



ISSN: 1350-6285 (Print) 1464-0716 (Online) Journal homepage: <https://www.tandfonline.com/loi/pvis20>

# Working memory capacity predicts search accuracy for novel as well as repeated targets

Lauren H. Williams & Trafton Drew

To cite this article: Lauren H. Williams & Trafton Drew (2018) Working memory capacity predicts search accuracy for novel as well as repeated targets, *Visual Cognition*, 26:6, 463-474, DOI: [10.1080/13506285.2018.1490370](https://doi.org/10.1080/13506285.2018.1490370)

To link to this article: <https://doi.org/10.1080/13506285.2018.1490370>



Published online: 02 Jul 2018.



Submit your article to this journal [↗](#)



Article views: 90



View Crossmark data [↗](#)



## Working memory capacity predicts search accuracy for novel as well as repeated targets

Lauren H. Williams  and Trafton Drew

Department of Psychology, University of Utah, Salt Lake City, Utah, USA

### ABSTRACT

Visual search behaviour is guided by mental representations of targets that direct attention toward relevant features in the environment. Electrophysiological data suggests these target templates are maintained by visual working memory during search for novel targets and rapidly transfer to long term memory with target repetition. If this account is correct, an individual's working memory capacity should be more predictive of search performance for novel targets than repeated targets. Across six experiments, we tested this hypothesis using both single (Experiments 5 and 6) and multiple (Experiments 1–4) target search tasks with three different types of stimuli (real world objects, letters, and triple conjunction shapes). Each target set was repeated for six consecutive trials. In addition, we estimated visual working memory capacity using a change detection working memory task. Overall, working memory capacity did not predict response time or efficiency in the visual search task. However, working memory capacity was equally predictive of search accuracy for both novel and repeated targets. These results suggest that working memory requirements do not substantially differ between novel and repeated target search, and working memory capacity may continue to play an important role in the encoding or maintenance of target representations after they are presumed to be in long term memory.

### ARTICLE HISTORY

Received 18 May 2017  
Accepted 11 June 2018

### KEYWORDS

Visual search; target templates; working memory; long term memory; repeated target search

The mechanisms that guide behaviour in visual search have long been of interest to visual attention researchers. For example, how do we find the broccoli in the produce section among so many other vegetables? Decades of research have led to the conclusion that search behaviour is guided by a combination of bottom-up (i.e., stimulus driven) and top-down (i.e., goal driven) information (Desimone & Duncan, 1995; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). Bottom-up mechanisms guide attention to the most salient items in the scene (e.g., red peppers in the produce section). However, top-down mechanisms limit the influence of stimulus-driven information and direct attention toward target relevant features in the environment (e.g., leafy green vegetables in the produce section). This top-down guidance is thought to occur through the maintenance of target representations held in working memory (Bundesen, 1990; Bundesen, Habekost, & Kyllingsbæk, 2005; Desimone & Duncan, 1995; Duncan & Humphreys, 1989; Miller, Erickson, & Desimone, 1996).

Neural evidence for the existence of target templates in working memory was initially observed

using single-unit recordings in monkeys (Chelazzi, Duncan, Miller, & Desimone, 1998; Chelazzi, Miller, Duncan, & Desimone, 1993). In these studies, monkeys were trained to respond to a cued target in a visual search array by making a saccadic eye-movement or pulling a lever. During the retention interval of the search task, enhanced activity was observed in neurons of the inferotemporal cortex that were tuned to respond to target features. This activity was interpreted using the biased competition model of attention, which posits that items compete for representation via top-down influence from target templates held in working memory (Desimone & Duncan, 1995).

Human evidence for target templates held in working memory has largely consisted of variations on a simple dual-task paradigm. The basic experimental design is to perform a visual search task after memorizing a set of items for a subsequent working memory test. In theory, if items held in working memory automatically bias attention toward matching features, then search performance should be impaired if a memorized item is included as a

distractor in the search array (Downing, 2000; Olivers & Eimer, 2011; Olivers, Meijer, & Theeuwes, 2006; Soto, Heinke, Humphreys, & Blanco, 2005). However, a more nuanced interpretation has emerged in recent years to account for inconsistent results in the literature (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Woodman & Luck, 2007). These researchers convincingly argue that the influence of working memory items is more strategic than automatic and is largely dependent on the characteristics of the visual search task (Carlisle & Woodman, 2011; Olivers, 2009; Woodman & Luck, 2007). Notably, simply maintaining a working memory load during visual search does not have a negative impact on search efficiency, which suggests that the working memory requirements for template maintenance are minimal (Downing & Dodds, 2004; Woodman, Vogel, & Luck, 2001; compare Oh & Kim, 2004; Woodman & Luck, 2004).

Although behavioural studies have led to mixed results, there is compelling evidence for target templates in working memory from an event related potential (ERP) component called the contralateral delay activity (CDA). The CDA is a lateralized component that provides a real-time index of the contents in working memory, such that the amplitude increases with the number of items maintained in working memory (Vogel & Machizawa, 2004). Consistent with the single-unit recording studies in monkeys (Chelazzi et al., 1993, 1998), the CDA is present during the retention interval prior to the onset of the search array (Carlisle, Arita, Pardo, & Woodman, 2011; Woodman & Arita, 2011). Notably, the amplitude of the CDA prior to search onset predicts an individual's later search performance, which suggests the CDA is a measure of the quality of the mental representation held in working memory (Carlisle et al., 2011).

These electrophysiological results provide convincing evidence that target templates are maintained in working memory. However, researchers have increasingly recognized that long term memory also plays a significant role in visual search. According to theories of automaticity, multiple exposures to a stimulus leads to representation in long term memory rather than working memory (Logan, 1988). Unlike working memory, long term memory retrieval is thought to be rapid, automatic, and free of capacity limitations. These properties of long term memory likely explain why search performance improves as the same target is repeated across multiple trials.

However, counterintuitively, much of the research on the relationship between working memory and visual search has utilized the same target throughout the experiment. The distinction between novel and repeated targets is an important consideration when interpreting this body of research and might explain the inconsistencies between behavioural studies. For example, Woodman, Luck, and Schall (2007) discovered that working memory load negatively interferes with performance during search for novel, but not repeated, targets. This suggests the role of working memory is diminished during repeated target search; target representations under these circumstances are likely maintained in long term memory rather than working memory.

In addition, the CDA provides neurophysiological evidence for the transfer of target templates to long term memory with target repetition (Carlisle et al., 2011). In this study, search targets were repeated for three, five, or seven consecutive trials. The amplitude of the CDA diminished with target repetition and approached zero in late repetition trials, which provides further evidence that target templates are transferred out of working memory with target repetition.

