THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY
2012, 65 (3), 401–407

Psychology Press
Taylor & Francis Group

Rapid communication

Working memory capacity and visual attention: Top-down and bottom-up guidance

Zach Shipstead, Tyler L. Harrison, and Randall W. Engle
School of Psychology, Georgia Institute of Technology, Atlanta, GA, USA

Previous studies have indicated that working memory capacity (WMC) is related to visual attention when selection of critical information must be made in the face of distraction. The present study examines whether WMC-related differences in flanker task performance might be decreased by displays that are designed to support bottom-up guidance of attention. Participants were required to respond to a centrally located target while ignoring a peripheral flanker. In one condition, bottom-up support was provided by embedding the target in a row of zeros. In another condition, the zeros were removed, thus emphasizing the role of top-down attention in selecting spatially defined information. It was found that the inclusion of zeros led to the elimination of WMC-related flanker effects. We conclude that bottom-up attentional guidance can attenuate the role of WMC in selective attention.

Keywords: Working memory capacity; Visual attention; Selective attention; Flanker task; Bottom-up.

Working memory capacity (WMC) is related to a person's ability to select goal-relevant information and ignore potential distraction. This relationship has been demonstrated several times using the Eriksen flanker task (Eriksen & Eriksen, 1974; Heitz & Engle, 2007; Redick & Engle, 2006; Unsworth & Spillers, 2010). This selective attention task requires test takers to rapidly indicate which of two potential target items (e.g., X or Z) is presented in the central location of a computer monitor. Each target is assigned to one of two responses (e.g., different keypresses). Typically, people are slower and less accurate to respond when the target is flanked by response-incompatible distractors (e.g., ZZXZZ) than when it is flanked by compatible (e.g., XXXXX), or neutral (e.g., PPXPP) items.

By the account of Lavie, Hirst, de Fockert, and Viding (2004; see also Kane & Engle, 2003), working memory biases visual attention toward "high-priority" targets and away from "low-priority" distraction through maintenance of attentional priorities. As evidence for this position, these researchers demonstrated that flanker effects increase substantially when participants are required to remember six randomly drawn digits. That is, top-down control is diminished when working memory is otherwise occupied.

Correspondence should be addressed to Zach Shipstead, Georgia Institute of Technology, School of Psychology, 654 Cherry Street, Atlanta, GA 30332-0170, USA. E-mail: zshipstead3@gatech.edu

This work was supported by Office of Naval Research Grant N00014-09-1-0129.

http://www.psypress.com/qjep
http://dx.doi.org/10.1080/17470218.2012.655698

This account has been supported by subsequent studies that have found a consistent relationship between WMC and performance in flanker tasks (Heitz & Engle, 2007; Redick & Engle, 2006; Unsworth & Spillers, 2010). However, an unexplored possibility is that bottom-up (i.e., stimulus-driven) guidance may assist low-WMC individuals. That is, attention can be biased toward relevant information by maximizing contrast between targets and distractors (e.g., Duncan & Humphreys, 1989; Wolfe, 1994). For individuals with low WMC, this guidance may facilitate the efficient rejection of distracting information.

We explored this possibility using Lavie's (1995) modified flanker task (Figure 1a) in which a target item is presented (i.e., the smaller letter in Figure 1a) in one of six horizontal positions at the vertical centre of a computer screen. The distractor item (i.e., the larger letter in Figure 1a) appears in a peripheral position, either above or below the target, with equal regularity. Thus, the target can be spatially defined, provided a test taker is capable of restricting attention to the relevant area of a computer monitor. Previous work has indicated that high-WMC individuals are particularly adept at maintaining attention at spatially defined regions (Poole & Kane, 2009); thus we predicted they would experience significantly smaller incompatibility effects than low-WMC individuals.

