

Working-memory capacity predicts the executive control of visual search among distractors: The influences of sustained and selective attention

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Abstract:

Variation in working-memory capacity (WMC) predicts individual differences in only some attention-control capabilities. Whereas higher WMC subjects outperform lower WMC subjects in tasks requiring the restraint of prepotent but inappropriate responses, and the constraint of attentional focus to target stimuli against distractors, they do not differ in prototypical visual-search tasks, even those that yield steep search slopes and engender top-down control. The present three experiments tested whether WMC, as measured by complex memory span tasks, would predict search latencies when the 1–8 target locations to be searched appeared alone, versus appearing among distractor locations to be ignored, with the latter requiring selective attentional focus. Subjects viewed target-location cues and then fixated on those locations over either long (1,500–1,550 ms) or short (300 ms) delays. Higher WMC subjects identified targets faster than did lower WMC subjects only in the presence of distractors and only over long fixation delays. WMC thus appears to affect subjects' ability to maintain a constrained attentional focus over time.

Keywords: Working memory; Executive control; Attention; Visual search; Individual differences.

Article:

A growing literature demonstrates that individual differences in working-memory capacity (WMC), as measured by complex span tasks such as reading span (Daneman & Carpenter, 1980), predict individual differences in performance of attention-control tasks that make few memory demands (Bleckley, Durso, Crutchfield, Engle, & Khanna, 2003; Colflesh & Conway, 2007; Colzato, Spapé, Pannebakker, & Hommel, 2007; Conway, Cowan, & Bunting, 2001; Conway, Tuholski, Shisler, & Engle, 1999; Elliott, Barrilleaux, & Cowan, 2006; Heitz & Engle, 2007; Hutchison, 2007; Kane, Bleckley, Conway, & Engle, 2001; Kane & Engle, 2003; Kiefer, Ahlegian, & Spitzer, 2005; Long & Prat, 2002; McCabe, Robertson, & Smith, 2005; Redick & Engle, 2006; Schweizer & Moosbrugger, 2004; Tuholski, Engle, & Baylis, 2001; Unsworth, Schrock, & Engle, 2004; but for mixed results, see Friedman & Miyake, 2004; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). As well, WMC predicts individual differences in attentional lapses during challenging daily-life activities (Alloway, Gathercole, Kirkwood, & Elliott, in press; Gathercole et al., 2008; Kane et al., 2007a). The purpose of many of these studies has been to test the *executive attention theory* of WMC (e.g., Engle & Kane, 2004; Engle, Kane, & Tuholski, 1999; Kane, Conway, Hambrick, & Engle, 2007b), but we also consider, below, their utility in demarcating the boundary conditions of the executive-attention construct.

The executive attention theory seeks to explain the fact that individual differences in WMC robustly predict individual differences in a wide variety of higher order cognitive tasks, such as language comprehension, complex learning, and inductive reasoning (for reviews, see Conway, Jarrold, Kane, Miyake, & Towse, 2007). Our view is that variation in WMC, and WMC's covariation with higher order cognition, are caused in part by executive-control processes involved in: (a) maintaining or recovering access to stimulus and goal representations in the face of distraction, memory interference, or response competition, and (b) resolving conflict among activated thoughts or action plans. Thus, the findings that people who differ in WMC also differ in their performance of "low-level" attention tasks that present potent distraction, or elicit significant response

conflict, provide clear support for our view (but see Friedman & Miyake, 2004; Schmiedek, Oberauer, Wilhelm, Süß, & Wittmann, 2007).

In particular, WMC predicts performance in tasks requiring attentional *restraint*, where subjects must stop themselves from responding habitually in favour of responding in a novel, goal-directed manner, such as in Stroop and antisaccade tasks (e.g., Hutchison, 2007; Kane et al., 2001; Kane & Engle, 2003; Kiefer et al., 2005; Long & Prat, 2002; McCabe et al., 2005; Unsworth et al., 2004). WMC also predicts performance in tasks requiring attentional *constraint*, where subjects must limit their focus to target objects, dimensions, locations, or events presented among distractors, such as in flanker and dichotic-listening tasks (e.g., Bleckley et al., 2003; Colflesh & Conway, 2007; Colzato et al., 2007; Conway et al., 2001; Conway et al., 1999; Elliott et al., 2006; Heitz & Engle, 2007; Redick & Engle, 2006). Restraint and constraint capabilities are also strongly correlated with one another (Friedman & Miyake, 2004), suggesting that these dimensions of attention control, along with WMC, may reflect a common set of mechanisms. For example, active maintenance of task goals in the face of conflict or distraction may enable the successful implementation of both attentional restraint and constraint functions (see Engle & Kane, 2004).

But how broadly does the WMC-attention association extend? Which particular executive-control functions do, and do not, share variance with WMC (and with restraint and constraint functions)? Executive control can be a rather vague, slippery construct, operationalized differently across psychology's various subfields (e.g., cognitive psychology vs. clinical neuropsychology), and even across investigators within subfields (e.g., Kane et al., 2007b; Oberauer, Süß, Wilhelm, & Sander, 2007). We have therefore attempted to exploit normal variation in WMC and its covariation—or lack thereof—with other constructs as a tool for inductive theory building about executive control. We have done so by exploring the boundary conditions of the relation between WMC and attention-task performance, with the hope that, in distinguishing classes of tasks that do versus those that do not correlate with WMC, we will learn something fundamental about these overlapping and nonoverlapping processing domains.

Central to the present investigation, Kane, Poole, Tuholski, and Engle (2006) reported several experiments testing WMC's association with performance of a variety of visual search tasks that have been proposed to involve top-down control processes (e.g., Wolfe, 1994), but do not present explicit restraint or constraint requirements. Subjects conducted relatively easy versus difficult feature-absence letter searches through regular or irregular displays (Experiment 1), or difficult conjunction searches through irregular displays of coloured bars or letters (Experiment 2). In all tasks, subjects made target-present versus target-absent judgements and the number of nontargets varied across trials. Although all of our search tasks yielded reliable and substantial reaction time (RT) slopes across display sizes, WMC was compellingly unrelated to performance. The top-down control processes required in prototypical visual search tasks, even quite difficult ones, thus appeared to be different from those reflected by WMC.

In a further attempt to clarify the relations among WMC, executive control, and visual attention, here we test subjects on search tasks where they must selectively constrain their focus to several potential target locations amid distractor locations. Thus, in our procedure, as often occurs in life, target objects might appear in any one of several places (e.g., one's house key on a desk or in an open drawer), but never in others (on a lampshade or on a slice of toast), and so a most efficient search would be restricted to only the allowable target locations. A ubiquitous finding in support of the spatial selectivity of attention comes from task preparations that cue target locations prior to their appearance: Subjects more quickly identify targets that appear in cued than in uncued locations (e.g., Müller & Findlay, 1988; Posner, 1980). Of particular interest here is the notion that limiting attention to multiple discontinuous locations in tasks like these depends upon top-down control processes, which may indicate their relation to WMC. For example, Awh, Matsukura, and Serences (2003; see also Awh, Sgarlata, & Kliestik, 2005) found that subjects' expectation of visual distractors affected their ability to limit the effects of those distractors in localizing and identifying a target. That is, responses to targets were less disrupted by distractors when they occurred in blocks with many (versus few) distractor-laden trials and in locations that

frequently (versus infrequently) presented distractors along with targets. With advance knowledge of impending difficulty, then, subjects proactively engaged attentional processes to counteract it.

The present experiments tested whether variation in WMC might predict the ability or propensity to use executive control to block distractor processing during the search for a visual target among nontargets appearing both in potential target locations and in distractor (nonallowable) locations. To preview, our findings are consistent with recent evidence that higher WMC subjects are faster (Heitz & Engle, 2007; Redick & Engle, 2006) and more accurate (Bleckley et al., 2003) than lower WMC subjects to identify or localize a single target appearing among other stimuli. That is, even though WMC does not predict visual-search performance when all presented stimuli are potential targets (Kane et al., 2006), we report here that WMC predicts search among multiple target locations when some locations can be excluded from consideration. Our findings also indicate that the search advantage for higher WMC subjects is limited to contexts in which constrained attentional focus must be maintained briefly over time.

EXPERIMENT 1

Our visual search task presented a 5 x 5 matrix of stimulus locations. Subjects identified a target presented only in 1 of 4 discontinuous locations (the corners of the internal 3 x 3 grid) within the matrix. Each trial began with a long fixation display, containing placeholder dots at all 25 stimulus locations, and we instructed subjects to focus only on the dots representing the 4 target locations (see Figure 1A). Clean trials presented stimuli only in these 4 locations; noise trials (see Figure 1B) presented stimuli in all 25 locations. Although previous studies have required subjects to split their attention among only 2 locations (Awh et al., 2003; Awh & Pashler, 2000; Awh et al., 2005), we used 4 target locations on the suggestion that the visual system can maintain up to four independent foci (e.g., Awh, Barton, & Vogel, 2007; Pylyshyn & Storm, 1988). We predicted that higher WMC subjects would identify search targets more quickly than would lower WMC subjects, but only in noise trials where distractor exclusion was necessary.