Both behavioural and electrophysiological studies suggest working memory has a smaller role in repeated target search. However, it is unclear how individual differences in working memory capacity relate to search performance after target templates have been transferred to long term memory. The strongest interpretation of the existing literature is that working memory capacity should play a substantially diminished role in repeated target search. This proposal is largely based on two pieces of evidence: (1) working memory load does not interfere with repeated target search and (2) electrophysiological evidence suggests that target templates are no longer held in working memory following target repetition. Alternatively, working memory capacity might be equally predictive of performance for both novel and repeated target search, which would suggest that template maintenance does not consume greater working memory resources for novel targets than repeated targets. In the current set of experiments, we compared the correlations between search performance and working memory capacity during novel and repeated target search. Template maintenance is just one aspect of visual search performance, and working memory capacity may influence other stages of processing.

However, by comparing novel and repeated search performance within the same individuals, we are able to quantify how the relationship between an individual's working memory capacity and their ability to find a target changes with target repetition. Over the course of six experiments, we found that the strength of the relationship between working memory capacity and search performance is unaffected by the number of target repetitions. Moreover, working memory capacity predicted overall search accuracy, but not response time or efficiency. This suggests that working memory may be more important for encoding and maintaining the target cue than overall search performance.

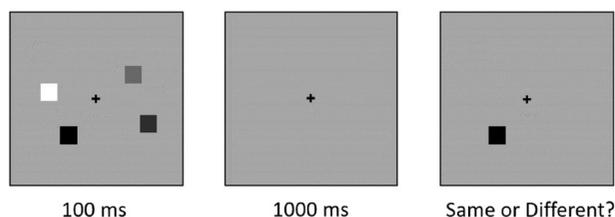
## Materials and methods

### Participants

Participants ( $n = 273$ ) were recruited from the University of Utah for course credit or US\$10 an hour. There were 54 participants in Experiment 1 (30 female, average age = 22), 52 in Experiment 2 (32 female, average age = 22), 52 in Experiment 3 (30 female, average age = 23), 50 in Experiment 4 (33 female, average age = 23), 38 in Experiment 5 (21 female, average age = 21), and 33 in Experiment 6 (17 female, average age = 20). The study was approved by the University of Utah's Institutional Review Board and all participants provided informed consent.

### Procedure

Across all experiments, participants were seated approximately 60 cm from a 21.5-inch LCD monitor with a refresh rate of 60 Hz. Experiments were programmed in Matlab using the Psychophysics toolbox (Brainard, 1997). The search stimuli subtended  $2.2^\circ$  in Experiments 1, 2, 4, 5, and 6. The search stimuli subtended approximately  $1.1^\circ$  in Experiment 3.



**Figure 1.** Change detection working memory task, set sizes four and eight.

### Working memory task

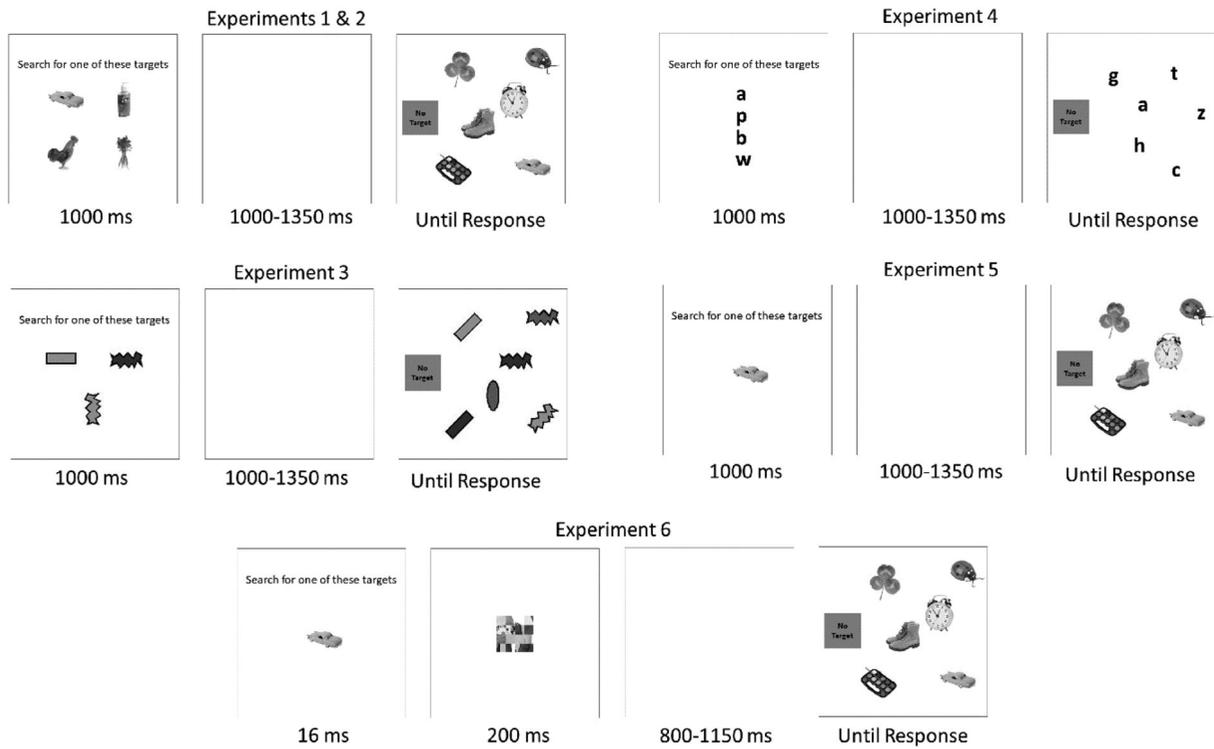
At the beginning of each experiment, participants completed a change detection working memory task (Figure 1) (Luck & Vogel, 1997). Each trial began with four or eight coloured squares presented around a central fixation cross for 100 ms. Following a 1000 ms retention interval, one of the squares reappeared in its original location. On half of the trials, the square was a different colour than its original presentation. The participant's task was to indicate if the square had changed colour using the "F" (same) or "J" (different) key. Working memory capacity was calculated using the formula,  $K = (\text{hit rate} - \text{false alarm rate}) * N$  (Cowan, 2001).