Based on work by Duncan and Humphreys (1989) and Wolfe (1994), we assumed that attention is exogenously drawn to areas of high local change. We thus included a second version of the Lavie flanker task in which the target was embedded in a line of zeros. Because zeros do not share visual features with either potential target (i.e., X or Z), we expected this manipulation to lead to a pop-out effect. The intent was to create a situation in which bottom-up processes could guide attention to appropriate information and thus allow low-WMC individuals to efficiently overcome the influence of distracting information.

Predictions

Given the assumption that high-WMC individuals are better equipped to constrain attention to only relevant spatial locations (Poole & Kane, 2009), they should be expected to outperform low-WMC individuals in the "no-line" task (Figure 1a). The "line" task (Figure 1b), on the other hand, should benefit low-WMC individuals. The bottom-up guidance provided by this condition should minimize the extent to which low-WMC individuals devote attentional resources to processing the distractor. It was thus predicted that, when the target was embedded in zeros, low-WMC individuals would show decreased distractor effects, relative to the no-line condition. Furthermore, we expected WMC-related differences in distractor effects to be minimized in the line condition.

Method

Participants

Twenty-seven low- and 26 high-WMC participants were recruited from our database of

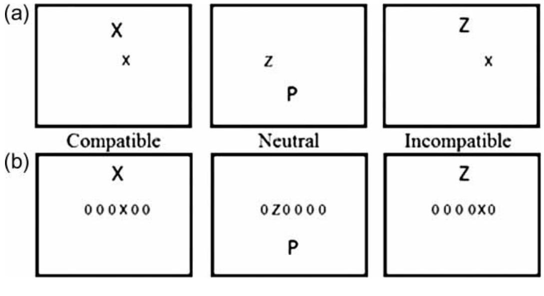

Figure 1. *The (a) no-line and (b) line conditions of the Lavie flanker task. The smaller, central letter serves as the target. The larger, peripheral letter serves as the distractor.*

previously screened participants. Data for 1 low-WMC participant were lost due to equipment failure. All participants were between the ages of 18 and 35 years and had normal or corrected-to-normal vision. Sessions lasted less than one hour. All participants were compensated with $20 or course credit in exchange for participation.

Prescreening

WMC was measured in a separate session and was defined as a composite score of performance on the automatic operation and symmetry span tasks. Each of these complex span tasks requires participants to remember lists of items (letters and spatial locations, respectively) while alternately completing processing tasks (solving mathematical operations and judging the symmetry of a grid-based picture, respectively). High WMC was defined as membership in the top quartile of all participants, while low WMC was defined as membership in the bottom quartile. Detailed descriptions of these tasks can be found in Unsworth, Heitz, Schrock, and Engle (2005) and Unsworth, Redick, Heitz, Broadway, and Engle (2009).

Design

Response times (RTs) and errors were separately entered into a 2 (array type: no-line vs. line) × 3 (compatibility: compatible, neutral, incompatible) × 2 (WMC: high vs. low) factorial analysis of variance (ANOVA). WMC was the only between-subjects factor. Array type was blocked, and compatibility was randomly manipulated on a trial-by-trial basis within a block.

Stimuli

The target letters used in this experiment were upper-case X and Z. The target appeared equiprobably in one of six positions in a row at the centre of the screen (see Figure 1). Within these six positions, the target either appeared alone (no-line) or embedded in a row of 0s (line) that occupied the five other positions. On compatible trials, the target and the distractor were the same letter. On incompatible trials, one was an X and the other a Z. On neutral trials, the letter P served as the distractor.

Participants sat at a distance of approximately 56 cm. The target letters subtended a visual angle of 0.65° vertical and 0.49° horizontal. The six positions in which the target appeared comprised a distance of 2.77° of visual angle. The distractor appeared in the central region of the screen either above or below the target array. It subtended a visual angle of 0.65° horizontal and 0.81° vertical. At its closest, the distractor was 1.06° from the target; at its farthest, it was 1.3° (depending upon which of six positions the target appeared).

