presented. The participants had to indicate which side of the target had a larger gap. They were required to provide a speeded response, and the search array disappeared as soon as they responded. If participants did not respond within 5,000 ms, an error sound was heard and that trial was removed from the analysis. At the end of the trial, a single colored square was presented as a memory test probe. The participants had to judge whether or not the color of the probe was identical to the color of the memory sample. However, fast their visual search response was, the interval from the onset of search array to the onset of the memory test probe was constantly 5,000 ms. Participants performed two blocks of 96 trials.

Results and Discussion

Five participants were excluded from the analysis because their error rates on the visual search task exceeded 10%. Search accuracy rates and RTs were analyzed through a within-subject one-way analysis of variance (ANOVA) with validity as the factor. Search accuracy rates were 96.9% for invalid trials and 97.6% for neutral trials, which were not significantly different across validity conditions, \( F(1, 19) = 3.34, p = .099 \). Mean RTs for trials with correct search responses and memory responses were analyzed, which showed that visual search times were nearly identical across validity conditions (\( M = 1,717 \) ms for invalid trials and \( M = 1,725 \) ms for neutral trials), \( F(1, 19) = .115, p = .74 \). On the other hand, memory performance was significantly better in invalid condition (95.1% for invalid trials and 91.5% for neutral trials), \( F(1, 19) = 12.94, p < .01, \eta^2 = .405 \). From the results of Experiment 1, we could not find any evidence of attentional capture by working memory. Visual search accuracy rates and RTs did not significantly differ across validity conditions, consistent with Experiment 1 and Experiment 2 in Woodman and Luck (2007). It should also be noted that relatively slow search RTs (\( M = 1,717 \) ms for invalid trials and \( M = 1,725 \) ms for neutral trials) would allow for cognitive control to come into effect.

To further investigate the interaction between perceptual difficulty and memory-driven attention capture, participants were split into two groups based on their RTs in neutral trials.\(^1\) Half of the participants were assigned to a fast search group, and the other half to a slow search group. As shown in Figure 3, the participants in the fast search group showed a pattern of attentional capture by working memory. Search RTs on invalid trials were slower than those on neutral trials (\( M = 1.611 \) ms for invalid trials and \( M = 1.542 \) ms for neutral trials). This difference was marginally significant, \( F(1, 9) = 3.761, p = .084 \). In contrast, for the slow search group, a negative bias against the memory-matching stimulus was observed. RTs for invalid trials were significantly faster than those for neutral trials (\( M = 1.842 \) ms for invalid trials and \( M = 1.912 \) ms for neutral trials), \( F(1, 9) = 7.73, p < .05, \eta^2 = .462 \). The interaction between search group and validity was significant, \( F(1, 18) = 10.90, p < .01, \eta^2 = .377 \). There were opposite effects of working memory depending on search speed. This is consistent with the argument that cognitive control would be critical to observe memory-driven attentional capture. When the search task was perceptually demanding enough, there would be sufficient time for cognitive control to be fully established to modulate the prioritization by working memory contents.

The finding that there was significantly higher memory accuracy for invalid trials fits with the data from Experiment 3 in Woodman and Luck (2007), in which memory load was increased to three objects. In that experiment, Woodman and Luck found that search times could be faster for invalid trials than for neutral trials, arguing against attentional capture by the memory-matching distractor. They suggested that attention was allocated to the target first, and after the search response, attention was allocated to the memory-matching distractor to consolidate the memory representation (termed a perceptual resampling account). We admit the possibility that perceptual resampling may have occurred in our experiments, but higher memory accuracy for invalid trials does not necessarily reflect strategic deployment of focal attention to the memory-matching distractor. That is, there might have been perceptual resampling, but it was not evident that this resampling was made through the strategic orienting of focal attention. It is possible that the memory representation happened to be refreshed during the presentation of the search stimuli. Indeed, if strategic orienting to the memory-matching stimulus occurred during search, then search times on invalid trials would have slowed relative to neutral trials. However, in Experiment 1, in which the search was difficult, there was no difference in mean search times across conditions, only higher memory accuracy for invalid trials. Further research is necessary to clarify the reason for better performance in the working memory task on invalid trials.