### Visual search task

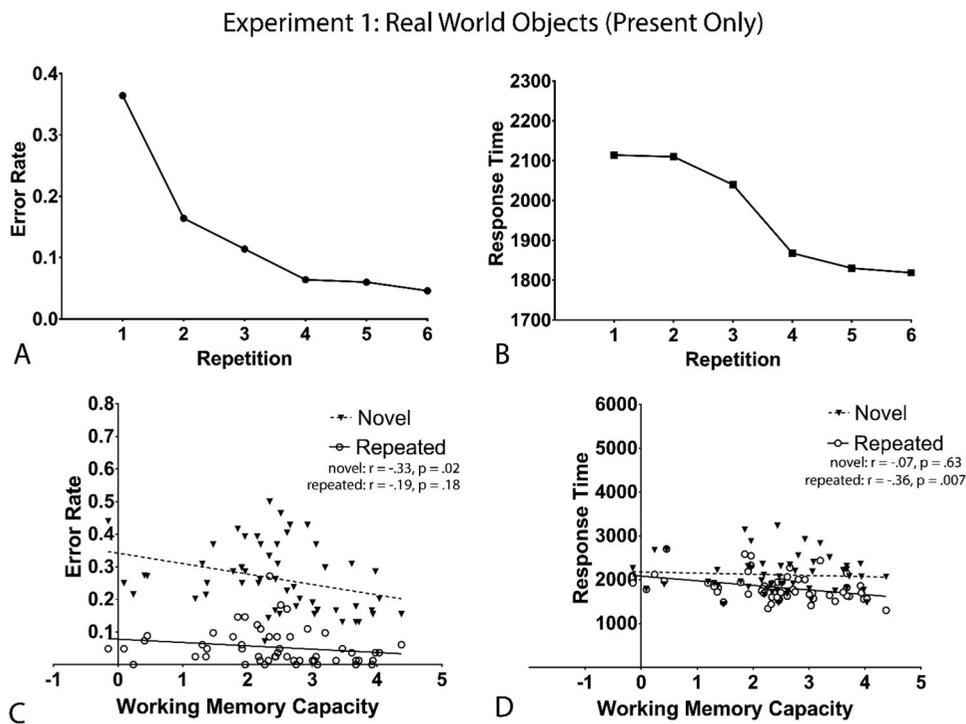
The visual search task consisted of eight practice trials followed by 240 experimental trials (Figure 2). On each trial, one (Experiments 5 and 6), three (Experiment 4), or four (Experiments 1–3) potential targets were presented on the screen for 16 ms (Experiment 6) or 1000 ms (Experiments 1–5). Each set of targets was repeated for six consecutive trials. In Experiments 1, 2, 5, and 6, the stimuli consisted of photorealistic real world objects (Brady, Konkle, Alvarez, & Oliva, 2008). In Experiment 3, the stimuli were letters from the Latin alphabet, excluding *i* and *l*. In Experiment 4, the stimuli were triple conjunction objects with overlapping features in a combination of shape, orientation, and colour (Nordfang & Wolfe, 2014). In Experiment 5, a mask consisting of jumbled portions of images in a  $3 \times 3$  grid was presented for 200 ms following the target. Following a 1000–1350 ms retention interval, a search array with six or 12 objects was presented on the screen until the participant clicked on the target or indicated the target was not present by clicking a box located on the left side of the screen. In Experiment 1, one of the targets was always present in the search array. In Experiments 2–6, a single target was present on half of the trials. Following each response, participants were given textual feedback on their performance.

### Exclusion criteria

In all experiments, individual trials were excluded from the analysis if the response time was greater than



**Figure 2.** Visual search task for Experiments 1 and 2 (real world objects), Experiment 3 (letters), Experiment 4 (triple conjunction shapes), Experiment 5 (real world objects – single target search), and Experiment 6 (real world objects – single target search with mask). Set sizes six and 12.



**Figure 3.** (a) Relationship between working memory capacity and error rate for Experiment 1. (b) Relationship between working memory capacity and response time for Experiment 1. (c) Repetition effects (error rate) for Experiment 1. (d) Repetition effects (response time) for Experiment 1.

15,000 ms or less than 200 ms. Less than 1% of the total trials were discarded in each study. None of the results or conclusions substantively differ if the outlying trials are included in the analysis or if we reduce the RT cutoff to 5000 ms.

## Results

Pearson correlations were calculated between working memory capacity and search performance for both novel (target repetitions 1 and 2) and repeated (target repetitions 5 and 6) targets. In order to compare the correlations between working memory capacity and performance for novel versus repeated target search, the correlation coefficients were transformed to a z-score using Fisher's  $r$  to  $z$  transformation. The inherent dependence between correlations obtained from the same sample was accounted for using recommendations from Steiger (1980), and statistical significance was calculated using an asymptotic z-test (Lee & Preacher, 2013).

### Experiment 1 (Real world objects – target present)

The error rate was significantly higher for novel targets ( $M = 26.3\%$ ,  $SD = 10.2\%$ ) than repeated targets ( $M = 5.3\%$ ,  $SD = 5.5\%$ ),  $t(53) = 13.349$ ,  $p < .001$  (Figure 3(a)). In addition, response time was significantly slower for novel targets ( $M = 2113$  ms,  $SD = 415$  ms) than repeated targets ( $M = 1826$  ms,  $SD = 311$  ms),  $t(53) = 6.633$ ,  $p \leq .001$  (Figure 3(b)). Search efficiency (RT  $\times$  Set Size function) did not differ between novel ( $M = 114.34$  ms/item,  $SD = 63.43$  ms/item) and repeated ( $M = 115.57$  ms/item,  $SD = 45.90$  ms/item) target search,  $t(53) = .121$ ,  $p = .90$ .

Working memory scores ( $M = 2.44$ ,  $SD = 1.05$ ) negatively predicted error rates for novel targets,  $r(52) = -.33$ ,  $p = .015$ , but not repeated targets,  $r(52) = -.186$ ,  $p = .178$  (Figure 3(c)). However, contrary to our hypothesis, correlations between novel and repeated targets were not significantly different from each other,  $z(53) = 1.678$ ,  $p = .093$ .

Working memory scores did not predict response time for novel targets,  $r(52) = -.068$ ,  $p = .625$  (Figure 3(d)). However, working memory scores negatively predicted response time for repeated targets,  $r(52) = -.36$ ,  $p = .007$ . These correlations were significantly different from one another but in the opposite direction of our hypothesis,  $z(53) = 2.614$ ,  $p = .009$ .

Working memory scores did not predict search efficiency (RT  $\times$  Set Size function) for novel targets,  $r(52) = .148$ ,  $p = .286$ , or repeated targets,  $r(52) = -.082$ ,  $p = .556$ . Correlations between novel and repeated targets did not significantly differ from each other,  $z(53) = 1.226$ ,  $p = .22$ .

### Experiment 2 (Real world objects – target present and absent)

In Experiment 2, target absent trials were added because response time is less variable in these trials and might provide a better estimate of the relationship between working memory and search performance. The error rate was significantly higher for novel targets ( $M = 28.5\%$ ,  $SD = 8.3\%$ ) than repeated targets ( $M = 11.7\%$ ,  $SD = 9.1\%$ ),  $t(51) = 17.391$ ,  $p < .001$  (Figure 4(a)). In addition, response time was significantly faster for novel targets ( $M = 2111$  ms,  $SD = 449$  ms) than repeated targets ( $M = 2204$  ms,  $SD = 423$  ms),  $t(51) = 3.009$ ,  $p = .004$  (Figure 4(b)). Search efficiency did not differ between novel ( $M = 111.034$  ms/item,  $SD = 63.144$  ms/item) and repeated ( $M = 122.715$  ms/item,  $SD = 53.80$  ms/item) target search,  $t(51) = 1.282$ ,  $p = .206$ .

