

Were you paying attention to where you looked? The role of executive working memory in visual search

MATTHEW S. PETERSON, MELISSA R. BECK, AND JASON H. WONG
George Mason University, Fairfax, Virginia

Recent evidence has indicated that performing a working memory task that loads executive working memory leads to less efficient visual search (Han & Kim, 2004). We explored the role that executive functioning plays in visual search by examining the pattern of eye movements while participants performed a search task with or without a secondary executive working memory task. Results indicate that executive functioning plays two roles in visual search: the identification of objects and the control of the disengagement of attention.

Recent evidence indicates an overlap between processes involved in working memory and processes involved in visual search (Han & Kim, 2004; Oh & Kim, 2004; Woodman & Luck, 2004). Working memory can be divided into the central executive and the perceptual stores (e.g., auditory and visual), and interference between two concurrent tasks can occur either because the tasks attempt to use the same perceptual representation system or because both tasks require resources from the central executive. In the case of visual search, a secondary working memory task with a strong central executive component can cause search to become less efficient and take longer to complete, as has been shown by Han and Kim. Participants who performed a visual search task simultaneously with a secondary task that involved counting backward by threes (a task with a strong central executive component, as well as an auditory component) took longer to complete their search. Passively remembering a sequence of seven digits (an auditory working memory task), however, had no effect on search. Given that these working memory tasks did not use the same perceptual representation system as that used by visual search (i.e., they were not visual in nature), this suggests that the counting task interfered with visual search by preventing the central executive from contributing to the search process. In the present article, we examine whether the central executive contributes to search by maintaining memories for previously searched items, by helping to identify search items, by maintaining attention on search items, or by assisting in saccade programming.

One possible role of executive function in visual search is to actively keep track of examined locations and, in turn, prevent revisitations (memory hypothesis). According to the memory hypothesis, loading executive working memory with a secondary task will lead to an increased rate at which items are revisited, which, in turn, will lead

to less efficient search. Although revisitation rates are typically low in a typical visual search task, the few revisitations that do occur are mostly willful reinspections of the item last examined (Peterson, Kramer, Wang, Irwin, & McCarley, 2001). Therefore, the memory hypothesis also predicts that when observers want to reinspect the last examined item, the memory for that item's location (Beck, Peterson, & Vomela, 2006) will no longer be available. This will cause the revisitation rate for the last examined item to decrease. Thus, loading executive working memory will increase the overall revisitation rate but will decrease memory-driven reinspections of the last examined item. Note, however, that this effect could be masked by failures in other systems that lead to an increase in revisits to the last item.

Alternatively, executive functioning might be needed to process and identify stimuli (identification hypothesis). This predicts that when executive processes are actively working on another task, more time will be required to identify an object. If gaze durations do not lengthen, items occasionally will go unprocessed. This may be similar to what occurs in inattention blindness (Mack & Rock, 1998). Inattention blindness occurs when viewers focus their attention on one aspect of the visual world, causing them to fail to notice a nonattended stimulus in their visual field. Similarly, if attention is focused on a secondary working memory task while a visual search task is completed, participants may examine an item but fail to identify it.

A third possible role for executive functioning is that it controls the disengagement of attention by inhibiting queued shifts of attention (attentional disengagement hypothesis; Kane, Bleckley, Conway, & Engle, 2001). Evidence for this hypothesis comes from the antisaccade task, in which the goal is to look away from an object that

M. S. Peterson, mpeters2@gmu.edu

suddenly appears. Errors—looking at the object rather than away—increase when a secondary executive task is performed (Roberts, Hager, & Heron, 1994). Premature shifts of visual attention during a search task could lead to inadequate processing of items.

A fourth possibility is that executive control is used in the programming of eye movements (saccade-programming hypothesis). This predicts that engaging in a concurrent executive task interferes with eye movement programming, which, in turn, leads to an increase in saccade latencies and an increase in saccade-targeting errors.

Since search times and accuracy do not allow us to discriminate between these four possible roles for executive attention, we examined eye movements during visual search, since this would allow us to determine how long each item was examined, as well as the order in which the items were viewed. We predicted that the pattern of eye movements would vary depending on whether or not participants were completing a concurrent executive working memory task. The exact changes in the pattern of eye movements would allow us to distinguish between the memory hypothesis, the identification hypothesis, the attentional disengagement hypothesis, and the saccade-programming hypothesis.