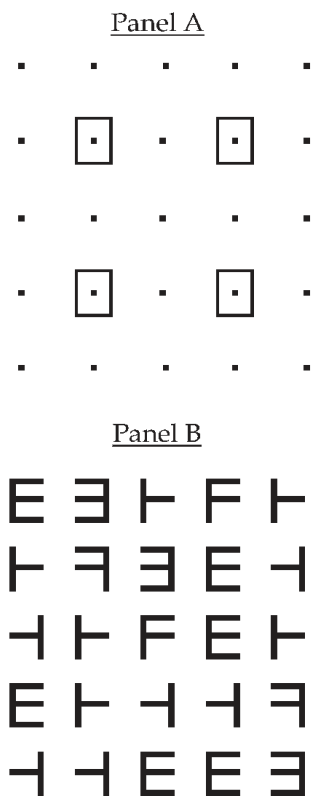


Figure 1. Sample displays for Experiments 1–3. Panel A: The fixation display. Boxes here highlight the target locations for Experiment 1, but they never appeared onscreen to subjects. Panel B: The search display, noise condition.

Method

Subjects

A total of 120 undergraduates at the University of North Carolina at Greensboro (UNCG) participated as partial fulfilment of a course requirement. Eligible subjects were between 18 and 35 years old with normal or corrected-to-normal vision.

Apparatus

All tasks were presented via Dell Optiplex GX110 computers with CRT colour monitors. Subjects responded in the visual search tasks using a Psychological Software Tools serial response box (Model 2.0) and recalled items from each working-memory span task on paper.

General procedure

We tested subjects individually, in two sessions, the first presenting two WMC tasks and the second presenting the search task; each session lasted approximately 60 min. The experimenter read aloud instructions presented onscreen. Subjects were free to complete the two sessions at any time within the same semester, resulting in up to 63 days between sessions.

WMC screening

Subjects completed two complex-span tasks of WMC (from Kane et al., 2004): operation-word span (OSPAN) and reading-letter span (RSPAN). Both tasks required subjects to immediately recall short lists of items presented in alternation with a processing task. In OSPAN, subjects verified equations while trying to remember words—for example, *IS (6 x 2) - 5 = 7 ? CLASS*. Subjects read the equation aloud, reported whether the equation was correct, and then read aloud the to-be-remembered word. The experimenter then immediately advanced the display to another equation–word string or a recall cue (“???”). RSPAN was identical to OSPAN except that subjects judged the meaningfulness of sentences while remembering sequences of letters (e.g., *Andy was stopped by the policeman because he crossed the yellow heaven ? X*). Both tasks presented one processing-memory string at a time, with each set of strings ranging from 2 to 5 items in length, and 4 sets of each length, for a total of 16 sets and 56 items per task. All subjects saw the same pseudo-randomized order of sets for each task. We scored each task as the mean proportion of target items recalled in correct serial order across sets (see Conway et al., 2005) and created a z-score WMC composite of OSPAN and RSPAN scores.

Visual search

We created stimuli using a Zurich Ex Bt font letter E (a sans serif font), in Microsoft Paint, with the centre horizontal bar lengthened to extend the same distance as the top and bottom bars. The E measured 11 x 15 pixels (0.5 x 0.7 cm). We created an F by removing the bottom horizontal bar of the E and created a horizontally tilted T by removing the top and bottom horizontal bars of the E; we created backward versions of the E, F, and tilted T by horizontally flipping each letter. The F and backward F served as targets for the search tasks, and the Es, Ts, and their backward versions served as nontargets. Subjects reported on each trial whether an F or backward F was present.

Stimuli appeared within a 5 x 5 grid measuring 106 x 120 pixels (4.9 x 5.7 cm), for a total of 25 possible locations; 5 pixels separated the stimuli both vertically and horizontally. The target always appeared in one of the four corners of the 3 x 3 matrix internal to the 5 x 5 matrix (see Figure 1). Subjects indicated whether an F or backward F appeared at one of the 4 target locations by pressing a response-box key; all subjects pressed the right key with their right index finger for Fs and the left key with their left index finger for backward Fs.

The program first presented a block of response-mapping practice trials in which a target was presented alone on each trial; all other locations were occupied with 2 x 2 pixel dots. Each trial presented one of the two targets in one of the four target locations five times each, yielding 40 trials (2 target types x 4 target locations x 5 repetitions) presented in a randomized order.

The program then presented a block of practice visual-search trials, consisting of half clean and half noise trials. Each clean trial presented one target in one of the four target locations and three distractors chosen at random, without replacement (such that there was only one example of each distractor type on each trial), in the remaining target locations. Dots appeared in all other locations. Similarly, each noise trial presented one target in one of the four target locations and three nontargets chosen at random, without replacement, in the remaining target locations.

In order to ensure that subjects would limit their searches to target locations (rather than simply searching the entire matrix), all noise displays presented false targets (Fs and backward Fs), or *lures*, in some nontarget locations. Each noise trial presented one lure in one of the five nontarget locations (within the internal 3 x 3 matrix); the lure matched the target on half the trials. The remaining locations within the 3 x 3 matrix were populated by four distractors, chosen at random, without replacement. Finally, each noise trial also presented two lures in two randomly selected locations outside the 3 x 3 matrix (along the outer border of the 5 x 5 matrix); the remaining outer locations were populated with distractors chosen at random, with the constraint that no single distractor appeared in the outer region more than four times per trial. This resulted in a total of 32 (2 target type x 4 target locations x 4 repetitions) practice trials, of which half were clean and half were noise. The experimental trials presented each of the two target types appearing in the four possible target locations 10 times, resulting in 80 clean trials and 80 noise trials, for 160 experimental trials total (2 target types x 4 target locations x 5 inner lure locations x 2 lure types x 2 trial types).

All trials first presented a blank screen for 500 ms followed by a fixation display for 1,500 ms. The fixation display had all 25 locations populated with 2 x 2 pixel dots. We instructed subjects to use the fixation dots as placeholders for the upcoming items and to focus attention on only the dots representing the four potential target locations to aid their search. The search display then appeared and remained onscreen until the response. Subjects performed the search task in the same session as two other visual search tasks (reported in Kane et al., 2006, Experiment 3), and their order was counterbalanced in a Latin-square design. Task order had no effect on the results.

Results

Subjects

We dropped the data from 16 of our 120 subjects: 3 non-native English speakers, 3 subjects with processing-task error rates $\geq .15$ in either WMC task (Conway et al., 2005), 1 with missing span data, and 9 due to computer malfunctions. This left 104 subjects with WMC and search data in the analyses. Of these subjects, 6 had error rates exceeding 30% on noise trials, and so we excluded their search data from analyses, leaving 98 subjects' data.

WMC screening

OSPAN and RSPAN scores reflected the mean proportion of items recalled correctly across all sets. Based on 104 subjects' data, means for OSPAN and RSPAN were .605 (SD = .131) and .636 (SD = .128), respectively. The span measures correlated at $r = .69$. We converted each span score to a z-score and then averaged them into a composite WMC measure, which was normally distributed (skewness = -0.55; kurtosis = 0.35).

Visual search

We set the alpha level at .05 for all analyses and report partial eta squared (η_p^2) as an estimate of effect size. We first use analysis of variance (ANOVA) to examine all experimental effects and then analysis of covariance (ANCOVA) to analyse main effects and interactions involving WMC, as a continuous variable (see Conway et al., 2005; Moore, Clark, & Kane, 2008; Oberauer, 2005). All RTs reported represent the means of individual subjects' medians.

RT. In order to illustrate the effects of interest, Figure 2A (clean trials) and Figure 2B (noise trials) present mean RTs by WMC, with subjects classified into three WMC groups: low, medium, and high. Recall, however, that all WMC analyses treated the variable as continuous, rather than as arbitrary, discrete groups.

A 2 (trial type: clean vs. noise) x 4 (target location: top left, 1; top right, 2; bottom left, 3; bottom right, 4) repeated measures ANOVA indicated that subjects identified targets more quickly on clean than on noise trials, $F(1, 97) = 581.46$, $MSE = 48,238.88$, $\eta^2_p = .86$, and in the top two locations versus the bottom two locations, $F(3, 291) = 89.93$, $MSE = 26,594.07$, $\eta^2_p = .48$, with the target location effect being stronger on noise than on clean trials, $F(3, 291) = 41.33$, $MSE = 14,218.34$, $\eta^2_p = .30$. An ANCOVA further indicated that higher WMC subjects identified targets faster than did lower WMC subjects, $F(1, 96) = 4.46$, $MSE = 195,920.09$, $\eta^2_p = .04$, and that these WMC differences were larger on noise than on clean trials, $F(1, 96) = 4.73$, $MSE = 46,452.50$, $\eta^2_p = .05$; WMC did not enter into any interactions with target location ($F_s < 1$). Considering clean trials only, WMC did not significantly affect search latencies, $F(1, 96) = 2.35$, $p = .13$ ($r = -.15$); on noise trials, however, higher WMC subjects showed significantly shorter search latencies than did lower WMC subjects, $F(1, 96) = 5.01$, $MSE = 196,317.83$, $\eta^2_p = .05$ ($r = -.23$, $p = .03$). Note that both clean and noise RTs were reliably measured; Cronbach's alpha calculated on subjects' mean RTs across the four target locations (and so, four variables) was .89 for clean trials and .82 for noise trials.

Error rates. Table 1 presents mean error rates by WMC group (low, medium, high) span, trial type (clean and noise), and target location; again ANCOVA treated WMC as continuous.

Subjects committed very few errors, and lower WMC subjects appeared to commit slightly fewer errors than did higher WMC subjects, at least on clean trials. A 2 (trial type: clean vs. noise) x 4 (target location: 1–4) repeated measures ANOVA indicated that error rates were not significantly higher on noise than on clean trials overall, $F(1, 97) = 2.86$, $p = .09$, but they did differ by target location, with generally higher error rates for bottom (3 and 4) versus top (1 and 2) locations, $F(3, 291) = 7.34$, $MSE = 0.002$, $\eta^2_p = .07$; this location effect did not vary between clean and noise trials, $F < 1$. ANCOVA further indicated that WMC had no significant effect on overall error rates, $F(1, 96) = 2.17$, $p = .14$, and that the apparent WMC x Trial Type interaction only approached conventional significance, $F(1, 96) = 3.19$, $p = .08$.