Working memory scores ( $M = 2.48$ ,  $SD = .941$ ) negatively predicted error rates for both novel targets,  $r(50) = -.392$ ,  $p = .004$ , and repeated targets,  $r(50) = -.325$ ,  $p = .019$  (Figure 4(c)). Contrary to our hypothesis, correlations between novel and repeated targets were not significantly different from each other,  $z(51) = .641$ ,  $p = .521$ .

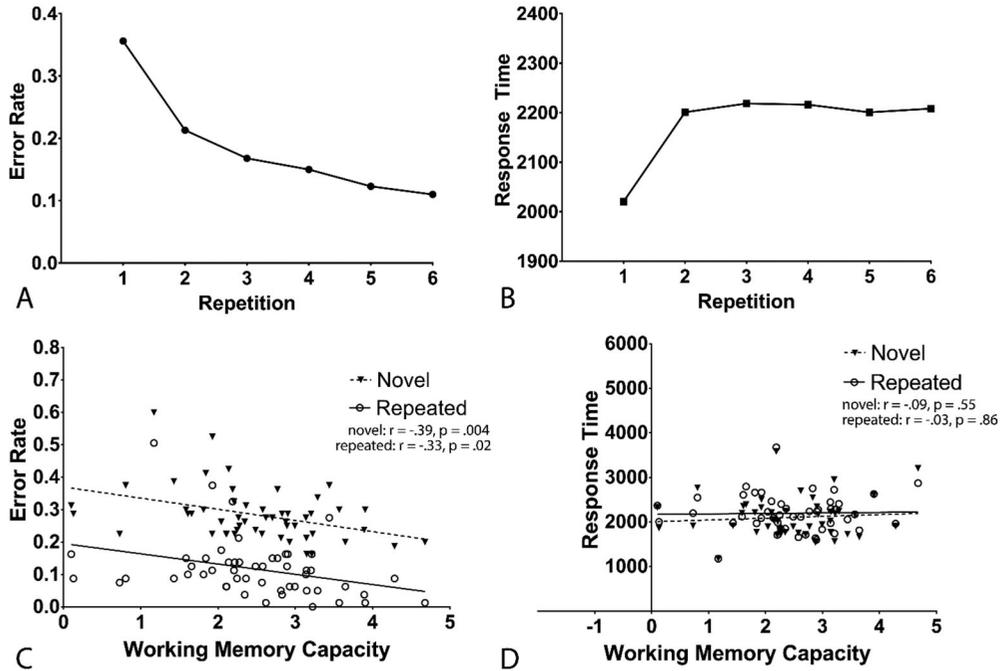
Working memory scores were not predictive of response time for novel targets,  $r(50) = .085$ ,  $p = .549$ , or repeated targets,  $r(50) = .025$ ,  $p = .86$  (Figure 4(d)). These correlations were not significantly different from each other,  $z(51) = .867$ ,  $p = .386$ .

Working memory scores did not predict search efficiency (RT  $\times$  Set Size function) for novel targets,  $r(50) = .15$ ,  $p = .289$ , or repeated targets,  $r(50) = .243$ ,  $p = .083$ . Correlations between novel and repeated targets did not significantly differ from each other,  $z(51) = .60$ ,  $p = .549$ .

### Experiment 3 (Letters)

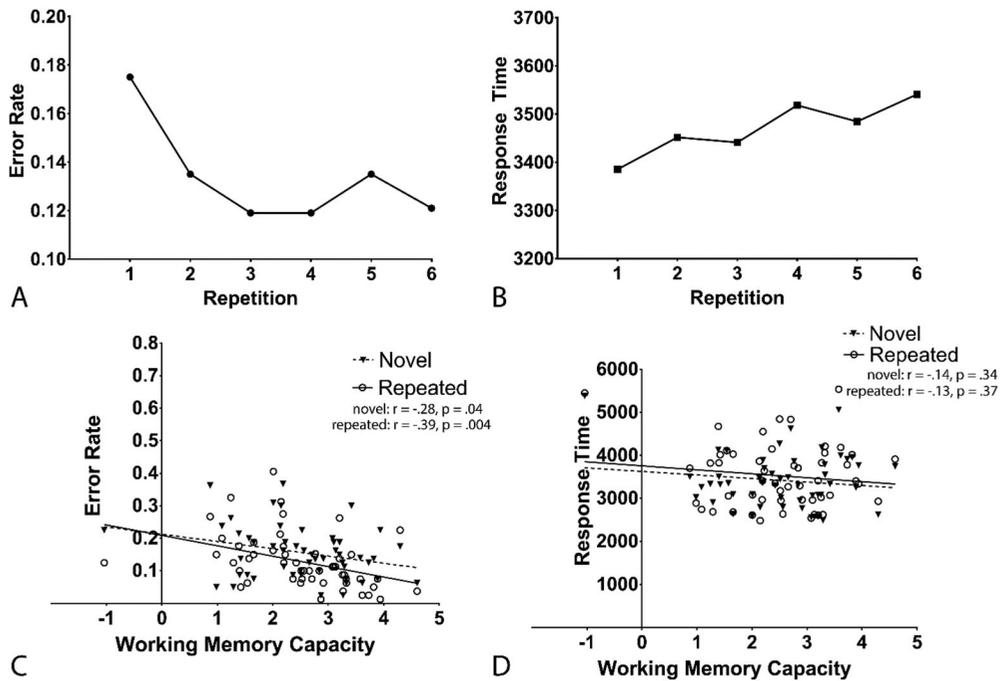
In Experiment 3, the stimuli were changed to letters in order to increase the degree of feature overlap and move closer to the stimuli (Landolt Cs) used in the

Experiment 2: Real World Objects (Present and Absent)



**Figure 4.** (a) Repetition effects (error rate) for Experiment 2. (b) Repetition effects (response time) for Experiment 2. (c) Relationship between working memory capacity and error rate for Experiment 2. (d) Relationship between working memory capacity and response time for Experiment 2.

Experiment 3: Letters



**Figure 5.** (a) Repetition effects (error rate) for Experiment 3. (b) Repetition effects (response time) for Experiment 3. (c) Relationship between working memory capacity and error rate for Experiment 3. (d) Relationship between working memory capacity and response time for Experiment 3.

electrophysiological studies by Woodman and colleagues (Carlisle et al., 2011; Woodman & Arita, 2011). The error rate was significantly higher for novel targets ( $M = 15.6\%$ ,  $SD = 8.2\%$ ) than repeated targets ( $M = 12.8\%$ ,  $SD = 8.4\%$ ),  $t(51) = 3.216$ ,  $p = .002$  (Figure 5(a)). Response time was significantly faster for novel targets ( $M = 3421$  ms,  $SD = 621$  ms) than repeated targets ( $M = 3527$  ms,  $SD = 746$  ms),  $t(51) = 2.336$ ,  $p = .023$  (Figure 5(b)). Search was significantly more efficient for novel ( $M = 266.087$  ms/item,  $SD = 93.707$  ms/item) than repeated ( $M = 294.045$  ms/item,  $SD = 108.505$  ms/item) target search,  $t(51) = 2.656$ ,  $p = .011$ .