Experiment 2

Experiment 2 was designed to further investigate whether working memory could guide attention involuntarily, using a less demanding visual search task. Here, the visual search task was made perceptually easier by decreasing target-distractor similarity. When perceptual processing of the search stimuli is easier, there should be less time for cognitive control to come into play, and stronger evidence for attentional capture should emerge.

Method

Participants. Fifteen undergraduate students at Yonsei University participated for course credits. All had normal or corrected-to-normal vision and were naïve as to the purpose of the experiment. Informed consents were obtained from all of the participants.

Stimuli and apparatus. Stimuli and apparatus were identical to those of Experiment 1, except that the target was designed to be more easily discriminated from distractors. Specifically, in Experiment 1, distractors had same-size gaps (0.07° × 0.29°) on both sides, and the target had a gap of the same size as the distractors on one side, and a slightly larger gap (0.07° × 0.43°) on the other side. In Experiment 2, the target had different gap sizes on each side, but the difference in gap size was increased (0.43° vs. 0.29° in Experiment 1, 0.57° vs. 0.29° in Experiment 2) whereas the distractors were identical to those of Experiment 1.

Procedure and design. The procedure and the design were identical to those of Experiment 1, except that the interval from the onset

\(^1\) RTs only for neutral trials, not including invalid trials, would provide an estimate of how fast each individual could complete processing of search stimuli.
of search array to the onset of the memory-test probe was constantly 4,000 ms. If participants did not respond within 4,000 ms, an error sound was heard and that trial was removed from the analysis.

Results and Discussion

Search accuracy rates, search RTs, and memory accuracy rates were analyzed through a within-subject one-way ANOVA. Search accuracy rates (98.6% for invalid and 99% for neutral trials) were not significantly different across validity conditions, $F(1, 14) = 3.49, p > .05$. Memory performance (93.4% for invalid trials and 92.4% for neutral trials) was also equivalent for each condition, $F(1, 14) = .76, p > .3$. The analysis of the mean RTs on trials with correct search and memory responses showed that search times for invalid trials were significantly slower than those for neutral trials ($M = 1,221$ ms for invalid trials and $M = 1,144$ ms for neutral trials), $F(1, 14) = 17.39, p < .01, \eta^2 = .554$. The results of Experiment 1 and Experiment 2 are shown in Figure 4. When the visual search task was perceptually easy (Experiment 2), search times for invalid trials were significantly slower than those for neutral trials, whereas overall differences in RTs were absent when the visual search task was perceptually demanding (Experiment 1). The RT data from Experiment 1 and Experiment 2 were analyzed through a two-way ANOVA with validity as a within subject

![Figure 3](image1.png)  
Figure 3. Results from Experiment 1. Participants were split into two groups depending on their search reaction times for neutral trials. Error bars represent standard errors.

![Figure 4](image2.png)  
Figure 4. Results from Experiments (Exp.) 1 and 2. Error bars represent standard errors. In Experiment 1, target-distractor similarity was high, inducing extended perceptual processing. In Experiment 2, perceptual processing was relatively less demanding because of low similarity between target and distractor.
factor and with perceptual difficulty as a between-subject factor. The interaction between validity and perceptual difficulty was significant, $F(1, 33) = 2.124, p < .05, \eta^2 = .138$. The analysis for search accuracy and memory accuracy did not reveal any significant interaction.

From Experiment 2, we found clear evidence that attention was captured by working memory, consistent with Soto et al. (2005). Indeed, there may have been initial attentional orienting to an item matching the memory stimulus in Experiment 1, in which the visual search task was relatively difficult, but this might have little overall effect on performance given the difficulty of the search task and given that cognitive control could then have been implemented. On the other hand, with the perceptually easy visual search task in Experiment 2, the initial prioritization by working memory would not be diminished because perceptual processing of search stimuli could be completed before cognitive control was implemented. Along with the results of Experiment 1, the significant interaction between Experiment 1 and Experiment 2 supported the argument that discrepancy between Soto et al. (2005) and Woodman and Luck (2007) could be induced by the difference in perceptual difficulty of the visual search task.