Discussion

Experiment 1 yielded a rare WMC-related effect on visual search. Higher WMC subjects identified targets more quickly than did lower WMC subjects when potential target locations appeared among nontarget and lure locations. Thus, WMC predicted search success when attention had to be constrained to discontinuous locations in order to avoid distractors. On clean trials, in contrast, where subjects searched among four stimuli in the absence of additional distractors (as in most visual-search tasks), WMC had no significant effects, aside from a statistically weak error-rate difference that actually favoured lower WMC subjects. Thus, consistent with previous work (Kane et al., 2006), WMC was unrelated to prototypical visual search.

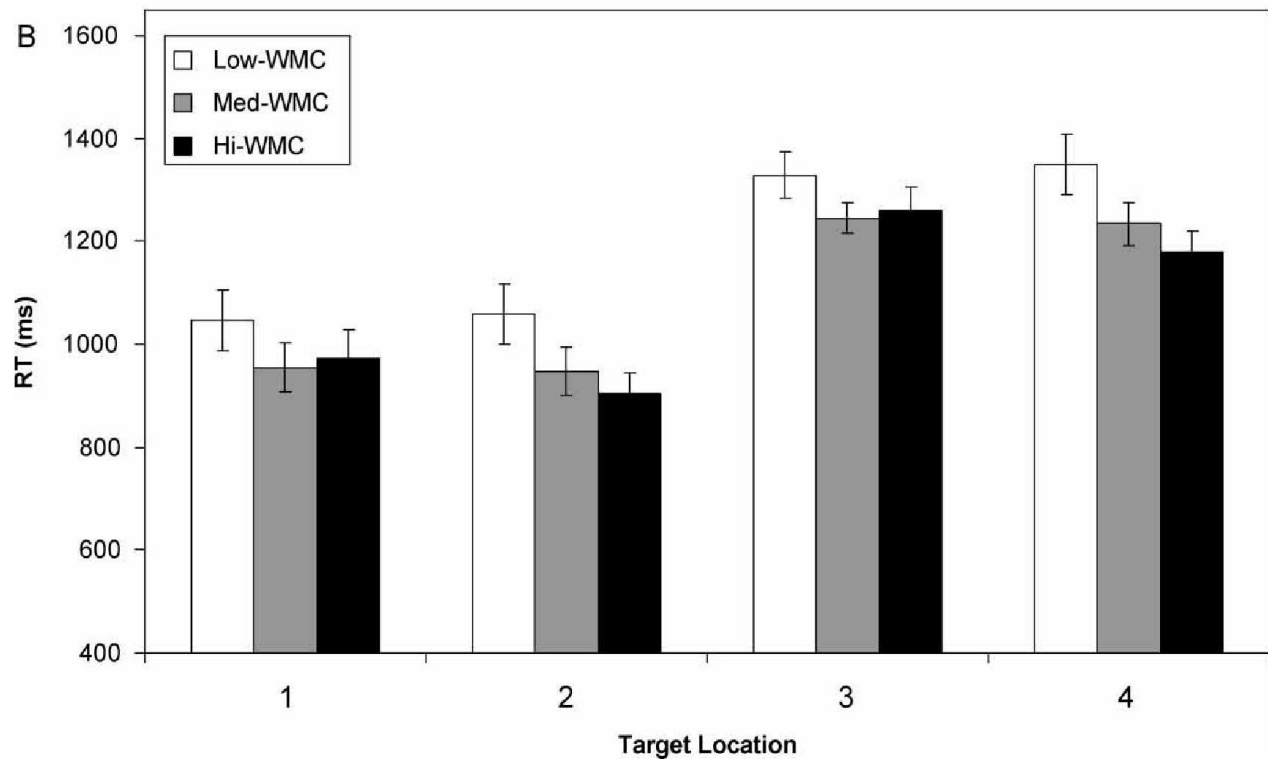
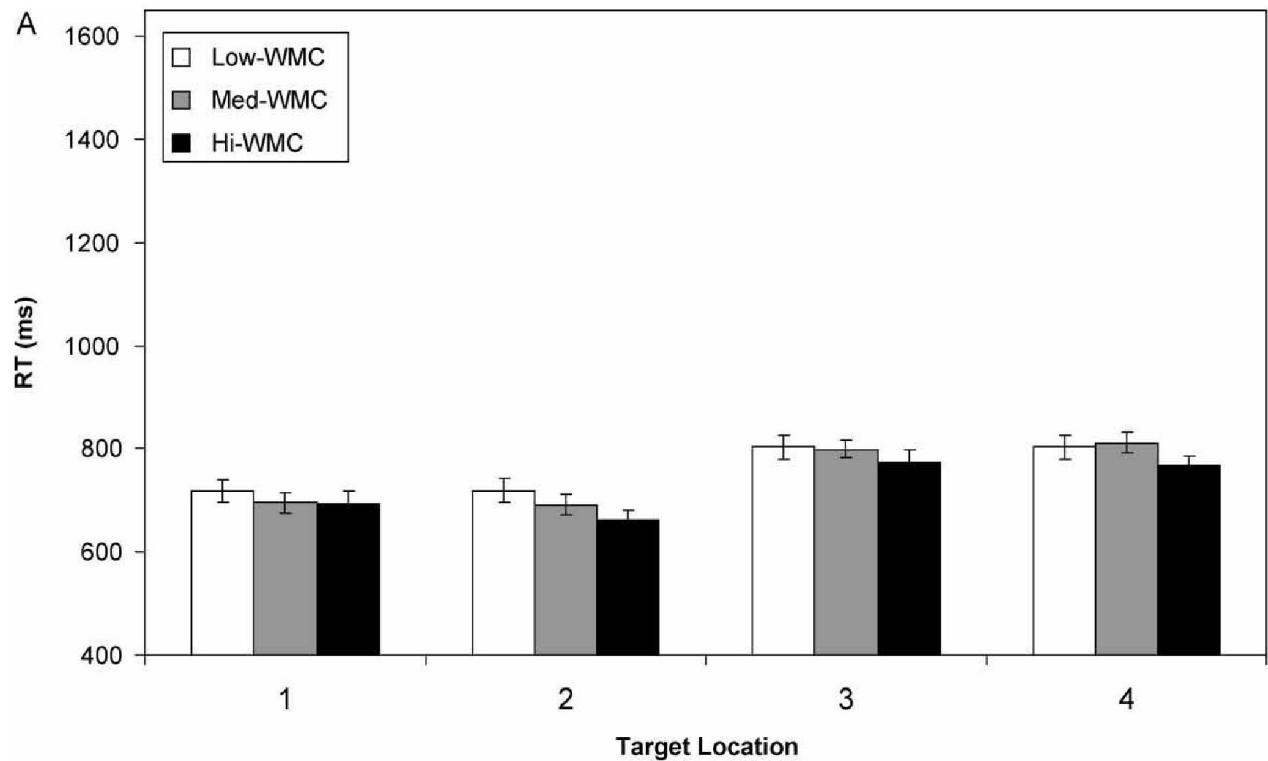


Figure 2. Means of median search reaction times (RTs; in ms) by target location and WMC group in Experiment 1. Low-WMC = subjects scoring in bottom third of the distribution on the z-score composite working-memory capacity (WMC) measure; med-WMC = subjects scoring in the middle third of the WMC distribution; high-WMC = subjects scoring in the top third of the WMC distribution. Target location: 1 = top left; 2 = top right; 3 = bottom left; 4 = bottom right. Error bars represent standard errors. Panel A depicts RTs from clean trials; Panel B depicts RTs from noise trials.

Table 1. *Experiment 1: Mean error rates by working-memory capacity group, target location, and trial type*

<i>Trials</i>	<i>Group</i>	<i>Target location</i>			
		<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>
Clean	Low WMC	.017 (.027)	.009 (.024)	.023 (.038)	.014 (.026)
	Medium WMC	.025 (.045)	.018 (.030)	.038 (.070)	.049 (.085)
	High WMC	.031 (.040)	.033 (.049)	.056 (.061)	.034 (.045)
Noise	Low WMC	.030 (.051)	.025 (.051)	.034 (.055)	.023 (.038)
	Medium WMC	.031 (.052)	.035 (.061)	.054 (.068)	.034 (.073)
	High WMC	.025 (.034)	.028 (.046)	.042 (.057)	.047 (.066)

Note: WMC = working-memory capacity. Standard deviations in parentheses. Low WMC, $n = 32$; medium WMC, $n = 34$; high WMC, $n = 32$.

EXPERIMENT 2

Because we previously failed to find WMC-related differences in several varieties of visual search (Kane et al., 2006), Experiment 2 sought to replicate our significant Experiment 1 findings. We also varied task difficulty across trials by asking subjects to split their attention among two, four, or eight potential target locations (versus four locations on all Experiment 1 trials). Introducing this location-number variable also made the search task generally more difficult than that in Experiment 1 because the particular locations to be searched changed from trial to trial, requiring subjects to repeatedly reconfigure their selective attentional focus according to symbolic cues that should prompt endogenous control processes.

Method

Methods were identical to those in Experiment 1 except where detailed below.

Subjects

A total of 103 UNCG undergraduates participated as partial fulfilment of a course requirement.