Working memory scores ( $M = 2.516$ ,  $SD = 1.033$ ) negatively predicted error rates for both novel targets,  $r(50) = -.283$ ,  $p = .042$ , and repeated targets,  $r(50) = -.393$ ,  $p = .004$  (Figure 5(c)). Contrary to our hypothesis, correlations between novel and repeated targets were not significantly different from each other,  $z(51) = 1.098$ ,  $p = .272$ .

Working memory scores were not predictive of response time for novel targets,  $r(50) = -.136$ ,  $p = .336$ , or repeated targets,  $r(50) = -.127$ ,  $p = .37$  (Figure 5(d)). These correlations were not significantly different from each other,  $z(51) = .144$ ,  $p = .885$ .

Working memory scores did not predict search efficiency (RT x Set Size function) for novel targets,  $r(50) = .063$ ,  $p = .657$ , or repeated targets,  $r(50) = -.028$ ,  $p = .844$ . Correlations between novel and repeated targets did not significantly differ from each other,  $z(51) = .865$ ,  $p = .387$ .

#### Experiment 4 (Triple conjunction shapes)

In Experiment 4, the stimuli were changed to triple conjunction shapes in order to increase the degree of feature overlap between targets and distractors. The error rate was significantly higher for novel targets ( $M = 38.7\%$ ,  $SD = 11.7\%$ ) than repeated targets ( $M = 28.1\%$ ,  $SD = 14.8\%$ ),  $t(49) = 7.968$ ,  $p < .001$  (Figure 6(a)). Response time was significantly faster for novel targets ( $M = 2365$  ms,  $SD = 814$  ms) than repeated targets ( $M = 2496$  ms,  $SD = 691$  ms),  $t(49) = 2.53$ ,  $p = .015$  (Figure 6(b)). Search efficiency did not differ between novel ( $M = 97.026$  ms/item,  $SD = 69.196$  ms/item) and repeated ( $M = 101.675$  ms/item,  $SD = 71.565$  ms/item) target search,  $t(49) = .399$ ,  $p = .692$ .

Working memory scores ( $M = 2.426$ ,  $SD = .951$ ) negatively predicted error rates for both novel targets,  $r(48) = -.353$ ,  $p = .01$ , and repeated targets,

$r(48) = -.386$ ,  $p = .006$  (Figure 6(c)). However, the correlations between novel and repeated targets were not significantly different from each other,  $z(49) = .367$ ,  $p = .713$ .

Working memory scores were not predictive of response time for novel targets,  $r(48) = .052$ ,  $p = .72$ , or repeated targets,  $r(48) = .13$ ,  $p = .368$  (Figure 6(d)). These correlations were not significantly different from each other,  $z(49) = 1.173$ ,  $p = .241$ .

Working memory scores did not predict search efficiency (RT x Set Size function) for novel targets,  $r(48) = .069$ ,  $p = .634$ , or repeated targets,  $r(48) = .187$ ,  $p = .193$ . Correlations between novel and repeated targets did not significantly differ from each other,  $z(49) = .70$ ,  $p = .484$ .

#### Experiment 5 (Real world objects – single target search)

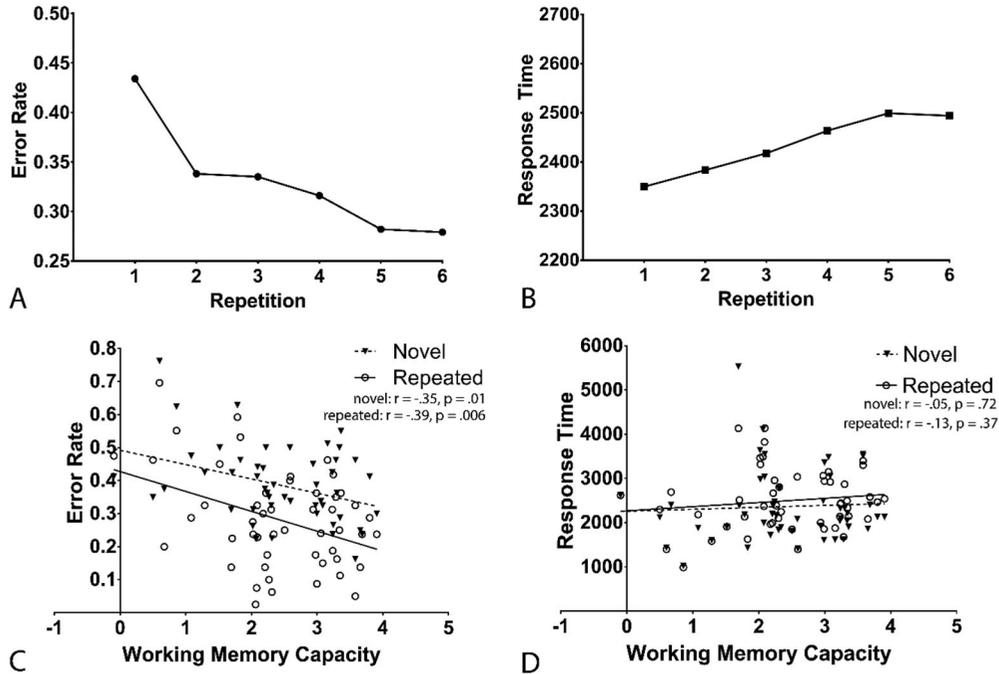
In Experiments 1–4, multiple targets were utilized to increase our ability to detect capacity related differences and avoid ceiling performance. However, it is possible that more than six repetitions are necessary for learning effects to occur when presented with multiple possible targets. In order to account for this possibility, we used a single target search task with real world object stimuli in Experiment 5.

The error rate did not significantly differ between novel targets ( $M = 5.16\%$ ,  $SD = 3.93\%$ ) and repeated targets ( $M = 4.57\%$ ,  $SD = 4.43\%$ ),  $t(37) = 1.34$ ,  $p = .19$  (Figure 7(a)). Response time did not significantly differ between novel targets ( $M = 1113.379$  ms,  $SD = 172.948$  ms) and repeated targets ( $M = 1115.74$  ms,  $SD = 179.627$  ms),  $t(37) = .234$ ,  $p = .82$  (Figure 7(b)). Search efficiency did not differ between novel ( $M = 25.123$  ms/item,  $SD = 19.757$  ms/item) and repeated ( $M = 23.038$  ms/item,  $SD = 24.293$  ms/item) target search,  $t(37) = .651$ ,  $p = .519$ .

Working memory scores ( $M = 2.33$ ,  $SD = .77$ ) did not predict error rates for novel targets,  $r(36) = -.249$ ,  $p = .13$ , or repeated targets,  $r(36) = -.297$ ,  $p = .07$  (Figure 7(c)). The correlations between novel and repeated targets were not significantly different from each other,  $z(37) = .482$ ,  $p = .63$ .