Experiment 3

A simple alternative account for the results of Experiment 1 and Experiment 2 could be that, because the visual search task in Experiment 1 was extremely difficult, any effect of working memory on the first deployment of attention could be washed out by the time the target was found. To confirm that the present results were not because of a floor effect, we designed Experiment 3, in which top-down knowledge about the memory item always being invalid, was absent, whereas the perceptual difficulty of the visual search task remained the same as Experiment 1. Without knowledge that the distractor would always be invalid, cognitive control may not be effective. In this case, validity effects of the memory item, when it re-appeared in the search display, should emerge even with difficult search. Participants could not predict whether the memory-matching item could be a target or a distractor because valid, invalid, and neutral trials were evenly distributed in randomized order within a single block in the experiment.

Method

Participants. Ten undergraduate students at Yonsei University participated for course credits. All had normal or corrected-to-normal vision and were naive as to the purpose of the experiment. Informed consents were obtained from all of the participants.

Stimuli and apparatus. Stimuli and apparatus were identical to those of Experiment 1. In Experiment 1 and Experiment 2, two thirds (64 trials) of the total number of trials were invalid trials and one third (32 trials) was composed of neutral trials within each block, and participants were instructed that the memory-matching item would never be a target. In the present experiment, however, valid trials in which the memory-matching item was a target were included, and each number of valid, invalid, and neutral trials was the same (32 trials each) within a single block. Thus, participants could not predict whether the memory-matching item would be a target or a distractor.

Procedure and design. The procedure and design were identical to those of Experiment 1 except that there were three levels (valid, neutral, and invalid) of validity. Participants performed two blocks of 96 trials.

Results and Discussion

The results of Experiment 3 are shown in Figure 5. Mean reaction times for trials with correct search and memory responses were analyzed through a within-subjects one-way ANOVA with validity (valid, neutral, and invalid) as the factor. The results showed a significant main effect of validity, $F(2, 18) = 60.86, p < .01$, and RTs for invalid trials were significantly slower than those for neutral trials ($M = 2,050$ ms for invalid trials and $M = 1,819$ ms for neutral trials), $t(9) = 4.03, p < .01$. The ANOVA on accuracy (98.9% for valid, 96.9% for neutral, and 95.6% for invalid trials) also revealed a significant main effect of validity, $F(2, 18) = 5.09, p < .05, \eta^2 = .361$. Soto et al. (2005) and Woodman and Luck (2007) also reported similar patterns. Although the visual search task was perceptually demanding, prioritization by working memory was apparent when participants had no foreknowledge that the memory item would always be invalid. From the result of Experiment 3, we conclude that lack of evidence of attentional capture by working memory in Experiment 1 was not because of the floor effect but because of reduced interference by top-down knowledge from the memory-matching distractor.

Memory performance was also analyzed through a within-subjects one-way ANOVA. There was a significant main effect of validity, $F(2, 18) = 4.50, p < .05, \eta^2 = .333$. The significant main effect of validity might suggest that strategic memory resampling took place, which would be consistent with the strategic orienting of focal attention in search. However, paired-sample $t$ tests showed that the memory accuracy was not different for between neutral and invalid trials (93.4% and 93.6%), though memory performance for valid trials (97.2%) was significantly higher than that for neutral trials, $t(9) = 3.21, p < .05$. If strategic resampling was
made reliably, the memory performance for invalid trials would also have been significantly higher than that for neutral trials.