General procedure

Subjects again completed separate WMC and visual search sessions, here with a maximum of 83 days between sessions. WMC screening proceeded just as in Experiment 1.

Visual search

On each trial, the search target appeared in one of the eight locations surrounding the central location within the 5 x 5 matrix (that is, in one of the eight locations along the internal 3 x 3 matrix) and never appeared in the central location or the outermost locations.

Each trial presented a symbolic cue to indicate the to-be-searched locations. An eight-armed asterisk (measuring 24 x 27 pixels) indicated that the target could appear in any of the eight potential target locations surrounding the central location in the display. Two different symbols indicated that only four locations could contain the target: A “+” symbol cued the locations directly above, below, to the left, and to the right of the central location, and an “x” symbol cued the four corner locations of the internal 3 x 3 matrix. Four different symbols cued two locations: Each was a straight line presented in an orientation indicating the to-be-searched locations, with a vertical line (|) cueing the locations above and below centre, a horizontal line (—) cueing the locations to the left and right of centre, and diagonally slanted lines (\ or /) cueing opposing vertices of the internal 3 x 3 matrix (e.g., upper left and lower right).

For the 8-location trials, only one F or backward F target appeared in any of the 8 locations surrounding the central location; the 4-location-cue trials (“+” and “x” cues) presented a target in one of the 4 cued locations, and the 2-location-cue trials presented a target in one of the 2 cued locations, surrounding the central location on

each display. Every trial also presented a lure in one of the noncued locations within the central 3 x 3 matrix (including the central location), matching the target on half the trials; on 8-cue trials the lure always appeared in the central location because it was the only inner location left. Finally, on all trials, the remaining noncued locations within the 3 x 3 matrix were populated with distractors chosen at random (such that no more than two of each distractor type appeared in those locations); the outermost locations (along the external 5 x 5 matrix) presented two lures (one F and one backward F) in randomly selected locations, with the remaining 14 locations populated with distractors chosen at random, such that no single distractor type appeared more than four times per display. The task presented 160 eight-cue trials (2 target types x 8 target locations x 2 lure types x 5 repetitions), 160 four-cue trials (2 target types x 4 target locations x 2 lure types x 5 lure locations x 2 cue types), and 160 two-cue trials (2 target types x 2 target locations x 2 lure types x 5 lure locations x 4 cue types).

As in Experiment 1, subjects first completed a block of 32 response-mapping trials (2 target types x 8 locations x 2 repetitions) presented in a random order. Each trial first presented a blank screen for 100 ms, followed by a fixation display containing 2 x 2 pixel square dots in all 25 stimulus locations for 1,500 ms and then a target display. Target displays presented only one F or backward F in one of the eight potential target locations, with all other locations containing dots, until response.

Subjects then completed a practice block of 32 search trials (eight of each 8-, 4-, and 2-location trial types) in a randomized order for each subject. Trials presented a blank screen for 500 ms followed by a symbolic cue indicating the target locations for 750 ms, then another blank screen for 100 ms; a fixation display then appeared for 1,500 ms, with all 25 stimulus locations populated with dots, followed by the search display, which remained onscreen until response.

Finally, the experimental block presented 480 trials (160 of each 8-, 4-, and 2-location trials) in a randomized order for each subject, with short breaks after 160 and 240 trials. The trial events for experimental trials matched those in practice trials.

Results

Subjects

We dropped the data from 10 of the 113 subjects, leaving data from 93 subjects in all analyses; 1 had participated in Experiment 1, 2 had processing-task error rates $\geq .15$ in at least one WMC task, and 7 had error rates $\geq .40$ in the search task.

WMC screening

The mean proportion of recall in OSPAN and RSPAN, based on 93 subjects' data, was .619 (SD = .139) and .660 (SD = .142), respectively; they correlated at $r = .74$. The resulting WMC composite was normally distributed (skewness = -0.46 , kurtosis = 0.07).

Visual search

RT. Figure 3 presents the mean RTs by WMC group (high, medium, and low, for illustrative purposes only) and number of cued locations. Higher WMC subjects seemed to outperform lower WMC subjects no matter how many locations were cued, but the differences between higher and lower WMC subjects appeared to be smallest with two cued locations.

A repeated measures ANOVA indicated that RTs increased with locations cued, $F(2, 184) = 435.31$, $MSE = 17,287.92$, $\eta^2_p = .83$. An ANCOVA (with WMC as a covariate) also confirmed that higher WMC subjects found targets faster than did lower WMC subjects, $F(1, 91) = 10.57$, $MSE = 240,160.90$, $\eta^2_p = .10$, and that this WMC effect increased with locations cued, $F(2, 182) = 4.42$, $MSE = 16,669.08$, $\eta^2_p = .04$. Despite this interaction, the correlations between WMC and search RTs were stable across locations cued, with $r_s = -.32$, $-.34$, and $-.29$, for two, four, and eight locations, respectively (all $p_s < .01$). Thus, whereas absolute RT differences between higher and lower WMC subjects widened over larger search arrays, the amount of RT variance accounted for by WMC (or the rank-ordering of subjects according to WMC) remained stable across array sizes.¹ Indeed, a hierarchical

regression analysis predicting 8-cue RTs found no significant WMC effect after accounting for the variance shared with 2-cue RTs ($\Delta R^2 = .00$; $F < 1$). RTs were again reliably measured; Cronbach's alpha = .96, calculated on subjects' mean RTs across the two target types (F, backward F) for two, four, and eight locations cued (i.e., across six variables).

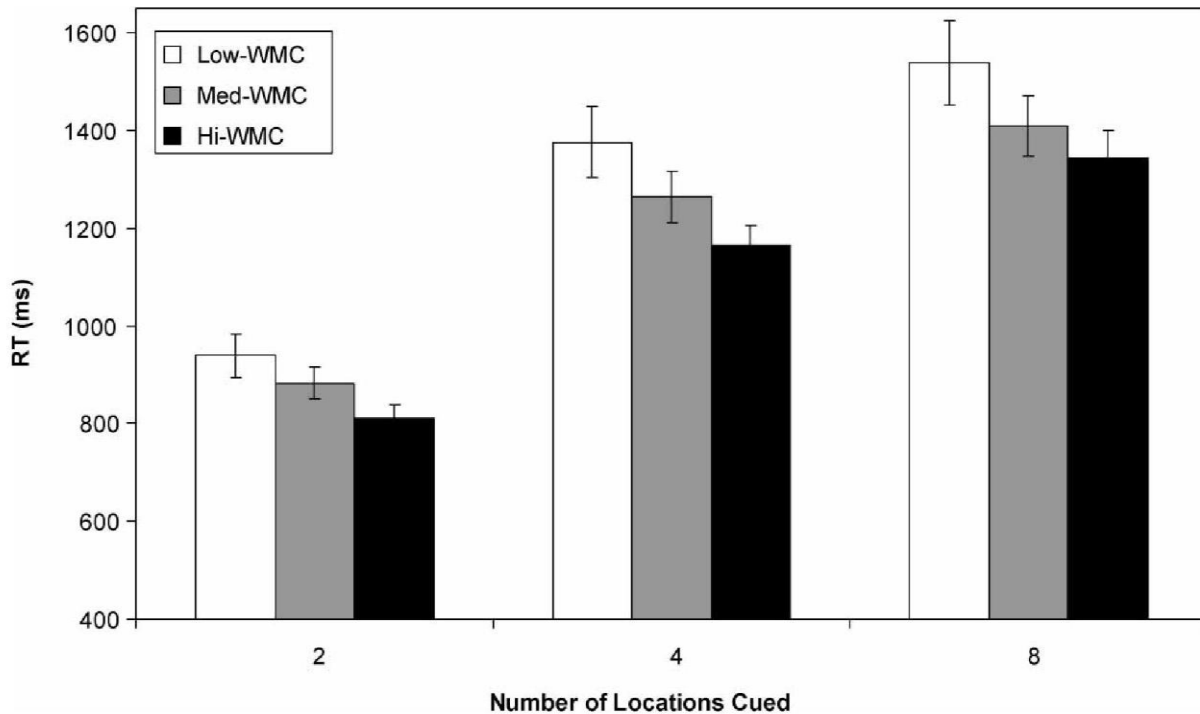


Figure 3. Means of median search reaction times (RTs; in ms) by number of locations cued and WMC group in Experiment 2. Low-WMC = subjects scoring in bottom third of the distribution on the z-score composite working-memory capacity (WMC) measure; med-WMC = subjects scoring in the middle third of the WMC distribution; high-WMC = subjects scoring in the top third of the WMC distribution. Error bars represent standard errors.

Error rates. Table 2 presents mean error rates by WMC and number of locations cued. Error rates were extremely low and did not appear to differ systematically across cells. Nonetheless, repeated measures ANOVA indicated that error rates varied significantly (though not substantially) with the number of locations cued, $F(2, 184) = 5.98$, $MSE = 0.001$, $\eta^2_p = .07$, with an apparently higher rate for 4-location trials ($M = .023$) than for 8-location trials ($M = .011$). An ANCOVA indicated no overall WMC effect on errors, $F < 1$, nor any WMC x Locations Cued interaction, $F(2,182) = 1.63$, $p = .20$.

Table 2. Experiment 2: Mean error rates by working-memory capacity group and number of locations cued

Group	Number of locations cued		
	2	4	8
Low WMC	.013 (.026)	.019 (.040)	.000 (.000)
Medium WMC	.023 (.050)	.029 (.063)	.015 (.035)
High WMC	.015 (.035)	.019 (.048)	.018 (.049)

Note: WMC = working-memory capacity. Standard deviations are reported in parentheses. Low WMC, $n = 31$; medium WMC, $n = 31$; high WMC, $n = 31$.