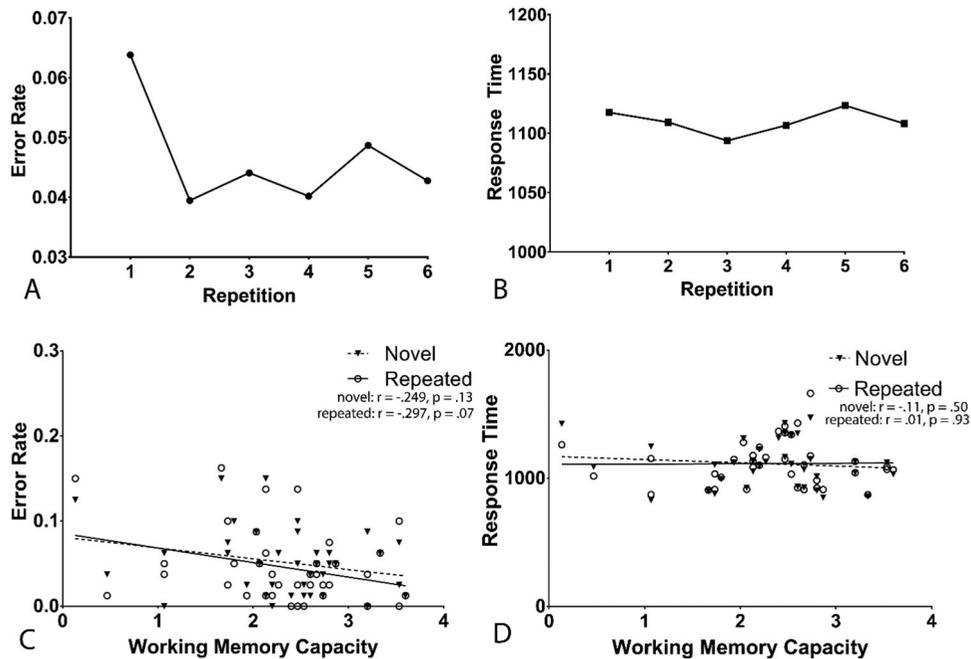
Working memory scores did not predict response time for novel targets,  $r(36) = -.113$ ,  $p = .50$ , or repeated targets,  $r(36) = .014$ ,  $p = .93$  (Figure 7(d)). The correlations between novel and repeated targets were significantly different than each other,  $z(37) =$

Experiment 4: Triple Conjunction Shapes



**Figure 6.** (a) Repetition effects (error rate) for Experiment 4. (b) Repetition effects (response time) for Experiment 4. (c) Relationship between working memory capacity and error rate for Experiment 4. (d) Relationship between working memory capacity and response time for Experiment 4.

Experiment 5: Real World Objects (Single Target Search)



**Figure 7.** (a) Repetition effects (error rate) for Experiment 5. (b) Repetition effects (response time) for Experiment 5. (c) Relationship between working memory capacity and error rate for Experiment 5. (d) Relationship between working memory capacity and response time for Experiment 5.

2.093,  $p = .04$ . However, this effect is small and in the opposite direction of our prediction.

Working memory scores did not predict search efficiency (RT x Set Size function) for novel targets,  $r(36) = -.255$ ,  $p = .122$ , or repeated targets,  $r(36) = -.084$ ,  $p = .616$ . Correlations between novel and repeated targets did not significantly differ from each other,  $z(37) = 1.18$ ,  $p = .24$

### **Experiment 6 (Real world objects – single target search with mask)**

With overall error at  $\sim 5\%$  and no effect of repetition on accuracy or RT, Experiment 5 may have suffered from a ceiling effect which would reduce our ability to detect differences in correlational strength as a function of repetition. In Experiment 6, target presentation was reduced to 16 ms and followed by a pattern mask in order to create more variability and increase our ability to detect individual differences in performance. The error rate was significantly higher for novel targets ( $M = 59.16\%$ ,  $SD = 13.97\%$ ) than repeated targets ( $M = 44.72\%$ ,  $SD = 23.25\%$ ),  $t(32) = 6.863$ ,  $p < .001$  (Figure 8(a)). Response time was significantly slower for novel targets ( $M = 1779.58$  ms,  $SD = 766.757$  ms) than repeated targets ( $M = 1629.713$  ms,  $SD = 571.62$  ms),  $t(32) = 3.039$ ,  $p = .005$  (Figure 8(b)). Search was significantly more efficient for novel ( $M = 68.01$  ms/item,  $SD = 75.45$  ms/item) than repeated ( $M = 33.795$  ms/item,  $SD = 37.067$  ms/item) target search,  $t(32) = 2.748$ ,  $p = .01$ .

Working memory scores ( $M = 2.38$ ,  $SD = .931$ ) negatively predicted error rates for novel targets,  $r(31) = -.42$ ,  $p = .015$ , but the correlation was only marginally significant for repeated targets,  $r(31) = -.332$ ,  $p = .059$  (Figure 8(c)). However, the correlations between novel and repeated targets were not significantly different from each other,  $z(32) = 1.053$ ,  $p = .293$ .

Working memory scores were not predictive of response time for novel targets,  $r(31) = -.039$ ,  $p = .83$ , or repeated targets,  $r(31) = -.004$ ,  $p = .982$  (Figure 8(d)). These correlations were not significantly different from each other,  $z(32) = .385$ ,  $p = .70$ .

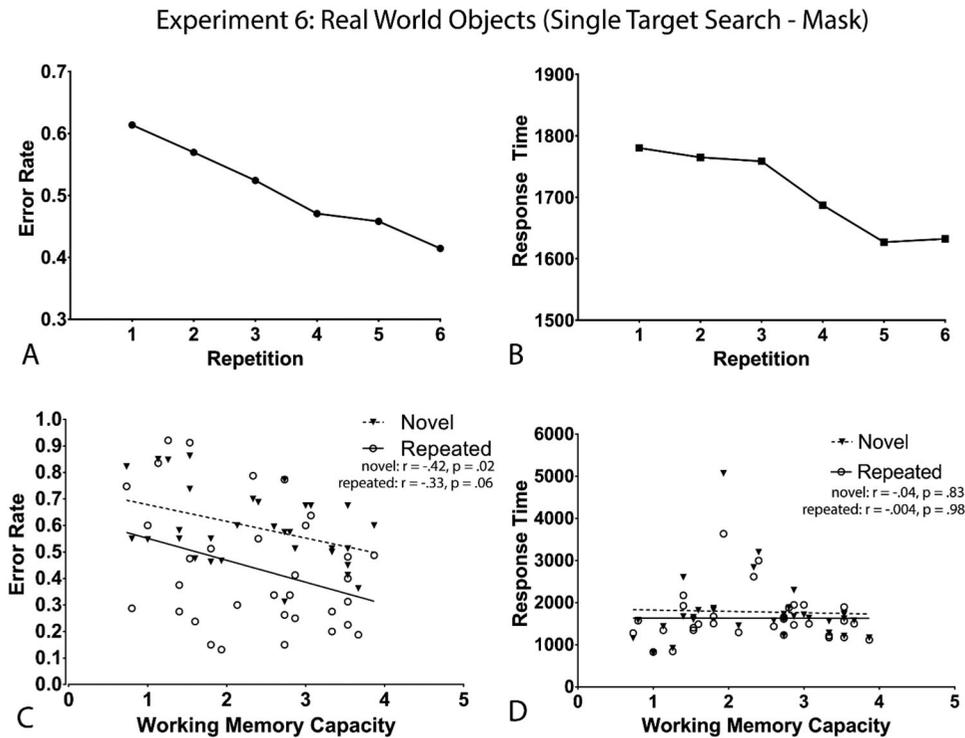
Working memory scores did not predict search efficiency (RT x Set Size function) for novel targets,  $r(31) = -.043$ ,  $p = .812$ , or repeated targets,  $r(31) = -.179$ ,  $p = .319$ . Correlations between novel and repeated targets did not significantly differ from each other,  $z(32) = .713$ ,  $p = .476$ .