In Experiment 3, we tried to eliminate any effects of cognitive control on the effects of working memory on attention by distributing valid, neutral, and invalid trials evenly within a single block (one third of total trials each). However, under this manipulation, the memory-matching item appeared in the search array on two thirds of the total trials, which might attract participants’ attention over time. To eliminate this learning of contingency, we designed another experiment (\(N = 9\)) in which half of total trials were neutral trials and the rest were divided evenly into invalid and valid trials (one-fourth invalid, one-fourth valid, and one-half neutral trials). In this experiment, the memory-matching color did not appear in the search array at a level greater than chance. The results showed the same pattern. A one-way ANOVA on search times revealed a significant main effect of validity, \(F(2, 16) = 59.09, p < .01\), \(\eta^2 = .881\). The difference between valid (\(M = 1,459\) ms) and neutral trials (\(M = 2,001\) ms) was significant, \(t(8) = 7.34, p < .01\). There was also a highly significant difference between invalid (\(M = 2,215\) ms) and neutral trials (\(M = 2,001\) ms), \(t(8) = 4.97, p < .01\). Search accuracy rates were not different significantly, but memory performance (95.4% for valid, 90.2% for neutral, and 91.9% for invalid trials) were significantly different, \(F(2, 16) = 6.25, p < .05\), \(\eta^2 = .439\). Memory performance for invalid and neutral trials did not differ, \(t < 1\).

Finally, we reduced the number of valid and invalid trials to one sixth of the total trials (one-sixth valid, one-sixth invalid, and two-thirds neutral) to further discourage participants to attend the memory-matching item. In this experiment (\(N = 11\)) the pattern of results was observed again. The main effect of validity on search times was significant, \(F(2, 20) = 37.17, p < .01\), \(\eta^2 = .788\). Paired t tests showed that RTs for valid trials (\(M = 1,342\) ms) were significantly faster than those for neutral trials (\(M = 1,758\) ms), \(t(10) = 5.427, p < .01\). The difference between neutral and invalid trials (\(M = 1,896\) ms) was also significant, \(t(10) = 3.96, p < .01\). Memory performance was significantly different between valid (99.4%) and neutral trials (94.8%), \(t(10) = 3.75, p < .01\), but the difference between invalid (96.3%) and neutral trials was not significant, \(p > .20\).

The results of Experiment 3 are also critical to defend against another important alternative: the load theory account (Lavie, 1995; Lavie, Hirst, De Fockert, & Viding, 2004). According to load theory, irrelevant distractors cannot be processed when the processing of relevant information consumes full perceptual capacity. The results of Experiment 1 could also be interpreted as the processing of low-salient relevant information (the small gap size in the squares) exhausting perceptual resources, so that irrelevant colors did not distract attention. This explanation is plausible and stands logically, but it can be ruled out for the following reasons. First, as already mentioned, the lack of difference between the invalid and neutral condition in Experiment 1 did not necessarily mean that the memory color had no effect—the faster participants showed capture by working memory whereas slower participants showed facilitated performance on invalid trials. These opposite effects cannot easily be linked to changes in a single processing resource. Second, the results of Experiment 3, in which there was no top-down knowledge, showed that the color was processed whereas participants performed the difficult search task. Although the search task remained demanding, there were sufficient resources available to enable the memory item to affect search.

### Experiment 4

Experiment 4 was designed to provide further evidence that cognitive control based on top-down knowledge of the memory item always being invalid could play a critical role in determining the effects of memory-driven attentional capture. A second goal was to assess the specific time course of cognitive control. The onset of the search display was delayed whereas the perceptual difficulty of the visual search task was the same as that in Experiment 2, in which attentional capture by working memory was evident. In previous experiments presented here, the visual search display followed the presentation of a memory stimulus. In Experiment 4, however, the memory stimulus was followed by the presentation of four colored squares occupying the positions of the search items. The squares were identical to the search items used in Experiment 2, except that they had no gaps on either side. During the presentation of these squares, cognitive control could be implemented based on knowledge that the memory-matching item would never be a target, but the search could not be initiated. The visual search display was defined by the removal of line segments in each square. The search onset could be either at a short (150 ms) or long delay (750 ms). Considering that it would take some time for cognitive control to be implemented, we expected that attentional capture by working memory would be observed in the short delay condition. In contrast, this capture effect would be diminished in the long-delay condition by the introduction of cognitive control. It is also possible that the capture effect would be reversed because cognitive control could deviate attention from the memory-matching distractor for a more efficient search.