Discussion

Experiment 2 replicated the Experiment 1 search advantage for higher WMC subjects over lower WMC subjects in noisy displays that required target locations to be searched amid distractor locations. Moreover, the WMC effect here was significant, and the contributions of WMC to performance were equivalent, whether subjects searched through two, four, or eight locations. Task difficulty, as reflected by mean RTs, therefore did not seem to correspond to executive-control demands, as reflected by WMC correlations with performance.

EXPERIMENT 3

Experiment 3 served two main objectives. First, we tested whether WMC predicts constrained visual search only when subjects attempt to split attention among multiple discontinuous locations, as in Experiments 1 and 2 (see also Bleckley et al., 2003), or whether higher WMC subjects might also show an advantage over lower WMC subjects in searching for a target in even a single location that changed from trial to trial. If the dual demand of constraining and splitting attentional focus is necessary to produce a WMC effect in visual search, then we should expect WMC equivalence on trials that cue a single target location.

Second, we assessed whether subjects actually used the target-location cues to proactively constrain their focus to those locations prior to the appearance of the search display. Although we instructed subjects to use the cues in this way, and although we gave them plenty of time to do so (with a 1,500-ms cue-to-stimulus interval, CSI), some subjects may have, instead, only reactively limited their focus to cued locations upon the appearance of the imperative stimuli. Indeed, several theorists have described executive control as involving proactive, sustained processes that work in advance of anticipated conflict and distraction, as well as reactive, tonic processes that work to resolve conflict and distraction only after they have arisen (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Braver, Gray, & Burgess, 2007; Jacoby, Kelley, & McElree, 1999). We have proposed that WMC is related to both of these types of control process (e.g., Engle & Kane, 2004; Kane et al., 2007b), and so the present findings might be accommodated by appeal to either or both mechanisms.

In order to specify how our subjects were accomplishing the search task and where individual differences in WMC were having their effects, we manipulated the time available for subjects to proactively constrain attention to the upcoming target locations. Between trial blocks, subjects either had a 1,550-ms CSI in which to focus their attention on the fixation-dot display (similar to Experiments 1 and 2) or had only a 300-ms CSI. If subjects in Experiments 1 and 2 reactively limited their search to cued locations only after the display appeared, then both CSIs here should yield WMC-related search differences because both CSIs should allow reactive control. If, however, our previous subjects had been engaging in proactive control, and if the locus of the WMC effects was in such proactive control, then we might find a search advantage for higher WMC subjects at only the long CSI, where such proactive control has suitable time to be implemented.

Method

The method was identical to that of Experiment 2 except as noted below.

Subjects

A total of 109 UNCG undergraduates participated as partial fulfillment of a course requirement.

Procedure

As in Experiments 1 and 2, subjects completed WMC and search tasks in two sessions, here separated by a maximum of 91 days.

WMC screening

In contrast to Experiments 1 and 2, here we screened subjects for WMC with automated versions of the OSPAN and RSPAN tasks (Unsworth, Heitz, Schrock, & Engle, 2005). Each task first presented a block of recall practice, with accuracy feedback, in which they saw series of letters to recall in serial order; for the test of each series, subjects saw a screen displaying the full stimulus set of 12 letters and used the computer mouse to click boxes next to the letters to indicate the order in which they appeared. Subjects then practised, with accuracy

feedback, the processing component of the task—verifying equations in OSPAN and judging sentences in RSPAN (by clicking on the word TRUE or FALSE displayed below the item). The program computed the mean time (and SD) to complete the processing items in each task for each subject and used a response deadline of $M + 1 \text{ SD}$ for the processing components of the subsequent OSPAN and RSPAN tasks. In the actual tasks, subjects viewed and judged a processing item before viewing the to-be-remembered letter for 800 ms. If the subject's processing-task response exceeded the deadline, the task continued and counted that trial as a processing error. After a series of 3–7 processing-letter pairs, the recall screen appeared until response. Each task calculated a score for each subject based on the number of memory items (out of 75) recalled in correct serial position, and, as in Experiments 1 and 2, we combined the two span scores into a z-score WMC composite.

Visual search

The basic task differed from that in Experiment 2 by cueing one, two, or eight locations per trial (rather than two, four, or eight), by adding small arrowheads to the symbolic cues to ease comprehension of one-location cues, and by presenting CSIs of either 1,550 or 300 ms, varied between blocks. Each CSI condition presented 64 eight-location trials (2 target types x 8 target locations x 2 lure types x 2 repetitions), 160 two-location trials (2 target types x 2 target locations x 4 cue types x 5 lure locations x 2 lure types), and 64 one-location trials. We over-sampled the 2-cue condition here so that, as in Experiments 1 and 2, the overall task context encouraged discontinuous attentional focus on most trials.

A total of 32 response-mapping practice trials first presented a blank screen for 50 ms, then a fixation display containing dots in all 25 locations for 875 ms, and another blank display for 50 ms; a target display then presented an F or backward F in one of the eight target locations, with all other locations containing dots, until response (with 2 target types x 8 locations x 2 repetitions).

A total of 64 search practice trials preceded 576 experimental trials, divided into two CSI blocks (1,550 vs. 300 ms) of 288 trials each, presented in random order (with 32 practice trials preceding each). CSI order was counterbalanced across subjects. Each search practice and experimental trial followed this sequence: A 500-ms blank screen preceded the 600-ms location cue; a subsequent 50-ms blank screen then preceded the fixation display, which presented dots in all 25 locations. The fixation display appeared for either 1,500 or 250 ms, blocked by CSI condition, followed by a 50-ms blank screen. The search display then appeared and remained onscreen until response.

Results

Subjects

We dropped the data from 6 subjects, 4 with $\geq 25\%$ search errors in any single condition, and 2 due to external disturbances (e.g., fire alarms) during the search session. We thus retained WMC and search data from 103 subjects.

WMC screening

Mean proportion correct for the OSPAN and RSPAN tasks were .679 (SD = .190) and .649 (SD = .199), respectively. The measures correlated at $r = .68$ and the resulting WMC composite was normally distributed (skewness = -0.51 ; kurtosis = -0.56).

Visual search

RTs. Figure 4A (short CSI) and 4B (long CSI) depict mean RTs by WMC group and number of locations cued. Higher WMC subjects outperformed lower WMC subjects with long CSIs, at all levels of cue number, consistent with Experiment 2. In contrast, search rates on short CSI trials did not seem to vary with WMC.

A 2 (CSI: short vs. long) x 3 (cued locations: 1, 2, or 8) repeated measures ANOVA indicated that RTs increased with number of locations cued, $F(2, 204) = 1,512.40$, $MSE = 20,243.87$, $\eta^2_p = .94$, and were longer following long CSIs than short CSIs, $F(1, 102) = 21.15$, $MSE = 24,210.42$, $\eta^2_p = .17$; a significant CSI x Locations Cued interaction seemed to indicate that the difference between long and short CSIs was greatest for

2-cue trials than for 1- and 8-cue trials, $F(2, 204) = 3.80$, $MSE = 3,646.42$, $\eta^2_p = .04$ (although long CSIs yielded significantly longer RTs than did short CSIs for all cued locations; all $t_s > 2.68$). According to an ANCOVA, higher WMC subjects identified targets faster than did lower WMC subjects, $F(1, 101) = 6.51$, $MSE = 104,021.87$, $\eta^2_p = .06$; moreover, this WMC effect was larger following long CSIs than short CSIs, $F(1, 101) = 4.15$, $MSE = 23,486.13$, $\eta^2_p = .04$, and with more locations cued, $F(2, 202) = 6.32$, $MSE = 19,239.55$, $\eta^2_p = .06$ (the three-way interaction was not significant, $F < 1$).

To follow up on these results, we conducted separate ANCOVAs on the long and short CSI conditions. For long CSIs, higher WMC subjects identified targets more quickly than did lower WMC subjects, $F(1, 101) = 9.08$, $MSE = 70,960.75$, $\eta^2_p = .08$, and this WMC difference increased with locations cued, $F(2, 202) = 6.61$, $MSE = 10,731.49$, $\eta^2_p = .06$. The correlations between WMC and search RT did not change across conditions, however ($r_s = -.25, -.24$, and $-.29$, for 1-, 2-, and 8-location trials, respectively; all $p_s < .02$). In parallel to Experiment 2, hierarchical regression predicting 8-cue RTs yielded a nonsignificant WMC effect after accounting for the variance shared with 2- cue RTs ($\Delta R^2 = .01$; $F = 3.05$, $p > .08$). Thus, we again found that increasing the number of possible target locations increased the spread of RTs between higher and lower WMC subjects without significantly affecting the rank ordering of those subjects by WMC.

For short CSIs, in contrast, WMC had no main effect, $F(1,101) = 2.31$, $p = .13$, but WMC interacted with number of locations cued, $F(2, 202) = 4.31$, $MSE = 12,173.99$, $\eta^2_p = .04$. The correlations between WMC and search RT were smaller and nonsignificant here, with $r_s = -.01, -.14$, and $-.18$ for 1-, 2-, and 8-location trials, respectively (all $p_s > .06$). Indeed, after removing one multivariate outlier (by Hadi robust outlier identification; Hadi, 1994), the correlations changed to $r_s = .08, -.04$, and $-.12$ (all $p_s > .23$); likewise, rerunning the ANCOVA for short CSIs after removing this subject now yielded a nonsignificant WMC x Locations Cued interaction, $F(2, 200) = 2.71$, $p = .07$. WMC thus affected search rates only on displays following long CSIs.