To reduce the ability of central executive processes to contribute to visual search, in one condition (the attend condition) we used a variation of the dual-counter task (Garavan, 1998; Sylvester et al., 2003), which requires participants to update and maintain two internal counters in working memory. The dual-counter task is an auditory task and was chosen because it is unlikely to interfere with the visual task at a perceptual level (Pashler, 1994; Wickens, 2002). To ensure that the tone-counting task was significantly difficult, we used a staircase method to adjust the duration of the semirandom intervals between the tones. In a control condition (the ignore condition), the participants heard the tones but performed only the search task.

The goal of the search task was to determine which target was present among a set of distractors and to respond with a buttonpress. Because the target in this task shared visual features with the distractors, there were no unique features that allowed the target to pop out and attract attention. In turn, this also allowed us to examine top-down contributions other than feature weighting. To prevent bottom-up information from guiding attention, we made the search stimuli small enough and spaced far enough apart that they were indistinguishable in peripheral vision and required direct fixation for identification (Peterson et al., 2001). This also had the side effect of discouraging the participants from using covert attention to scan the environment independently of eye movements and, in turn, allowed us to use eye movements to track the course of search on a moment-by-moment basis (Peterson et al., 2001).

METHOD

Participants

The participants were the first author, 3 naive George Mason University undergraduates, and 5 naive graduate students (6 of

them female, 3 male). The undergraduates received course credit, and the graduate students received \$10 for their participation. The average age of the participants was 25.8 years, and all had normal or corrected-to-normal vision.

Apparatus and Stimuli

A Power Macintosh G4 (Dual 1 GHz), equipped with a 20-in. (viewable) ViewSonic P225fb capable of operating at 120 Hz at a resolution of 640×480 pixels, running custom software, was used to present the stimuli, control the timing of experimental events, and record the participants' response times. This computer was networked to a Dell Pentium 4 that collects eyetracking data in conjunction with an EyeLink II system (SR Research). The EyeLink II tracker samples at a rate of 250 Hz and has a 0.2° spatial resolution. The head was stabilized by means of a chinrest located 70 cm from the monitor.

For all the experiments, only saccades that landed on an item were counted as fixations, and consecutive fixations on the same item were considered a single gaze. Fixations were classified as landing on an item if they were within 40 pixels (1.85°) of the center of the item. Eye movements were classified as saccades if either (1) they exceeded a speed greater than 30 deg/sec and acceleration exceeded $8,000 \text{ deg/sec}^2$ or (2) acceleration exceeded $8,000 \text{ deg/sec}^2$ and the distance exceeded 0.2° . Outliers were removed by excluding all trials on which manual response times exceeded three standard deviations above the mean of each cell, and only trials with correct manual responses were included. Gaze durations less than 100 msec were excluded from analysis.

The stimuli consisted of white Ts and Ls approximately 0.14° tall and 0.14° wide (3×3 pixels), drawn on a black background. The minimum distance between the stimuli was 3.7° (80 pixels). Targets were Ts rotated left or right of vertical. Distractors were normal or mirror imaged Ls rotated 0° , 90° , 180° , or 270° . Each display contained a total of 16 items: one target and 15 distractors.

The tones consisted of sine and square waves with a fundamental frequency of 440 Hz. Tone duration was 250 msec, with 50 msec of ramp up and ramp down. The tones were of approximately equal loudness and were presented monaurally.

Design and Procedure

Figure 1 shows the sequence of events. The participants fixated a central cross and pressed the space bar to start each trial. If the participant fixated within 2° of the cross, a drift correction occurred, and the trial proceeded. After 750 msec, the tone sequence began. The initial random interval between the tones ranged from 600 to 1,200 msec, it was decreased by 100 msec after three consecutive correct tone responses and was increased 100 msec for every trial on which there was one incorrect response (Brown, 1996). The tones preceded the search display by 3,000 msec and continued playing until the participant responded to the search display with a keypress. The participant's search task was to determine which target, a left or a right 90° -rotated T, was present. The participant responded by pressing the "z" or "/" key on the computer keyboard, and the mapping of the keys to target identity was counterbalanced across participants.

After the search task was completed, on the *attend* trials, the participants were presented with two screens so they could enter their responses to the tone-counting task. On the *ignore* trials, this step was skipped. The participants recorded their counts for each tone type by fixating a number (1–24; each number was highlighted when it was fixated by the participant) and pressing the space bar to record their response.

Each experimental session consisted of eight blocks of 16 trials for 128 trials during a single 45-min session. The order of the blocks was counterbalanced across participants. Blocks consisted entirely of either attend or ignore trials, and the participants were informed of the type of block before each began. The experimental trials were preceded by blocks of 10 tone-only practice trials and 10 search-only practice trials.