### Method

#### Participants

Nineteen undergraduate students at Yonsei University participated for course credits. All had normal or corrected-to-normal vision and were naïve as to the purpose of the experiment. Informed consents were obtained from all of the participants.

#### Stimuli and apparatus

Identical stimuli and apparatus to those of Experiment 2 were used, and the presentation of four colored squares was included to delay the onset of the visual search. The squares were identical to the search items except that they had no gap on either side.

#### Procedure and design

A sample trial sequence is shown in Figure 6. The procedure was identical to that of Experiment 2 except that a 150-ms or 750-ms presentation of four squares was inserted between the offset of the memory stimulus and the onset of the search stimuli. There were two within-subject factors: delay of the search onset (150 ms and 750 ms), and validity (invalid and neutral). Participants performed two blocks of 144 trials. Each block consisted of 96 invalid trials and 48 neutral trials. There was an equal number of 150-ms delay and 750-ms delay trials for each validity condition within a single block. A total of four trial types were presented in random order.

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2 We thank an anonymous reviewer for raising this issue.
Results and Discussion

The results for Experiment 4 are shown in Figure 7. Search accuracy and memory accuracy were analyzed through a within-subject two-way ANOVA with validity (invalid and neutral) and delay (150 ms and 750 ms) as factors. Search accuracy rates were 99.1% for the 150-ms delay-neutral condition, 99.3% for the 150-ms delay-invalid condition, 99.0% for the 750-ms delay-neutral condition, and 99.5% for the 750-ms delay-invalid condition. Memory accuracy rates were 95.4% for the 150-ms delay-neutral condition, 95.9% for the 150-ms delay-invalid condition, 95.1% for the 750-ms delay-neutral condition, and 96.3% for the 750-ms delay-invalid condition. Across the validity and delay conditions, there was no significant contrast, and no interaction.

Mean RTs for trials with correct search and memory responses were also analyzed through a within-subjects two-way ANOVA. There was a significant main effect of delay, $F(1, 18) = 19.44, p < .01, \eta^2 = .646$. The main effect of validity approached significance, $F(1, 18) = 3.34, p = .084$. More importantly, there was a significant interaction between delay and validity, $F(1, 18) = 32.46, p < .01, \eta^2 = .643$. This highly significant interaction was induced by the opposite effect of working memory contents on search performance. In the 150-ms delay condition, visual search performance was impaired by memory-driven attention capture. Search times for invalid trials were slower than those for neutral trials ($M = 1,202$ ms for invalid trials and $M = 1,092$ ms for neutral trials), $F(1, 18) = 6.20, p < .01, \eta^2 = .561$. In contrast, in the 750-ms delay condition, the presence of memory-matching distractor was beneficial for the visual search task. Search times for invalid trials were 43 ms faster than those in neutral trials ($M = 1,077$ ms for neutral trials and $M = 1,034$ ms for invalid trials), and this difference was significant, $F(1, 18) = 4.77, p < .05$.

The results from Experiment 4 showed that attentional capture by working memory interfered with visual search when the search display appeared with only a short interval during which place markers were introduced at the locations of the search items. In contrast, when there was enough time for cognitive control to be implemented after the memory display (with a longer delay interval during which time the location markers appeared), presenting the memory item in the search display was beneficial for search. In this last case, participants appeared to be biased against selecting the item matching to memory, facilitating selection of the target (one of the remaining set).

General Discussion

The current study investigated whether the contents of information maintained in working memory could guide spatial attention. The present results showed that working memory contents captured attention. However, the effect of memory-driven attentional capture was modulated by cognitive control based upon top-down knowledge that the distractor could (in some cases) always be invalid. To observe this top-down modulation on the effect of memory-driven attentional capture, the data suggest that there needs to be enough time for cognitive control to be fully established; either the perceptual processing of search stimuli needs to be extended over time or the onset of the visual search needs to be delayed long enough for cognitive control to be properly implemented and exert its effect. Participants also require a “set” to do this, because, even when the memory item was sometimes valid, there was evidence for attentional capture from working memory even with a difficult (and slow) search task.