Procedure

Each trial began with a silver dot presented at central fixation for 1,000 ms. This was immediately followed by the target display, which was presented for 100 ms. Participants were allowed 1,400 ms from the offset of the display to respond. Consistent with the procedure of Lavie (1995), participants responded with the index finger and thumb of their right hand. They pressed with their finger to respond that the target had been an X and with their thumb to respond that the target had been a Z. A green sticker was placed on the number 2 of the keypad for X; a red sticker was placed on the 0 for Z.[1] Incorrect responses were followed by a 500-ms tone. Each block was 72 trials long followed by a 30-s rest break and a reiteration of the instructions. Fourteen blocks were performed during each session.

Participants performed 24 trials of response-mapping practice with each array type (i.e., no-line and line) and a neutral distractor. Additionally, the first two blocks of each session were discarded as practice.

---

[1] It might be argued that using the 0 key would affect performance in the line condition, as the display contains a row of 0s. One-way ANOVAs for response time (RT) and accuracy in the line condition revealed no effects of target type ($p = .90$ for RT, and $p = .45$ for errors) or distractor type (X vs. Z; $p = .84$ for RT, and $p = .77$ for errors).

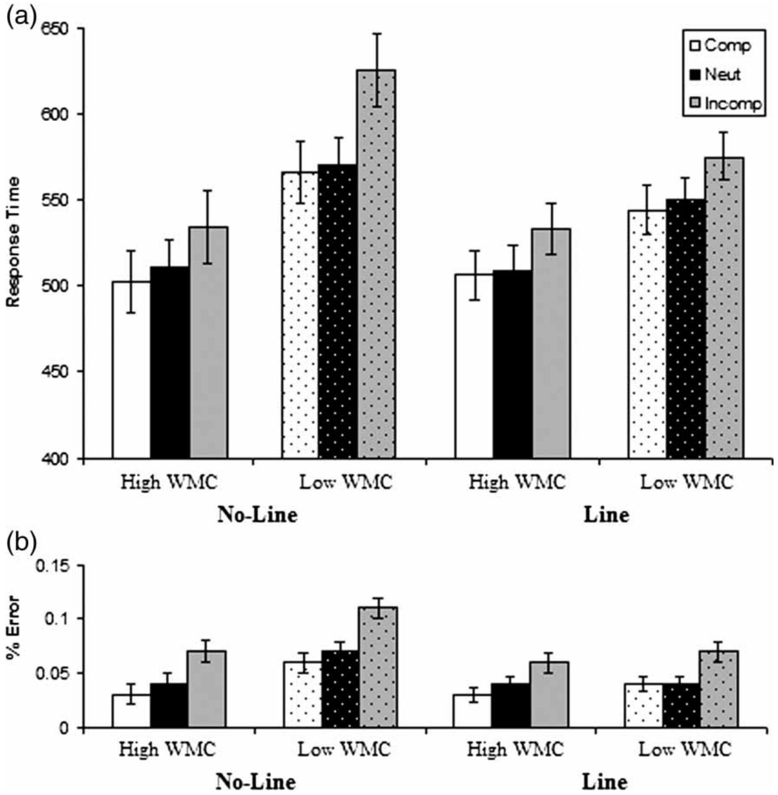

Figure 2.. *(a) Response times and (b) errors for high- and low-WMC (working memory capacity) individuals in the no-line and line conditions. Comp = compatible. Neut = neutral. Incomp = incompatible. Error bars represent ±1 standard error of the mean.*

Results

Data analysis

Only data for correct responses were included in the RT analysis. Nonresponses and responses less than 100 ms were discarded. This resulted in the removal of 1.6% of all trials. Adjustments for volitions of the sphericity assumption were made using the Huynh–Feldt correction.