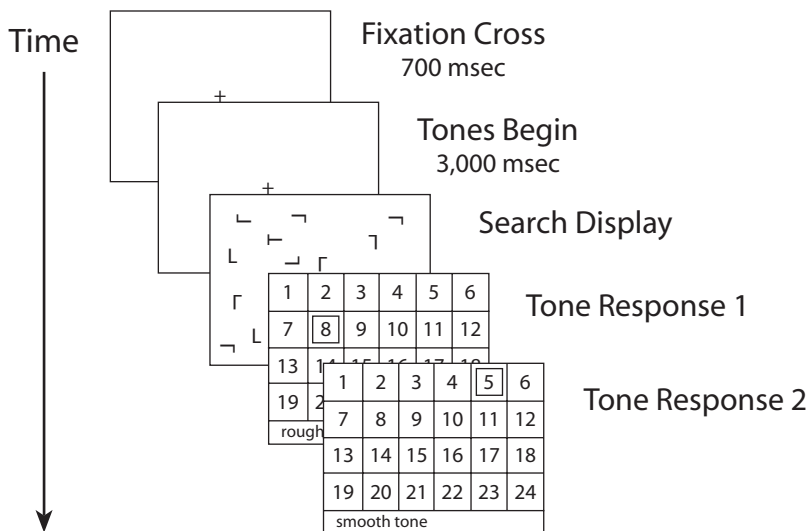


Figure 1. Each trial began with a fixation cross at the center. After 700 msec, presentation of the tones began, followed 3,000 msec later by the search display. The tones continued until the participant responded to the search display. In the *attend* condition, the participants entered their tone count by fixating one of the numbered squares and pressing the space bar to record their response. In the *ignore* condition, the answer screens did not appear. The stimuli in the figure are not to scale.

RESULTS

Manual Responses and Number of Gazes

The effects of the tone task on manual response times, accuracy, and number of gazes were analyzed using paired *t* tests. The addition of the tone task led to more gazes per trial [$t(8) = 2.55, p < .05; M = 8.5, SEM = 0.29$, for attend trials, and $M = 8.1, SEM = 0.24$, for ignore trials] and longer response times [$t(8) = 2.32, p < .05; M = 4,540$ msec, $SEM = 257$ msec, for attend trials, and $M = 4,080$ msec, $SEM = 210$ msec, for ignore trials] but did not have a significant effect on response accuracy ($t < 1; M = .973$). Search rates were calculated by dividing the active search time (sum of the fixation and saccade durations, excluding the initial fixation on the fixation cross) by the number of search items. Search rates were significantly quicker in the ignore than in the attend condition [$t(8) = 2.94, p < .05; M = 342$ msec, $SEM = 14.9$ msec, for ignore trials, and $M = 370$ msec, $SEM = 15.7$ msec, for attend trials]. This demonstrates that the concurrent tone task decreased search efficiency by lengthening response times and increasing the number of gazes. Overall, accuracy for the tone task was 86%, indicating that the participants found the task somewhat difficult.

Revisitation Rates

Figure 2 shows the revisitation rates as a function of lag (2–12) and tone task. Lag is defined as the number of gazes since an item was last examined, with lag 2 being the earliest an item could be revisited. Because some participants had empty cells beyond lag 12, the analysis was limited to lags 2–12. Revisitation rates were analyzed using a two-way repeated measures ANOVA, with tone task and lag as factors. The revisitation rate was affected

by lag [$F(10,80) = 22.8, p < .01$], and more important, the overall revisitation rate (summed over lags) of reexamining an item increased for the attend condition, from 4.3% to 6.5% [$F(1,8) = 9.5, p < .05$]. Lag and tone task failed to interact [$F(10,80) < 1$]. For both conditions, revisits to the target made up a disproportionate share of lag 2 revisits [ignore = 23.8% and attend = 17.1%; one-tailed paired *t* test, $t(8) = 1.97, p < .05$]. Three of the hypotheses for the role of executive function in visual search predicted an increase in the revisit rate, but the memory hypothesis predicted a decrease at lag 2. Further analysis of the eye movements will allow us to distinguish between the identification and the disengagement hypotheses.