## **General discussion**

Previous research has shown that target templates are initially maintained in working memory and are transferred to long term memory after a short run of target repetitions (Carlisle et al., 2011). Based on this evidence, we hypothesized that working memory capacity would be more predictive of performance in search for novel targets than repeated targets. However, across six experiments with three different types of stimuli, the correlations between working memory capacity and search performance were equivalent for both novel and repeated target search. This evidence suggests that maintaining representations for novel targets does not consume more working memory resources than repeated targets. Notably, this pattern holds using both single (Experiments 5 and 6) and multiple (Experiments 1–4) potential targets. For simplicity, we have focused on novel (1–2 repetitions) and repeated (5–6 repetitions) targets in our analyses. However, the pattern of no reliable connection between repetition and working memory capacity is consistent across all six experiments when we examine middle (3–4) repetitions as well.

These results are inconsistent with prior research, which found that a concurrent working memory load reduced search efficiency for novel, but not repeated, target search (Woodman et al., 2007). However, one limitation of the dual task approach is that the concurrent tasks might interact in unexpected ways. For example, more executive control might be needed to perform a concurrent working memory task during novel target search than repeated target search. In addition, the secondary task may interfere with working memory processes that are unrelated to template maintenance, such as keeping track of rejected distractors (Emrich, Al-Aidroos, Pratt, & Ferber, 2009; Emrich, Al-Aidroos, Pratt, & Ferber 2010) or filtering efficiency (Luria & Vogel, 2011).

Overall, we found small to moderate correlations between working memory capacity and search accuracy, but no correlations between working memory capacity and response time or search efficiency. These six experiments provide strong evidence that the relationship between working memory capacity and overall search performance is weak. The significant correlations are with search accuracy, which



**Figure 8.** (a) Repetition effects (error rate) for Experiment 6. (b) Repetition effects (response time) for Experiment 6. (c) Relationship between working memory capacity and error rate for Experiment 6. (d) Relationship between working memory capacity and response time for Experiment 6.

suggests that working memory capacity primarily predicts which individuals will better encode or maintain an accurate target representation, irrespective of target repetition. In other words, individuals who are likely to forget items in the working memory task are also likely to forget the target cue. However, the correlational nature of this research prevents conclusions about the precise nature of working memory capacity limitations in visual search. Target templates are presumed to be in long term memory after target repetition, but working memory might continue to be involved during other stages of processing. This proposal is compatible with electrophysiological studies demonstrating the CDA is present throughout the search task using paradigms that repeated the same one or two targets throughout the experiment (Emrich et al., 2009; Luria & Vogel, 2011). Although the continued presence of the CDA suggests working memory is involved in subsequent stages of visual search, each group of researchers interpreted the CDA activity using a different theoretical framework. Luria and Vogel (2011) proposed the CDA reflects the ability to filter out irrelevant distractors in the search array, which is consistent with prior research

showing a close association between working memory capacity and filtering efficiency (Vogel, McCollough, & Machizawa, 2005). In contrast, Emrich et al. (2009) interpreted the CDA as a measure of the maintenance of rejected distractors in working memory. This proposal is based on the distractor tagging literature, which proposes that rejected distractors are maintained in working memory in order to prevent attention from being redeployed to the same objects or locations (for a review, see Shore & Klein, 2000). Theoretically, individuals with higher working capacity should be able to maintain more rejected distractors in working memory, leading to more efficient search performance. However, our results suggest that working memory capacity is not a limiting factor for search performance beyond search accuracy. In future research, it may be fruitful to test these interpretations of the CDA directly in order to better understand the functional significance of working memory during visual search tasks.

Our results indicate that working memory resources do not substantially differ between novel and repeated target search. However, there are alternative explanations that should be considered. One

possibility is that working memory capacity is associated with differences in the quality of the mental representations held in memory. In novel target search, the amplitude of the CDA during the retention interval predicts subsequent search performance (Carlisle et al., 2011). Similarly, the amplitude of the CDA tracks fluctuations in performance during working memory tasks (Adam, Robison, & Vogel, 2018). This evidence suggests the CDA is an index of how consistently representations are stored in working memory. If poor representations in working memory lead to poor representations in long term memory, working memory capacity should be predictive of search performance in both novel and repeated target search. Similarly, working memory capacity may predict the rate of transfer between memory stores, which is consistent with work from other domains (Kikumoto & Mayr, 2017). In which case, the observed correlations would not diminish for repeated target search if high capacity individuals had transferred representations to long term memory but low capacity individuals had not. However, if this account is correct, high capacity individuals should show a larger learning benefit with target repetition, which was not the case in any of our experiments. Finally, the observed correlations with working memory capacity may reflect general cognitive abilities or non-search related task performance (e.g., motivation, response tendencies, or attentional lapses; Adam, Mance, Fukuda, & Vogel, 2015) rather than the working memory requirements of visual search. However, by comparing correlations between novel and repeated target search within the same task and individuals, we have attempted to isolate the working memory contributions specific to template maintenance. Although the precise nature of the role of working memory cannot be concluded from this research alone, we have obtained consistent results from six experiments that allow us to say with some certainty that the importance of working memory resources is not substantially different between novel and repeated target search.

## Conclusion

Recent electrophysiological research suggests that working memory has a diminished role in search for repeated targets, which is proposed to explain some of the inconsistent results in the behavioural literature. For example, studies have shown that visual search is

unaffected by a concurrent working memory load if the targets are repeated across trials. However, search is less efficient under working memory load if the search targets are novel (Woodman et al., 2007). Our results demonstrate that working memory capacity remains a small to moderate predictor of search accuracy with target repetition, but has no consistent relationship with overall search performance. This evidence casts doubt on the proposal that working memory requirements are greater for novel target search than repeated target search. Moreover, our results are broadly consistent with theories of attention that propose a role of working memory during other stages of search, as well as studies demonstrating a neural correlate of active working memory representation (the CDA) is present throughout visual search tasks (Emrich et al., 2009; Luria & Vogel, 2011). However, our results suggest the role of working memory in visual search may be more related to target template encoding or maintenance than overall search performance.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Funding

This work was supported by the Binational Science Foundation (Grant #2015301 to TD), the National Science Foundation Graduate Research Fellowship Program (Grant #1747505), and the Department of Defense (Grant #W911NF-07-2-0055).