Response times

Figure 2a indicates that high-WMC individuals were faster responders (517 ms) than low-WMC individuals (572 ms). However, it also indicates that low-WMC individuals' decreased their response times (RTs) when responding to line arrays (556 ms), relative to no-line arrays (587 ms). High-WMC individuals' RTs, on the other hand, were unaffected by array type (515 ms for no-line; 516 ms for line). These observations are supported by main effects of WMC, $F(1, 50) = 6.22$, $p < .02$, $\eta_p^2 = .11$, array type, $F(1, 50) = 7.46$, $p = .008$, $\eta_p^2 = .13$, and an interaction of the two variables, $F(1, 50) = 8.33$, $p = .006$, $\eta_p^2 = .14$.

Figure 2a further indicates that participants' RTs were slowed by incompatible distractors (567 ms), relative to both neutral (534 ms; $p < .001$) and compatible distractors (529 ms; $p < .001$). Pairwise comparisons indicated that RTs in neutral and compatible distractor conditions were not reliably different ($p = .08$). When responding to no-line arrays, low-WMC individuals were particularly affected by incompatible distractors (incompatible − neutral = 56 ms), both relative to line arrays (25 ms) and relative to high-WMC individuals, whose distractor effects did not differ between no-line (25 ms) and line arrays (25 ms). These observations are supported by a main effect of compatibility, $F(1.82, 90.93) = 107.40$, $p < .001$, $\eta_p^2 = .68$, an interaction of compatibility with array type, $F(1.63, 81.31) = 7.09$, $p = .003$, $\eta_p^2 = .12$, and a three-way interaction of these variables with WMC, $F(2, 100) = 4.80$, $p = .01$, $\eta_p^2 = .09$.

The three-way interaction indicates that, relative to neutral trials, low- and high-WMC individuals were differently slowed by incompatible distractors in the no-line condition (see Figure 2a), but experienced similar distractor interference in the line condition. In order to verify this interpretation, we conducted separate 2 (WMC) × 2 (neutral vs. incompatible) ANOVAs for the no-line and line array types. For no-line arrays, an interaction of WMC and compatibility was found, $F(1, 50) = 7.79$, $p = .007$, $\eta_p^2 = .14$, indicating that low-WMC individuals showed a larger distractor effect than high-WMC individuals. However, for line arrays, this interaction did not approach significance, $F(1, 50) = 0.02$, $p = .90$, $\eta_p^2 < .001$. Similar tests involving neutral versus compatible distractors did not result in significant interactions of WMC and compatibility for either array type (both $p > .47$; $\eta_p^2 < .01$).

Errors

Participants made fewer response errors (Figure 2b) for line (5%) displays than for no-line displays (6%). Low-WMC individuals decreased their errors when responding to line arrays (8% for no-line vs. 5% for line) to a larger extent than did high-WMC individuals (5% for no-line vs. 4% for line). These observations are supported by a main effect of array type, $F(1, 50) = 14.48$, $p < .001$, $\eta_p^2 = .23$, and an interaction of array type with WMC, $F(1, 50) = 4.72$, $p = .04$, $\eta_p^2 = .09$. A main effect of WMC fell short of significance ($p = .11$; $\eta_p^2 = .05$).

Overall compatibility effects were found. Relative to neutral displays (5% error), participants made fewer errors when the distractor was compatible (4%) and more errors when the distractor was incompatible (8%; both $p < .007$). The size of these effects was modulated by display type. In the no-line condition, respective error rates for compatible, neutral, and incompatible distractors were .04, .05, and .09. For the line condition, they were .04, .04, and .07. However, no interactions with WMC were found (all $p > .25$; $\eta_p^2 < .03$). These observations are supported by a main effect of compatibility, $F(1.64, 81.95) = 70.32$, $p < .001$, $\eta_p^2 = .58$, and an interaction of compatibility by array type, $F(1.84, 92.21) = 3.22$, $p = .05$, $\eta_p^2 = .06$.