Gaze Durations

Initial gaze durations (excluding subsequent revisits) were analyzed using a two-way repeated measures ANOVA, with tone task and visitation type (never revisited or revisited) as factors (see Figure 3). Because manual response decisions could contaminate gaze durations when fixating the target, gazes on the target were excluded from analysis. Gaze durations in the attend condition were not significantly different from gaze durations in the ignore condition [$F(1,8) = 1.38, p > .10$].

On the other hand, whether or not an item was later revisited affected initial gaze durations [$F(1,8) = 23.31, p < .01$], with gazes that later led to revisits roughly 38 msec shorter than gazes that did not ($M = 283.7$ msec, $SEM = 8.3$ msec, and $M = 245.3$ msec, $SEM = 6.5$ msec, respectively). In addition, the tone task and the type of initial visitation (later revisited or not) interacted [$F(1,8) = 6.39, p < .05$]. Post hoc contrasts revealed that attending to the tone task led to significantly longer gaze durations for items that were never revisited, as compared with ignoring

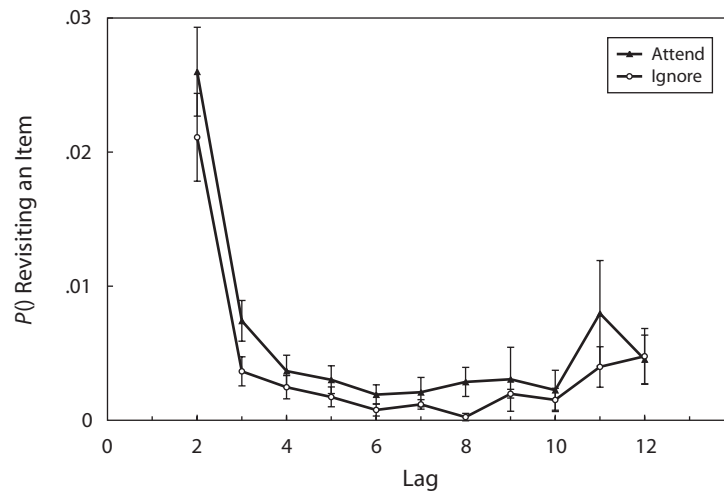


Figure 2. The probability of reexamining an item as a function of the number of intervening saccades between gazes (lag). Filled triangles are for trials in the attend condition, and open circles are for trials in the ignore condition. Error bars represent the standard error of each cell mean.

the tone task [$F(1,8) = 8.9, p < .025$], providing support for the identification hypothesis. However, there was no effect on the initial gaze duration of items that were later revisited [$F(1,8) < 1$]. Therefore, gaze durations for items that were later revisited were shorter in both the attend and the ignore conditions. This is in disagreement with the saccade-programming hypothesis, which predicts that engaging in an executive task should lead to an increase in saccade latencies (gaze durations).

Saccade Stereotypicality

To examine whether the counting task interfered with saccade programming, we examined both the accuracy of saccade targeting and search regularity. The tone task had no effect on saccade targeting, with saccades landing an average of 0.90° and 0.88° from the targeted items in the attend and ignore conditions, respectively [$t(9) = 0.52, p = .62$].

We examined search regularity using the search surface analysis of Peterson, Beck, and Vomela (2007). In brief, the analysis examines the stereotypicality of a search condition by examining the order in which screen locations are typically examined, and a flat surface is fit to the examination order of the screen coordinates. If the participant has a bias to examine the top left corner of the display first, the fit will be tilted; likewise, if a participant has no bias and each location has an equal possibility of being examined first, the best-fitting surface will be flat. There was no significant difference between the average degrees of tilt for the ignore and the attend conditions [$M = 30.5^\circ$ and 33.1° , respectively; $t(9) = 0.9, p > .1$], and the direction of the tilt was highly correlated between conditions [$F(1,9) = 85, p < .05, R^2 = .92$]. Had the tone task interfered with saccade programming, this would have led to increased programming errors and a more random and, hence, flatter search surface.