Previous studies have reported different effects from items held in working memory on visual search. Evidence for attentional capture was reported by Soto et al. (2005), whereas Woodman and Luck (2007) found either no effect or that attention was biased...
away from a memory item that reappeared in a search display. We suggest that the observed contradiction between these two studies could reflect differences in the perceptual difficulty of the search tasks used. In the present study, the perceptual difficulty of the search was varied systematically by manipulating target-distractor similarity. In Experiment 1, we did not observe an overall difference in search times in invalid trials (when the memory item matched a distractor) and neutral trials (when the memory item was absent from search). Furthermore, fast participants tended to show memory capture, whereas slow participants showed attentional guidance away from memory items (slowed and speeded RTs on invalid relative to neutral trials). In Experiment 2, other aspects of the tasks were maintained but target-distractor similarity decreased and capture by working memory was observed, pointing to an effect of the perceptual difficulty of search.

Woodman and Luck (2007) also tried to explain the results of Soto et al. (2005), pointing out that Soto et al. used a short interval between the onset of the memory task and the onset of the search. In Soto et al.’s (2005) experiments, the memory prime was briefly presented three times and the interval between the offset of the memory prime and the onset of the search display was short (a 188-ms interstimulus interval). On the other hand, Woodman and Luck used an interval that was long (a 500-ms interstimulus interval) enough for the cognitive system to formulate a template for rejection. Woodman and Luck speculated that this difference in time course could induce contradictory results. That is, it might take some time for the cognitive system to reconfigure attentional setting to formulate a template for rejection. Olivers et al. (2006) also suggested the rapid time course of memory stimulus presentation as a potential factor. According to Olivers et al., participants in the Soto et al. experiments would still have been encoding the memory items even after the offset of the memory stimulus. In the current study, however, we have observed clear evidence of attentional capture by working memory, using nearly identical durations of stimuli presentation (506 ms) and interstimulus interval (506 ms) to those used by Woodman and Luck. In addition, top-down modulation was also observed with the same time course of stimuli presentations. The duration of the memory stimuli and the interstimulus interval used in the current study was long enough for encoding and consolidation of the memory item into a working memory store (Vogel, Woodman, & Luck, 2006). Furthermore, Soto and Humphreys (2007) also showed attentional capture by working memory using a fairly long duration of memory stimulus presentation (2 s).

One more thing to be noted here is that the long duration of a memory sample or an interstimulus interval might not necessarily guarantee the effective establishment of cognitive control required for the visual search task. Even when we used a relatively long interstimulus interval before the search onset, cognitive control was not effective with the easy search task. Several studies have also shown evidence for memory-driven attentional capture using relatively long durations for the memory cue or long interstimulus intervals between the memory cue and the search display (Soto & Humphreys, 2006, 2007). As our Experiment 4 results showed, sufficient time after the onset of any search-related stimuli (750-ms after the presentation of search item place marker) would be required to initiate and implement cognitive control necessary to influence visual search.

Although showing that prioritization by working memory features can be involuntary, we are not suggesting that this prioritization is strictly automatic. Cognitive control appears to modulate this prioritization, eliminating differences in visual search across the validity conditions under some circumstances. Previous studies on attentional capture have also shown that automatic capture of attention can be overridden by top-down strategies or modulated by target-nontarget similarity (Bacon & Egeth, 1994; Leber & Egeth, 2006; Proulx & Egeth, 2006). Furthermore, Woodman and Luck (2007) showed that participants could respond faster for invalid trials by deviating attention away from the location of the memory-matching distractor. Our data also showed that memory-driven attentional capture could be modulated by cognitive control, in line with Woodman and Luck. Other studies have also demonstrated that the influence of working memory contents on concurrent visual search can be flexible and susceptible to various factors, such as competition between memorized items, the activation level of memory representations and the type of memory encoding taking place (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Olivers, Meijer, & Theeuwes, 2006). Of special note, as Soto et al. (2005) suggested, top-down activation by information in working memory may be diminished if there are additional loads that demand working memory resources. Recent studies demonstrated that memory-driven attentional capture is reduced when more than one item should be maintained in working memory, or response mapping was varied across trials (Olivers, 2008; Soto & Humphreys, 2008).