Discussion

The present experiment demonstrates that WMC-related differences in selective attention can be eliminated through bottom-up guidance. While low-WMC individuals typically experience difficulty when attempting to exclude distraction, they can be aided by environments that guide focal attention toward critical information. High-WMC individuals, on the other hand, did not benefit from bottom-up guidance. Rather, their performance was stable across no-line and line conditions. We interpret this as further evidence that (a) working memory is critical to carrying out the priorities of visual attention (Lavie et al., 2004), and (b) high-WMC individuals are particularly adept at proactively constraining attention to critical spatial locations (Poole & Kane, 2009).

Attentional guidance or perceptual load?

An alternative explanation of the present results can be constructed using Lavie's (1995) perceptual-load theory. From this perspective, the decreased distractor effects shown by low-WMC individuals would be the result of processing capacity being depleted by the addition of zeros to the display. Thus, fewer resources would be available to process the distractor. This explanation is contradicted by two properties of high perceptual load (cf. Lavie & Cox, 1997). First, under high perceptual load, attention functions as a serial process. As a result, RTs increase. In the present study, the addition of zeros did not slow the responses of participants. In fact, low-WMC individuals were faster to respond when zeros were added. Second, the effects of perceptual load tend to be all or none, rather than graded. In the present study, distractor effects were diminished by the addition of zeros; however, a significant flanker effect was found in all conditions.

Distractor dilution (Tsal & Benoni, 2010) provides a similar account of the present results. From this perspective, neutral item features (e.g., zeros) compete with the distractor, thus degrading the quality of its visual representation. Unlike perceptual load, distractor dilution *is* associated with RT decreases (Tsal & Benoni, 2010), such as those shown by low-WMC individuals. However, this perspective must be reconciled with the lack of a dilution effect for high-WMC individuals. We thus argue that dilution provides a viable mechanism of bottom-up influences, provided one assumes this process is sometimes made unnecessary (or obscured) by efficient attentional constraint.

Early or late selection?

We interpret the present results as indicating that high-WMC individuals can facilitate the processing of critical information by maintaining attention at spatially defined locations, thus minimizing the influence of distractors (i.e., early selection; cf. Driver, 2001). However, Heitz and Engle (2007) report that, in the first 300–400 ms of a trial, high- and low-WMC individuals are equally susceptible to incompatible distractors. As the trial progresses, high-WMC individuals reach asymptotic accuracy at a faster rate. This was taken as a sign that all people are initially affected by distractors to an equal degree, but high-WMC individuals rapidly constrain focal attention to only relevant information (i.e., late selection; cf. Deutsch & Deutsch, 1963).

Similarly, ERP and time-course analyses reveal that that high- and low-WMC individuals are similarly susceptible to attentional capture, but differ in their ability to reallocate visual attention (Fukuda & Vogel, 2009, 2011). This is in line with the findings of Heitz and Engle (2007) and readily explains the results of the no-line condition (i.e., high-WMC individuals more readily disengage from the distractor). However, the line condition is problematic. Specifically, why is the benefit of zeros limited to low-WMC individuals?

We argue that the nature of the display biases the point at which attention intervenes in processing. For instance, Heitz and Engle (2007) used a traditional flanker task in which the target is always the middle of five items (e.g., XXZXX). This paradigm may encourage late selection because the target is partially defined through its spatial relationship to the flankers (cf. Logan & Zbradoff, 1999). However, when the target is separated from distractors (e.g., the no-line condition), spatial information becomes a more effective cue for locating the target. Assuming an individual is incapable of maintaining spatial focus (cf. Poole & Kane, 2009), the distractor of the no-line condition can still define the target: The distractor is always the larger of the two items. The line condition, on the other hand, should promote early selection by guiding attention (e.g., Duncan & Humphreys, 1989; Wolfe, 1994) to the target.