DISCUSSION

The present findings have important implications for theories of visual search, executive working memory, and control of saccadic eye movements. Although the addition of the tone task led to increased revisitations, the results suggest that the increased revisitations were not due to a memory failure. The memory hypothesis predicts that performing a secondary task that loads executive processes should impair memory, which should increase the revisitation rate. However, if memory is impaired, willful reexaminations at lag 2 (Peterson et al., 2001) should decrease, which is contrary to our findings. Further evidence against the memory hypothesis has come from recent research suggesting that frontal areas involved in executive attention do not play a role in actively maintaining locations in spatial working memory (Postle, Awh, Jonides, Smith, &

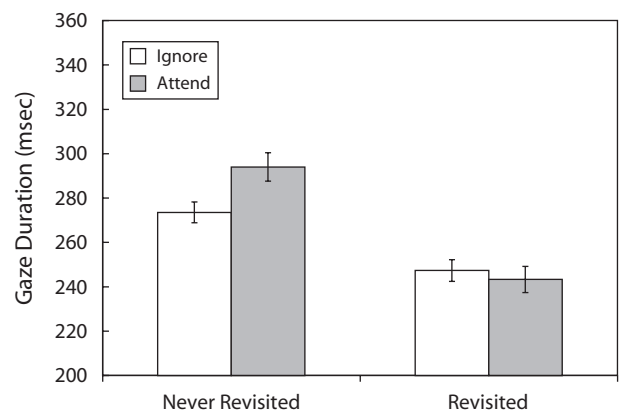


Figure 3. Mean duration of initial gazes as a function of whether an item was later revisited and whether the tone task was attended or ignored.

D'Esposito, 2004; Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000).

The results support the identification hypothesis, which predicts that loading executive working memory should lead to slower processing of items, which will, in turn, lead to increased gaze durations. In support of this prediction, the gaze durations for items that were not revisited were longer in the attend condition than in the ignore condition, which might be expected if increased workload slows the processing of items (Pashler, Carrier, & Hoffman, 1993). However, the identification hypothesis does not predict our finding that initial gaze durations should be shorter for items that are later revisited. One item of note is that our executive working memory task had a smaller effect on search than did the tasks used by Han and Kim (2004). Our task increased search rates by almost 10%, whereas the task in Han and Kim roughly doubled their search slopes. It may very well be that a more difficult working memory task might have a stronger, if not different, pattern of effects on eye movements.

Instead, these short initial gaze durations in both conditions suggest that revisitations are partially due to premature shifts of attention. That is, these items were not processed long enough to be fully identified. In the attend condition, loading executive working memory with the tone task led to an increase in the number of these short gazes (and increased revisits), as predicted by the disengagement hypothesis. The shorter gaze durations suggest that loading executive working memory increases the likelihood that attention will be disengaged prematurely, before identification of an item has been completed. These short gazes led to processing that was too short to adequately identify the items and to increased rates of revisitation. Therefore, loading executive working memory during visual search increases both the amount of time needed to identify the items and the probability that a premature shift of attention will occur before an item has been fully identified.

Executive Functioning and Visual Attention

Central executive functioning plays at least two roles in visual search: identifying items and controlling the disengagement of attention. In regard to object identification, executive functioning is particularly important when objects are in unusual views, such as our rotated Ts (Baragwanath & Turnbull, 2002). With respect to shifts of attention, when executive functioning is engaged in another task, inhibitory mechanisms are unavailable to inhibit queued shifts of attention (Zingale & Kowler, 1987). Because the stimuli in this experiment had equal luminance and were unidentifiable in peripheral vision, these shifts are unlikely to be due to attentional weighting of features but, instead, are symptoms of a lack of attentional control (Lavie, Hirst, de Fockert, & Viding, 2004; Roberts et al., 1994). In saliency models of attentional guidance, a master map of saliency is computed on the basis of bottom-up feature differences and top-down weighting (Itti & Koch, 2000; Wolfe, 1994), and attention examines items in descending order of their saliency. In the experiment presented here, we minimized the featural differences,

leaving only top-down weighting to guide attention. This master saliency map could act as a series of queued attentional shifts (Gnadt & Andersen, 1988), with executive control used to prevent attention from shifting to the next most salient item. If attention leaves prematurely, the mistake is quickly realized, and attention returns to the last examined item, as evidenced by the large number of target revisits at lag 2. Support for this has been found in antisaccade tasks, in which increased activity of neurons in the superior colliculus and frontal eye fields predicts a greater likelihood of erroneous prosaccades (Everling, Dorris, & Munoz, 1998; Everling & Munoz, 2000). The antisaccade task is also sensitive to executive functioning, with erroneous prosaccades increasing when a concurrent executive task is performed (Roberts et al., 1994). Likewise, patients with damage to the dorsolateral prefrontal cortex, an area involved in executive control, show increase prosaccade errors (Gaymard, Ploner, Rivaud, Vermersch, & Pierrot-Deseilligny, 1998). Taken as a whole, this suggests that one role of executive control is to prevent premature shifts of attention from occurring.