Furthermore, we also provided corroborating data showing that cognitive control could play a critical role on the effect of memory-driven attentional capture. Using an easier search task, a significant effect of attentional capture by working memory was observed when the onset of visual search was delayed by 150 ms. However, when there was enough time (750 ms) for cognitive control to be implemented, the effect of memory-driven attentional capture was reversed and the presence of the memory-matching distractor benefitted visual search. Further study would be necessary to quantify the tipping point where top-down control could begin to exert its effect by manipulating search set size.3

A number of previous studies showed top-down guidance of attention in visual search (Duncan & Humphreys, 1989; Wolfe, Cave, & Franzel, 1989). These studies have suggested that top-down activation of a target template would prioritize items associated with the features of the target. It has also been suggested that the target template and working memory would share a common visual representation (Olivers, Meijer, & Theeuwes, 2006). In other words, the target template might be stored in visual working memory along with other search-irrelevant items to be remembered. Top-down activation of the target template would prioritize the target features along with other task-irrelevant features maintained in visual working memory. However, cognitive control based upon top-down knowledge could dissociate the target template from other working memory contents.

Smith and Jonides (1999) suggested that working memory was not a unitary system and it likely consists of short-term storage and executive control components, in line with Baddeley and Hitch (1974). In Baddeley and Hitch’s concept of working memory,

3 We thank an anonymous reviewer for raising this issue.
short-term storage, consisting of several subsystems (visuo-spatial memory and verbal memory), is used for the temporary maintenance of information, whereas the central executive control has a role to manipulate stored information and to maintain the goal and the attentional set of the concurrent task. Han and Kim (2004) also showed that loading short-term memory and central executive had different effects on concurrent selective attention tasks, supporting the distinction between storage and manipulation of information. We hypothesize that the maintenance of visual information is mediated mainly by visual short-term memory. The executive control would compute how the contents stored in visual memory were related with the current attentional set or task relevance. Based upon this argument, the central executive would determine which information in working memory would be prioritized or inhibited. In our experiments, the target shape and the memory color would be stored in visual working memory. These contents, maintained in visual short-term memory (working memory for temporary storage), could be, by default, prioritized for subsequent visual selection. The central executive would make a decision that the item with the target feature should be prioritized continually. In the case where the memory item is always invalid, the executive would decide to reset the initial default prioritization of the item in memory and inhibit that stimulus. A similar proposal was also discussed in Logan and Gordon (2001) and Woodman and Luck (2007).

To conclude, the present study showed that information in working memory could capture attention in the early stage of visual processing, consistent with Soto et al. (2005). Using the same task with systematic variation of stimuli parameters, we also observed that this initial capture of attention by working memory could be modulated by cognitive control, consistent with Woodman and Luck (2007). Perceptual difficulty and the time course of cognitive control are factors that alter how the contents of working memory influence visual attention, provided there is sufficient time for cognitive control to come into play and participants are strategically biased against information in working memory. We also provided a hypothesis describing the interaction between the executive control and short-term storage within the working memory system. More empirical research is necessary to clarify how the executive control would manipulate stored information and prioritize or inhibit the memory-matching contents among competing visual inputs.

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New Editors Appointed, 2011–2016

The Publications and Communications Board of the American Psychological Association announces the appointment of 3 new editors for 6-year terms beginning in 2011. As of January 1, 2010, manuscripts should be directed as follows:

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Manuscript submission patterns make the precise date of completion of the 2010 volumes uncertain. Current editors, Cynthia Garcia Coll, PhD, Annette M. La Greca, PhD, and Keith Rayner, PhD, will receive and consider new manuscripts through December 31, 2009. Should 2010 volumes be completed before that date, manuscripts will be redirected to the new editors for consideration in 2011 volumes.