As an additional means to test the specificity and strength of this WMC effect at long CSIs, hierarchical regression analyses predicting each long CSI condition RT (1-, 2-, 8-location), found significant WMC effects even after controlling for RT variance in its respective short CSI condition: for 1-location RTs, $\Delta R^2 = .06$; $F = 10.02$, $p < .01$; for 2-location RTs, $\Delta R^2 = .03$; $F = 4.20$, $p < .06$; for 8-location RTs, $\Delta R^2 = .03$; $F = 5.86$, $p < .02$. RTs were reliably measured for both short and long CSI conditions; Cronbach's alpha, calculated from each subject's mean RTs for the 1-, 2-, and 8- locations-cued trials (3 variables), was .78 for short and .85 for long CSI blocks.

Error rates. Table 3 presents mean error rates by WMC group, number of locations cued, and CSI. Though error rates were very low overall, the highest seemed to occur at short CSIs, and with two cued locations, with no obvious effects of WMC. Indeed, a 2 (CSI) x 3 (number of locations cued) repeated measures ANOVA indicated that more errors occurred following short than following long CSIs, $F(1, 102) = 11.58$, $MSE = 0.001$, $\eta^2_p = .10$, and that error rates varied with locations cued, $F(2, 204) = 39.95$, $MSE = 0.00$, $\eta^2_p = .30$; these variables did not interact, $F(2, 204) = 1.17$, $p = .31$. ANCOVA indicated no significant WMC effects (all $F_s < 1.22$, $p_s > .27$).

Discussion

Experiment 3 demonstrated again that, in a task requiring subjects to reconfigure their constrained attentional focus from trial to trial and to sustain that focus over a 1.5-s interval, higher WMC subjects identified targets faster than did lower WMC subjects. Moreover, the high-WMC advantage held whether subjects searched through one, two, or eight potential target locations amid distractors.

The fact that WMC-related differences emerged even on 1-location trials indicates that our previous findings did not depend upon our asking subjects to split their attention across discontinuous locations. It also seems to indicate that WMC did not affect search processes, per se, in these experiments, because WMC's effects were strong even when only a single stimulus, in one cued location, was to be identified.

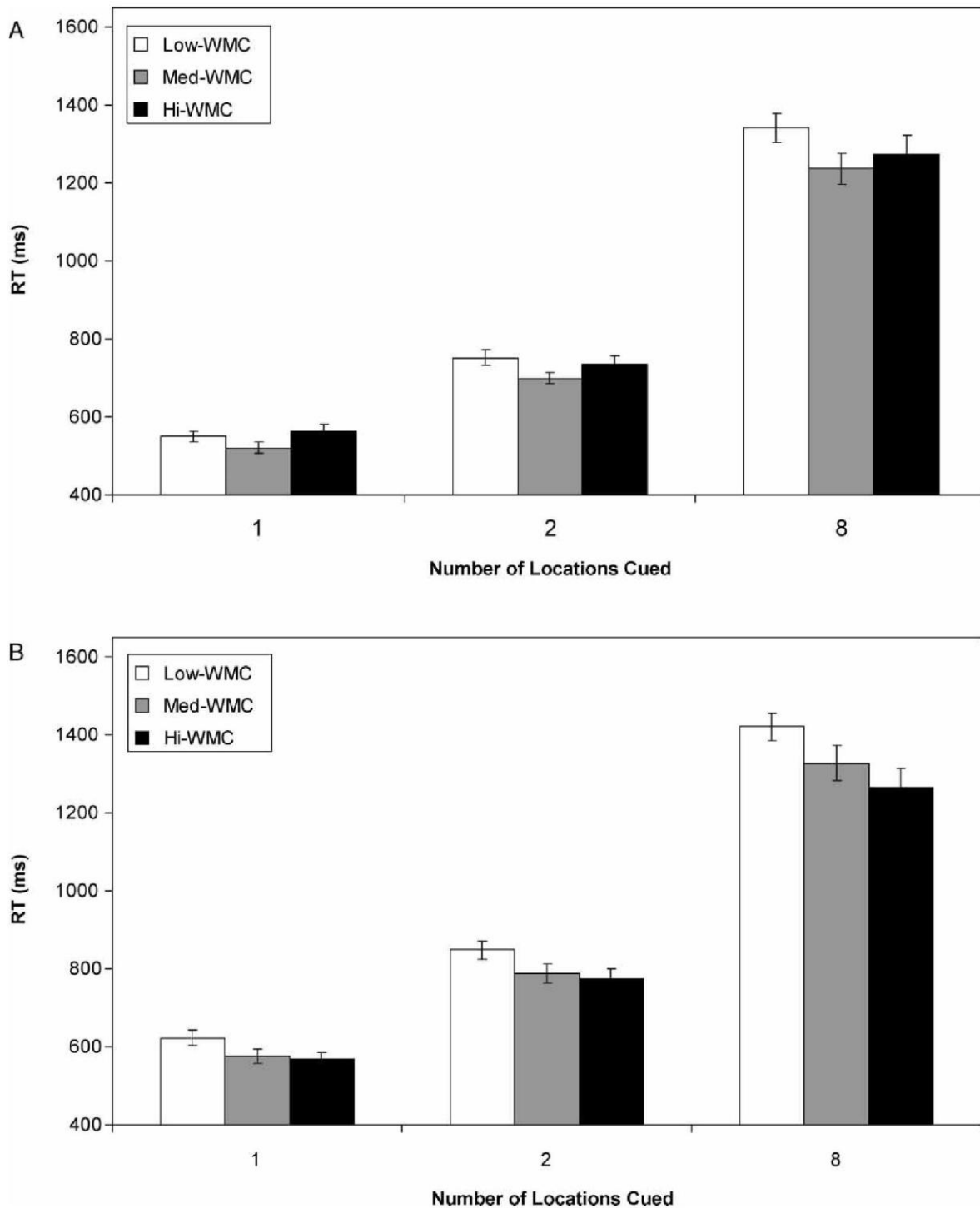


Figure 4. Means of median search reaction times (RTs; in ms) by number of locations cued and WMC group in Experiment 3. Low-WMC = subjects scoring in bottom third of the distribution on the z-score composite working-memory capacity (WMC) measure; med-WMC = subjects scoring in the middle third of the WMC distribution; high-WMC = subjects scoring in the top third of the WMC distribution. Error bars represent standard errors. Panel A depicts RTs from short cue-to-stimulus interval (CSI) trials; Panel B depicts RTs from long CSI trials.

Although ANCOVAs indicated an interaction between WMC and number of locations cued, which might seem to implicate WMC in search rate, follow-up analyses indicated that the locations-cued variable simply increased the mean RT difference between lower and higher WMC subjects without changing the statistical association between WMC and search RT (replicating the findings from Experiment 2). Individual differences in WMC did not account for significantly more variance in 8-location RTs than they did in 1-location RTs, suggesting that

WMC affected similar cognitive processes, in the same ways, across conditions. The consequences of those processing differences for RTs, however, increased with more locations cued. Perhaps this was simply an artifact of the 8-location trials being more difficult than the others, as conditions yielding slower and less accurate performance tend also to yield more between-subject variability (see Cerella, 1985). Or, perhaps, lower WMC subjects' relative difficulty in constraining search resulted in more processing of nontarget items or more accumulation of decision noise when more locations were cued for search (see Pashler, 1997).

Table 3. *Experiment 3: Mean error rates by working-memory capacity group, cue-to-stimulus interval, and number of locations cued*

CSI	Group	Number of locations cued		
		2	4	8
Short: 300 ms	Low WMC	.014 (.019)	.031 (.019)	.021 (.037)
	Medium WMC	.016 (.021)	.037 (.030)	.029 (.035)
	High WMC	.011 (.013)	.026 (.022)	.016 (.035)
Long: 1,550 ms	Low WMC	.008 (.015)	.026 (.026)	.015 (.021)
	Medium WMC	.011 (.012)	.030 (.024)	.013 (.015)
	High WMC	.009 (.011)	.022 (.027)	.012 (.026)

Note: WMC = working-memory capacity. CSI = cue-to-stimulus interval. Standard deviations are reported in parentheses.

In any case, the most important result from Experiment 3 was that WMC-related differences in response latencies were larger in the long than in the short CSI condition: Higher and lower WMC subjects identified targets equally quickly following a short CSI, but higher WMC subjects identified targets more quickly than did lower WMC subjects when the search arrays followed relatively long CSIs; moreover, regression analyses indicated that individual differences in WMC accounted for performance variance in long CSI conditions beyond that captured by short CSI conditions. Although we had assumed that providing a longer CSI would be helpful to subjects, allowing them considerable time to configure and limit their focus to the target locations, it instead increased search latencies overall and seemed to hurt especially the lower WMC subjects. Higher and lower WMC subjects thus seemed equally able to initially establish a limited attentional focus to one, two, or eight locations on each trial (whether they established and maintained that focus proactively during the 300-ms CSI, or instead established it reactively, only after the search array appeared), but only high WMC subjects were able to actively maintain that constrained focus over a significant period of time.

GENERAL DISCUSSION

Three experiments yielded consistent and straightforward results. Individual differences in WMC predicted performance in visual search tasks that asked subjects to maintain a restricted scope of search, to particular stimulus locations in the display while ignoring stimuli in other locations. WMC effects were minimal, however, when all presented stimuli could potentially be the target (i.e., on “clean” trials from Experiment 1), consistent with our previous null WMC findings in prototypical search tasks (Kane et al., 2006). WMC effects were also minimal when subjects were able to conduct their searches very soon after encoding the location cue—that is, when a short CSI eliminated the need to maintain attentional focus over a brief delay (Experiment 3). The emerging picture from these experiments is that higher WMC subjects are better able than lower WMC subjects to proactively maintain a constrained attentional focus in the service of efficient visual search.