AUTHOR NOTE

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REFERENCES

- BARAGWANATH, B. A., & TURNBULL, O. H. (2002). Central executive secondary tasks in object recognition: An analogue of the unusual views deficit in the neurologically normal? *Brain & Cognition*, **48**, 268-272.
- BECK, M., PETERSON, M. S., & VOMELA, M. (2006). Memory for where, but not what, is used during visual search. *Journal of Experimental Psychology: Human Perception & Performance*, **32**, 235-250.
- BROWN, L. G. (1996). Additional rules for the transformed up-down method in psychophysics. *Perception & Psychophysics*, **58**, 959-962.
- EVERLING, S., DORRIS, M. C., & MUNOZ, D. P. (1998). Reflex suppression in the anti-saccade task is dependent on prestimulus neural processes. *Journal of Neurophysiology*, **80**, 1584-1589.
- EVERLING, S., & MUNOZ, D. P. (2000). Neuronal correlates for preparatory set associated with pro-saccades and anti-saccades in the primate frontal eye field. *Journal of Neuroscience*, **20**, 387-400.
- GARAVAN, H. (1998). Serial attention within working memory. *Memory & Cognition*, **26**, 263-276.
- GAYMARD, B., PLONER, C. J., RIVAUD, S., VERMERSCH, A. I., & PIERROT-DESEILLIGNY, C. (1998). Cortical control of saccades. *Experimental Brain Research*, **123**, 159-163.
- GNADT, J. W., & ANDERSEN, R. A. (1988). Memory related motor planning activity in posterior parietal cortex of macaque. *Experimental Brain Research*, **70**, 216-220.
- HAN, S.-H., & KIM, M.-S. (2004). Visual search does not remain efficient when executive working memory is working. *Psychological Science*, **15**, 623-628.
- ITTI, L., & KOCH, C. (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision Research*, **40**, 1489-1506.
- KANE, M. J., BLECKLEY, M. K., CONWAY, A. R. A., & ENGLE, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General*, **130**, 169-183.
- LAVIE, N., HIRST, A., DE FOCKERT, J. W., & VIDING, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General*, **133**, 339-354.
- MACK, A., & ROCK, I. (1998). *Inattention blindness*. Cambridge, MA: MIT Press.

- OH, S.-H., & KIM, M.-S. (2004). The role of spatial working memory in visual search efficiency. *Psychonomic Bulletin & Review*, **11**, 275-281.
- PASHLER, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, **116**, 220-244.
- PASHLER, H., CARRIER, M., & HOFFMAN, J. (1993). Saccadic eye movements and dual-task interference. *Quarterly Journal of Experimental Psychology*, **46A**, 51-82.
- PETERSON, M. S., BECK, M. R., & VOMELA, M. (2007). Visual search is guided by prospective and retrospective memory. *Perception & Psychophysics*, **69**, 123-135.
- PETERSON, M. S., KRAMER, A. F., WANG, R. F., IRWIN, D. E., & MCCARLEY, J. S. (2001). Visual search has memory. *Psychological Science*, **12**, 287-292.
- POSTLE, B. R., AWH, E., JONIDES, J., SMITH, E. E., & D'ESPOSITO, M. (2004). The where and how of attention-based rehearsal in spatial working memory. *Cognitive Brain Research*, **20**, 194-205.
- ROBERTS, R. J., JR., HAGER, L. D., & HERON, C. (1994). Prefrontal cognitive processes: Working memory and inhibition in the antisaccade task. *Journal of Experimental Psychology: General*, **123**, 374-393.
- ROWE, J. B., TONI, I., JOSEPHS, O., FRACKOWIAK, R. S. J., & PASSINGHAM, R. E. (2000). The prefrontal cortex: Response selection or maintenance within working memory? *Science*, **288**, 1656-1660.
- SYLVESTER, C.-Y. C., WAGER, T. D., LACEY, S. C., HERNANDEZ, L., NICHOLS, T. E., SMITH, E. E., & JONIDES, J. (2003). Switching attention and resolving interference: fMRI measures of executive functions. *Neuropsychologia*, **41**, 357-370.
- WICKENS, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science*, **3**, 159-177.
- WOLFE, J. M. (1994). Guided Search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review*, **1**, 202-238.
- WOODMAN, G. F., & LUCK, S. J. (2004). Visual search is slowed when visuospatial working memory is occupied. *Psychonomic Bulletin & Review*, **11**, 269-274.
- ZINGALE, C., & KOWLER, E. (1987). Planning sequences of saccades. *Vision Research*, **27**, 1327-1341.

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