## ORCID

Lauren H. Williams  <http://orcid.org/0000-0002-0680-2464>

## References

- Adam, K. C., Mance, I., Fukuda, K., & Vogel, E. K. (2015). The contribution of attentional lapses to individual differences in visual working memory capacity. *Journal of Cognitive Neuroscience*, 27(8), 1601–1616.
- Adam, K. C. S., Robison, M. K., & Vogel, E. K. (2018). Contralateral delay activity tracks fluctuations in working memory performance. *Journal of Cognitive Neuroscience*, 26, 1–12.
- Brady, T. F., Konkle, T., Alvarez, G. A., & Oliva, A. (2008). Visual long-term memory has a massive storage capacity for object details. *Proceedings of the National Academy of Sciences*, 105(38), 14325–14329.
- Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, 10(4), 433–436.

- Bundesden, C. (1990). A theory of visual attention. *Psychological Review*, 97(4), 523–547.
- Bundesden, C., Habekost, T., & Kyllingsbæk, S. (2005). A neural theory of visual attention: Bridging cognition and neurophysiology. *Psychological Review*, 112(2), 291–328.
- Carlisle, N. B., Arita, J. T., Pardo, D., & Woodman, G. F. (2011). Attentional templates in visual working memory. *Journal of Neuroscience*, 31(25), 9315–9322.
- Carlisle, N. B., & Woodman, G. F. (2011). Automatic and strategic effects in the guidance of attention by working memory representations. *Acta Psychologica*, 137(2), 217–225.
- Chelazzi, L., Duncan, J., Miller, E. K., & Desimone, R. (1998). Responses of neurons in inferior temporal cortex during memory-guided visual search. *Journal of Neurophysiology*, 80(6), 2918–2940.
- Chelazzi, L., Miller, E. K., Duncan, J., & Desimone, R. (1993). A neural basis for visual search in inferior temporal cortex. *Nature*, 363, 345–347.
- Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *The Behavioral and Brain Sciences*, 24(1), 87–114.
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, 18, 193–222.
- Downing, P. E. (2000). Interactions between visual working memory and selective attention. *Psychological Science*, 11(6), 467–473.
- Downing, P., & Dodds, C. (2004). Competition in visual working memory for control of search. *Visual Cognition*, 11(6), 689–703. <http://doi.org/10.1080/1350628034400044>
- Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, 96(3), 433–458.
- Emrich, S. M., Al-Aidroos, N., Pratt, J., & Ferber, S. (2009). Visual search elicits the electrophysiological marker of visual working memory. *Plos One*, 4(11), e8042.
- Emrich, S. M., Al-Aidroos, N., Pratt, J., & Ferber, S. (2010). Rapid communication: Finding memory in search: The effect of visual working memory load on visual search. *Quarterly Journal of Experimental Psychology*, 63(8), 1457–1466.
- Houtkamp, R., & Roelfsema, P. R. (2006). The effect of items in working memory on the deployment of attention and the eyes during visual search. *Journal of Experimental Psychology: Human Perception and Performance*, 32(2), 423–442.
- Kikumoto, A., & Mayr, U. (2017). The nature of task set representations in working memory. *Journal of Cognitive Neuroscience*, 29(11), 1950–1961.
- Lee, I. A., & Preacher, K. J. (2013, September). Calculation for the test of the difference between two dependent correlations with one variable in common [Computer software]. Retrieved from <http://quantpsy.org>
- Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review*, 95(4), 492–527.
- Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, 390, 279–281.
- Luria, R., & Vogel, E. K. (2011). Visual search demands dictate reliance on working memory storage. *Journal of Neuroscience*, 31(16), 6199–6207.
- Miller, E. K., Erickson, C. A., & Desimone, R. (1996). Neural mechanisms of visual working memory in prefrontal cortex of the macaque. *The Journal of Neuroscience*, 16(16), 5154–5167.
- Nordfang, M., & Wolfe, J. M. (2014). Guided search for triple conjunctions. *Attention, Perception, & Psychophysics*, 76(6), 1535–1559.
- Oh, S. H., & Kim, M. S. (2004). The role of spatial working memory in visual search efficiency. *Psychonomic Bulletin & Review*, 11(2), 275–281.
- Olivers, C. N. (2009). What drives memory-driven attentional capture? The effects of memory type, display type, and search type. *Journal of Experimental Psychology: Human Perception and Performance*, 35(5), 1275–1291.
- Olivers, C. N., & Eimer, M. (2011). On the difference between working memory and attentional set. *Neuropsychologia*, 49(6), 1553–1558.
- Olivers, C. N., Meijer, F., & Theeuwes, J. (2006). Feature-based memory-driven attentional capture: Visual working memory content affects visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, 32(5), 1243–1265.
- Shore, D. I., & Klein, R. M. (2000). On the manifestations of memory in visual search. *Spatial Vision*, 14(1), 59–75.
- Soto, D., Heinke, D., Humphreys, G. W., & Blanco, M. J. (2005). Early, involuntary top-down guidance of attention from working memory. *Journal of Experimental Psychology: Human Perception and Performance*, 31(2), 248–261.
- Steiger, J. H. (1980). Tests for comparing elements of a correlation matrix. *Psychological Bulletin*, 87(2), 245–251. <http://doi.org/10.1037/0033-2909.87.2.245>
- Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature*, 428, 748–751.
- Vogel, E. K., McCollough, A. W., & Machizawa, M. G. (2005). Neural measures reveal individual differences in controlling access to working memory. *Nature*, 438, 500–503.
- Wolfe, J. M. (1994). Guided search 2.0 a revised model of visual search. *Psychonomic Bulletin & Review*, 1(2), 202–238.
- Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided search: An alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human Perception and Performance*, 15(3), 419–433.
- Woodman, G. F., & Arita, J. T. (2011). Direct electrophysiological measurement of attentional templates in visual working memory. *Psychological Science*, 22(2), 212–215.
- Woodman, G. F., & Luck, S. J. (2004). Visual search is slowed when visuospatial working memory is occupied. *Psychonomic Bulletin & Review*, 11(2), 269–274.
- Woodman, G. F., & Luck, S. J. (2007). Do the contents of visual working memory automatically influence attentional selection during visual search? *Journal of Experimental Psychology: Human Perception and Performance*, 33(2), 363–377.
- Woodman, G. F., Luck, S. J., & Schall, J. D. (2007). The role of working memory representations in the control of attention. *Cerebral Cortex*, 17(1), i118–i124.
- Woodman, G. F., Vogel, E. K., & Luck, S. J. (2001). Visual search remains efficient when visual working memory is full. *Psychological Science*, 12(3), 219–224.