But is it “search”?

Although WMC appears to affect the ability to maintain a selective attentional focus in advance of, and during, a nominal visual-search task, our results do not indicate that WMC affects search processes per se. WMC accounted for not only the same amount of variance in target identification RTs across location-cued set sizes (1, 2, 4, and 8) but also the same variance in these RTs, suggesting that increasing the size of the search set does not change the WMC contribution to performance. Whether subjects searched through one or eight cued

locations in order to find the target stimulus, higher WMC subjects identified that target more quickly than did lower WMC subjects. These findings are consistent with our previous null WMC findings in visual search, where lower WMC subjects did not show steeper search slopes over larger set sizes than did higher WMC subjects. Whatever mix of top-down and bottom-up processes are used to guide search through static displays that are typically used in visual search experiments (see Wolfe, 1994), then, they do not seem to rely on the executive processes linked to WMC. Instead, WMC seems to come into play only in search contexts demanding a selective (“constrained”) attentional set.

Indeed, a recent demonstration of WMC related effects on visual search (Sobel, Gerrie, Poole, & Kane, 2007; conducted at about the same time as the current Experiment 3) identified an additional variety of selective attentional focus that is sensitive to WMC. Rather than asking subjects to limit their attention to particular locations in space, we gave subjects the opportunity to constrain their focus to a particularly diagnostic stimulus feature (line orientation) as a means to speed their search. Specifically, Sobel et al. isolated bottom-up and top-down contributions to search by presenting conjunction stimuli (target: red horizontal arrow; distractors: red vertical and green horizontal arrows), where one dimension was highly salient (colour: red vs. green), and the other was highly salient on some trials (orientation: 0° vs. 90° from horizontal) and quite subtle on others (0° vs. 20° from horizontal). All displays presented 21 stimuli, varying in the number of colour versus orientation distractors. Prior research has shown that subjects search along the dimension with the fewer exemplars in a display (e.g., Bacon & Egeth, 1997; Zohary & Hochstein, 1989), and that this is driven by bottom-up, automatic processing of those distinct stimuli; however, when the minority dimension is perceptually nondistinct, such as with subtle orientation differences, subjects will often continue to search on the salient dimension (i.e., colour), no matter how many of these salient items are presented (Sobel & Cave, 2002). We therefore predicted that both higher and lower WMC subjects would show equivalent selective search along the less frequent dimensions in displays with distinct colours and orientations, because performance here is driven by bottom-up processes. They did. However, higher WMC subjects should more effectively use orientation as a search cue when it involves subtle distinctions that do not trigger bottom-up processing. They did, indicating that WMC can affect visual search under conditions requiring that the bottom-up guidance of attention be overridden in favour of goal-directed strategic behaviour, with higher WMC subjects better able to selectively constrain attention to nonsalient stimulus features in their environment among distractors. We must await further research, however, to determine whether feature-based constraint of search (pursued by Sobel et al., 2007) and location-based constraint of search (pursued here) involve identical control mechanisms.

WMC and visual attention constraint

This inference, that higher WMC subjects more effectively limit attentional focus to goal-relevant stimulus locations or dimensions than do lower WMC subjects, is broadly consistent with conclusions drawn from visual-attention tasks not involving search, where only one or two targets must be localized or identified. For example, Heitz and Engle (2007) varied response deadlines in a flanker task and showed that higher WMC subjects reached asymptotic performance before lower spans did. Conditional accuracy functions indicated that subjects began each trial with a broad focus of attention that encompassed more of the flanker array (a central target flanked by four distractors), and that over time subjects narrowed their focus more tightly to the target stimulus within the array. Higher WMC subjects thus seemed to constrain their focus to targets among distractors more rapidly than did lower WMC subjects.

Using a very different procedure, and producing results strikingly close to ours, Bleckley et al. (2003) cued subjects to localize a masked letter appearing on one of three concentric rings while also identifying a masked letter at central fixation (which was internal to all three rings, like a bulls-eye). Subjects saw the word “close”, “medium”, or “distant” and then viewed a bulls-eye fixation display and attempted to split attention between the centre point and the cued ring. Target displays were then presented very briefly (calibrated for each subject) and then pattern masked. Lower WMC subjects accurately localized targets regardless of whether they appeared on the cued ring or on a ring interior to it (the design included invalidly cued trials), indicating that they focused attention as a spotlight surrounding the entire area internal to the cued ring. Higher WMC subjects, in contrast, were less accurate on trials where the target appeared interior to the cued ring, indicating that they effectively

constrained attention to only the cued ring (e.g., Egly & Homa, 1984). Thus, in a task where visual attention had to be fixed to different locations on different trials, higher WMC subjects did so more effectively than lower WMC subjects (for a replication, see Bleckley, 2001).

What may be particularly noteworthy about the Bleckley et al. (2003) method is that both the location cues and the subsequent fixation displays were presented for 2,000 ms, which is quite close to the long CSIs that yielded significant WMC effects in our experiments. In both studies, then, subjects had to maintain a constrained attentional focus over 1–2 s, and so the Bleckley et al. findings may reflect, at least in part, lower WMC subjects' inability to maintain that focus. In fact, a separate study that dramatically changed the trial-sequence dynamics yielded WMC equivalence in performance (Bleckley, 2001). Subjects here received no verbal cue before each trial; instead, the last 350 ms of the fixation display cued the target ring by flashing that ring in colour. Here, as in our short CSI condition (300 ms; Experiment 3), high and low WMC subjects performed equivalently, with low WMC subjects performing more like typical high WMC subjects (i.e., selectively attending to the cued ring and not to the rings internal to it). It seems that the flashing cue, appearing right before the target array, eliminated the WMC effect by eliminating the need to proactively sustain a restricted attentional focus. Again, as in our Experiment 3, lower WMC subjects appear as able as higher WMC subjects to initially establish a constrained attentional set; they simply cannot hold onto it as long as higher WMC subjects can.

Before leaving the topic of WMC and attentional constraint, we should consider whether the present cued-search tasks were essentially variations on the flanker task and, thus, whether our significant WMC effects simply reflected susceptibility to flanker interference (Heitz & Engle, 2007). Recall that we included lure stimuli (Fs and backward Fs) in nontarget locations as a means to require that subjects search only through target locations rather than through the entire array (as in standard visual-search tasks). As noted by an anonymous reviewer, these lures, particularly the one presented within the central 3 x 3 matrix containing the target locations, may have elicited a form of flanker interference. That is, the presence of a target-matching lure may have provided less response conflict (thus allowing shorter response latencies) than the presence of a mismatching lure. We note that flanker interference effects are typically seen in preparations with a single, predictable target location presented amid predictably located distractors (unlike here), with flankers that uniformly conflict with or support the target response (unlike here). Nonetheless, we tested whether any of our RT effects, including those involving WMC, may have reflected flanker-type conflict. We did so by reconducting our analyses to include whether the lure presented in the internal 3 x 3 matrix matched or conflicted with the target.

We found significant experimental effects of lure matches versus mismatches only in Experiments 2 and 3, where lure match interacted only with the number of locations cued (both $F_s > 3.20$, $ps < .05$). In both experiments, follow-up *t* tests indicated that responses to lure-match trials were significantly faster than those to mismatch trials only with 8 locations cued (and, in Experiment 3, only at the long CSI). Here, lure match RTs were 30–40 ms shorter than mismatch RTs (Experiment 2, $M_s = 1,407$ ms vs. 1,449 ms; Experiment 3, long CSI, $M_s = 1,324$ ms vs. 1,354 ms). We cannot currently say whether this lure “flanker” effect was limited to 8-location trials in Experiments 2 and 3 because the lure location was always predictable (it could only appear in the central matrix location) or because the lure was always adjacent to the target (horizontally, vertically, or diagonally).

What we can say is that lure interference had nothing to do with the significant WMC effects we found in Experiments 1–3. WMC neither interacted with lure match (all $F_s < 1$), nor entered into any higher level interactions with it (all $F_s < 1.22$, except for the WMC x Lure Match x Target Location interaction in Experiment 1, where $F < 2.10$, $p > .10$). It may seem surprising that, if WMC is ostensibly related to attention control capabilities, lower WMC subjects were not more vulnerable to distractor lures than were higher WMC subjects. However, the work by Lavie and her colleagues on perceptual load and distractor interference (e.g., Forster & Lavie, 2007; Lavie, 1995; Lavie & Cox, 1997) suggests strongly that lures should have relatively weak effects—and individual differences in lure susceptibility should be reduced or eliminated—on inefficient, high-load search tasks such those we used here (i.e., spatial-configuration search; Huang & Pashler, 2005).

Theoretical approaches to WMC variation

Our main finding, that individual differences in WMC predict individual differences in maintaining selective focus to target stimulus locations among distractor locations, seems inconsistent with theories of WMC variation based on mental processing speed, or the idea that WMC differences arise from individual differences in the speed of low-level, “elementary” cognitive processes (e.g., Hale, Myerson, Emery, Lawrence, & Dufault, 2007; Jensen, 1998; Kail & Salthouse, 1994). If processing speed were primary, and its effects as ubiquitous as is typically claimed, then we would expect to see WMC differences in all of the task conditions studied here, including on clean trials (without distractors; Experiment 1) and on short CSI trials (where search arrays appeared soon after the cue displays; Experiment 3). Speed theories cannot easily account for the fact that WMC differences emerged only on long-CSI noise trials, and not in these other conditions (and not in prototypical visual search tasks; Kane et al., 2006; Sobel et al., 2007).