Contrary to this assumption, Luria and Vogel (2011) have recently proposed that inefficient filtering typically prevents low-WMC individuals from engaging early selection. This leads to memory being overloaded with irrelevant information. From this perspective, the addition of zeros may aid performance by loading limited-capacity memory with information that has no mapping to potential responses. Thus, attentional allocation to the distractor would be minimized. Critically, Fukuda and Vogel (2009) found that high- and low-WMC individuals are equally capable of overriding capture by response-irrelevant information. Future research should attempt to differentiate between these bottom-up-guidance and irrelevant-capture explanations of the present results.

Conclusions

High-WMC individuals typically outperform low-WMC individuals on tasks that require selection between critical and distracting stimuli (Heitz & Engle, 2007; Redick & Engle, 2006; Unsworth & Spillers, 2010). The present study, however, suggests a qualification. WMC is related to visual selection to the degree that top-down processes are required to separate the target item from distracting information. However, WMC-related differences in selective attention are eliminated in situations where visual context can guide attention to the target.

Original manuscript received 13 August 2011
Accepted revision received 8 November 2011

REFERENCES

Deutsch, J. A., & Deutsch, D. (1963). Attention: Some theoretical considerations. *Psychological Review*, *70,* 80–90.

Driver, J. (2001). A selective review of selective attention research from the past century. *The British Psychological Society*, *92,* 53–78.

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, *96,* 433–458.

Eriksen, B. A., & Eriksen, C. A. (1974). Effects of noise letters upon the identification of a target letter in a non-search task. *Perception & Psychophysics*, *16,* 143–149.

Fukuda, K., & Vogel, E. K. (2009). Human variation in overriding attentional capture. *The Journal of Neuroscience*, *29,* 8726–8733.

Fukuda, K., & Vogel, E. K. (2011). Individual differences in recovery time from attentional capture. *Psychological Science*, *22,* 361–368.

Heitz, R. P., & Engle, R. W. (2007). Focusing the spotlight: Individual differences in visual attention control. *Journal of Experimental Psychology: General*, *136,* 217–240.

Kane, M. J., & Engle, R. W. (2003). Working memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General*, *132,* 47–70.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, *21,* 451–468.

Lavie, N., & Cox, S. (1997). On the efficiency of visual selective attention: Efficient visual search leads to inefficient distractor rejection. *Psychological Science*, *8,* 395–398.

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.

Logan, G. D., & Zbradoff, N. J. (1999). Selection for cognition: Cognitive constraints on visual spatial attention. *Visual Cognition*, *6,* 55–81.

Luria, R., & Vogel, E. K. (2011). Visual search demands dictate reliance on working memory storage. *Journal of Neuroscience*, *31,* 6199–6207.

Poole, B. J., & Kane, M. J. (2009). Working-memory capacity predicts the executive control of visual search among distractors: The influences of sustained and selective attention. *Quarterly Journal of Experimental Psychology*, *62,* 1430–1454.

Redick, T. S., & Engle, R. W. (2006). Working memory capacity and Attention Network Test performance. *Applied Cognitive Psychology*, *20,* 713–721.

Tsal, Y., & Benoni, H. (2010). Diluting the burden of load: Perceptual load effects are simply dilution effects. *Journal of Experimental Psychology: Human Perception and Performance*, *36,* 1645–1656.

Unsworth, N., Heitz, R. P., Schrock, J. C., & Engle, R. (2005). An automated version of the operation span task. *Behavior Research Methods, Instruments, and Computers*, *37,* 498–505.

Unsworth, N., Redick, T. S., Heitz, R. P., Broadway, J. M., & Engle, R. W. (2009). Complex working memory span tasks and higher-order cognition: A latent-variable analysis of the relationship between processing and storage. *Memory*, *17,* 635–654.

Unsworth, N., & Spillers, G. J. (2010). Working memory capacity: Attention, memory, or both? A direct test of the dual-component model. *Journal of Memory and Language*, *62,* 392–406.

Wolfe, J. M. (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review*, *1,* 202–238.