Our findings do seem, in contrast, broadly consistent with a number of theories suggesting that WMC variation is at least partially due to variation in some attentional or executive-control capabilities (e.g., Barrouillet, Lépine, & Camos, 2008; Braver et al., 2007; Cowan, 2005; Hasher, Lustig, & Zacks, 2007). But the devil is in the details. Our own “executive-attention” view is that WMC variation, and its covariation with higher order cognitive abilities, is driven largely by attention control mechanisms involved in maintaining accessibility to goal-relevant stimulus representations and action plans, actively restraining goal-inappropriate responses and thoughts and actively constraining conscious focus to goal-relevant stimuli in the environment (e.g., Engle & Kane, 2004; Engle et al., 1999; Heitz, Unsworth, & Engle, 2005; Kane et al., 2007b). As we have already noted, our view has evolved through an inductive process of seeking boundary conditions for the relations among WMC and various attentional phenomena. The present results advance this inductive process (and thus challenge our previous conceptions) by suggesting that WMC-related differences in attentional constraint, evident in prior work using both auditory and visual paradigms (Bleckley et al., 2003; Colzato et al., 2007; Conway et al., 2001; Conway et al., 1999; Heitz & Engle, 2007; Redick & Engle, 2006; Sobel et al., 2007), may sometimes depend upon the requirement to actively maintain a selective focus over time. Thus, just as our studies of restraint tasks such as antisaccade and Stroop have suggested that WMC-related differences in withholding inappropriate responses are influenced by differences in actively maintaining access to goal representations (Kane et al., 2001; Kane & Engle, 2003; Unsworth et al., 2004), so too may WMC related differences in limiting processing of distractors be influenced by differences in actively sustaining focus to target locations (or away from distractor locations). Future research should therefore consider whether WMC effects in dichotic listening and flanker paradigms reflect, at least in part (or, at least in some contexts), variation in mechanisms of active maintenance.

Our findings pose some challenge (or opportunity for refinement) for other views of WMC, as well. For example, the inhibitory-deficit theory of WMC holds that attentional mechanisms involved in suppressing the processing of distractor information, deleting no-longer relevant representations from working memory and preventing pre-potent behaviours from being elicited inappropriately, are a critical source of WMC variation and its covariation with higher order cognition (e.g., Hasher et al., 2007; Hasher, Zacks, & May, 1999; Lustig, May, & Hasher, 2001). Considerable data favour this view, including most that also support our executive attention theory (the two theories make many similar predictions; see Kane et al., 2007b, for a discussion). Indeed, nomothetic research indicates that successful performance in location-cueing tasks like the ones we used here depends on the active blocking of items in distractor locations, rather than the enhancement of items in target locations (Awh et al., 2003; Awh & Pashler, 2000; Awh et al., 2005; Doshier & Lu, 2000), and this blocking may be accomplished by inhibitory mechanisms (although that has not yet been settled; see Awh et al., 2003). The only apparent wrinkle here for the inhibitory theory, then, is that WMC did not predict response latencies following short CSIs. A proponent of inhibition might therefore argue either that inhibition is not involved when subjects must search a display after having only 300 ms to fixate on the possible target locations, or that WMC-related deficits in inhibition are only seen when an inhibitory set must be maintained over a longer period. However, the former seems unlikely, given that inhibition is argued to operate in tasks that present targets and distractors simultaneously, without precues (e.g., Lustig, Hasher, & Tonev, 2006; May, 1999; Yang & Hasher, 2007), and the latter seems to indicate that active maintenance may be necessary for

effective inhibition, a view to which we, but not Hasher and colleagues, subscribe (see Hasher et al., 2007; Kane et al., 2007b).

Finally, with respect to attentional views of WMC, Barrouillet, Camos, and their colleagues have argued for a time-based resource-sharing theory (TBRS) that is also at odds with some of the present findings (Barrouillet, Bernadin, & Camos, 2004; Barrouillet, Bernadin, Portrat, Vergauwe, & Camos, 2007; Barrouillet et al., 2008; Lépine, Barrouillet, & Camos, 2005). TBRS theory claims that any attention-demanding, resource-intensive activity will vary with WMC, even fundamental cognitive processes that do not seem to impose significant executive-control requirements. As compelling confirmatory evidence, they have demonstrated significant WMC related differences in quite simple tasks, such as naming digits, adding two single-digit numbers, and subitizing one–four digits (Barrouillet et al., 2008; but see Tuholski et al., 2001). They have also shown that WMC span tasks may interpolate very simple naming, retrieval, or choice tasks between memoranda and account for as much variance in higher order cognitive abilities as do traditional WMC span tasks involving more complex processing. At the same time, TBRS theory cannot easily explain why WMC does not predict target identification latencies in clean search trials (see also Kane et al., 2006; Sobel et al., 2007) or in noise trials following short CSIs. Surely, visual search for a target among numerous physically similar nontargets and distractors involves some variety of attention- or resource-intensive processes (Desimone & Duncan, 1995; Treisman & Sato, 1990; Wolfe, 1994). The challenge for TBRS theory, then, as it is for our executive attention view, is to determine the nature of those processes that do, versus do not, vary with WMC (see also Barrouillet et al., 2008). To date, their work suggests that WMC variation is linked to “attention” tasks demanding simple memory retrieval, and ours suggests that WMC variation is not linked to “attention” tasks requiring the movement of visual focus over potentially relevant target locations in order to make a choice response (i.e., whether a target is present or absent, or which of two target types is present). Our two views have yet to converge on the precise nature of the WMC–attention association, but continued work along these lines holds considerable promise.

Before ending our discussion of WMC theories, we must take note of how a recent nonattentional view might accommodate the present findings. Oberauer and colleagues propose that WMC variation reflects primarily the ability to create, maintain, and dissolve temporary mental bindings among a limited number of independently activated representations within a cognitive coordinate system, as in binding visual objects to spatial locations, auditory stimuli to temporal sequences, and abstract concepts to schematic roles, or in mapping novel responses to particular stimuli (e.g., Oberauer, 2005; Oberauer et al., 2007; Wilhelm & Oberauer, 2006). One strength of this view is that such relational integration seems important not only to prototypical WMC tasks, but also to the fluid-reasoning and attention-control tasks that WMC variation predicts so well. In contrast, attentional theories of WMC have yet to posit specific hypotheses about how the attention control mechanisms that are associated with WMC actually contribute to higher order cognitive capabilities, especially where restraint of habitual responses or constraint of attentional focus against distraction are not obviously relevant.

That said, we interpret the present findings to both conflict with and support the binding theory of WMC. A difficulty for the binding view is that, as in our previous visual search studies (Kane et al., 2006; Sobel et al., 2007), we find no evidence for WMC-related difficulties in establishing, maintaining, or implementing novel response mappings. Higher and lower WMC subjects performed equivalently in tasks requiring that an arbitrary association be made between left/right key-presses and target present/absent or forwardF/backward-F decisions, as indicated by our clean trials in Experiment 1 and short CSI trials in Experiment 3. We suggest that prior research indicating WMC-related differences in stimulus–response mapping during choice RT tasks (Wilhelm & Oberauer, 2006) actually used incompatible mappings that elicited considerable response conflict, rather than truly arbitrary mappings, and thus elicited contributions of executive-attention mechanisms to resolve the conflict.

Our main results, however, appear to support a version of the binding view: Higher WMC subjects were better able than lower WMC subjects to maintain selective focus to target locations among distractor locations over a 1,500-ms delay. If one allows that successful performance in our long CSI condition required a sort of binding

between cued target locations and the locations' status as a to-be-searched target versus a to-be-ignored distractor, then our findings suggest that higher WMC subjects better maintained those bindings (which were, perhaps, equivalently established regardless of WMC, based on the short CSI data). Indeed, previous research has suggested that subjects learn to associate different stimulus locations with different probabilities of seeing distractor noise (Awh et al., 2003, 2005), and that subjects may establish and retrieve episodic associations between targets, distractors, and their locations (Neill, Valdes, Terry, & Gorfein, 1992). It thus seems reasonable to entertain that subjects can flexibly bind stimulus locations to different goals (e.g., "search there" vs. "don't search there") or to different probabilities of reinforcement (e.g., "likely target location" vs. "unlikely target location") and maintain them over time with varying degrees of success. From our perspective, though, arguing for WMC-related variation in the maintenance of location-goal or location-reinforcement bindings is empirically indistinguishable from our arguing for WMC related variation in the maintenance of selective, focal attention to target locations.

CONCLUSIONS

Although individual differences in WMC, as measured by complex span tasks, have been associated with a variety of attention-control capabilities, principally in restraining strong but inappropriate responses and in constraining conscious focus against distractors, it has not been associated with prototypical visual search. Here, in three experiments, we demonstrate that WMC variation does predict search latencies when target locations that are cued for search are interspersed among distractor locations. At least, WMC predicts search here when subjects must maintain their focus on those cued target locations over a brief delay. In the absence of distractors to be avoided, or a delay between cues and targets, higher and lower WMC subjects performed equivalently. Our findings thus suggest that higher and lower WMC subjects can initially engage a selective visual focus equally well, but also that lower WMC subjects cannot as effectively maintain that selective focus over time.

Notes:

¹ For a methodological discussion of individual-differences and developmental research producing similar discrepancies between ANOVA-based interactions on one hand and correlation- or regression-based results on the other hand, see Salthouse (2000).

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