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Individual Differences in Working Memory Capacity Predict Learned Control Over Attentional Capture

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Although individual differences in working memory capacity (WMC) typically predict susceptibility to attentional capture in various paradigms (e.g., Stroop, antisaccade, flankers), it sometimes fails to correlate with the magnitude of attentional capture effects in visual search (e.g., Stokes, 2016), which is 1 of the most frequently studied tasks to study capture (Theeuwes, 2010). But some studies have shown that search modes can mitigate the effects of attentional capture (Leber & Egeth, 2006). Therefore, the present study examined whether or not the relationship between WMC and attentional capture changes as a function of the search modes available. In Experiment 1, WMC was unrelated to attentional capture, but only 1 search mode (singleton-detection) could be employed. In Experiment 2, greater WMC predicted smaller attentional capture effects, but only when multiple search modes (feature-search and singleton-detection) could be employed. Importantly this relationship was entirely independent of variation in attention control, which suggests that this effect is driven by WMC-related long-term memory differences (Cosman & Vecera, 2013a, 2013b). The present set of findings help to further our understanding of the nuanced ways in which memory and attention interact.

Public Significance Statement
As we go through our daily lives, an abundance of information is competing for our attention: the nasty driving conditions, the radio advertisement, the unhappy toddler in the backseat. One of the hallmarks of the human cognitive system is its ability to devote attention to the most relevant information on a moment-to-moment basis. The present study leveraged individual differences to examine how we can learn to avoid having our attention captured by irrelevant information in the environment. In our cognitive system, memory and attention play fascinatingly interconnected roles. Our results show that the ability to develop and use memories that can help our attention operate in future situations is an important component of a well-functioning cognitive system.

Keywords: working memory, attention control, attentional capture, visual search

Although working memory capacity (WMC) and attention control (AC) have important relations when it comes to individual differences in cognitive abilities (Engle, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Unsworth, Fukuda, Awh, & Vogel, 2014), the relations among WMC, AC, and susceptibility to attentional capture are rather ambiguous. Theoretically, individuals with greater WMC, who also tend to have better control over their attention, should be more resistant to attentional capture. Evidence consistent with this notion comes from various paradigms showing that individuals with greater WMC are more resistant to Stroop interference (Kane & Engle, 2003), show greater accuracy on the antisaccade task (Kane, Bleckley, Conway, & Engle, 2001), are less susceptible to auditory capture in dichotic listening (Conway, Cowan, & Bunting, 2001), and are more flexible in selective-attention tasks (Bleckley, Durso, Crutchfield, Engle, & Khanna, 2003). At the latent level, WMC and AC share about 30%–50% of their variance (Kane et al., 2016; McVay & Kane, 2012; Unsworth & Spillers, 2010; Unsworth et al., 2014).

The covariance between WMC and AC is theoretically driven by an executive-attention ability that allows individuals to keep task goals active in mind and avoid the intrusion of irrelevant internal or external information. Therefore, it follows from this conceptualization that individuals with greater WMC should show less susceptibility to attentional capture. Specifically, within the executive-attention view, WMC should predict attentional capture due to its covariance with AC. In other words, AC should mediate the WMC-capture relationship. However, the relationship between WMC and capture may be specific to instances in which there is some conflict or prepotent response to overcome (Conway & Kane, 2001), and not all sources of conflict are related to WMC (Meier & Kane, 2015). Further, it is important to note that WMC is not related to all manifestations of goal-directed external attention. For example, when completing the Stroop task, individual differences in WMC only predict resistance to Stroop interference when there is a relatively high proportion of congruent trials (Kane & Engle, 2003). When there is an equal proportion of congruent

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and incongruent trials, high- and low-WMC individuals perform about equally (Kane & Engle, 2003). Similarly, although accuracy on the antisaccade task is correlated with WMC, there is no relationship between WMC and performance on the prosaccade task (Kane et al., 2001). Finally, the relationship between WMC and speed on tasks like psychomotor vigilance is driven by differences in the slowest trials, indicating that generally high- and low-WMC individuals perform about equally, but that low-WMC individuals experience more frequent lapses that result in long response times (Unsworth, Redick, Lakey, & Young, 2010). Together, this evidence suggests that WMC is specifically related to AC when individuals must maintain a specific task goal in mind. Any deviation of attention away from this goal from irrelevant internal or external information will cause worse performance, and this is when WMC-related differences generally arise (Kane & Engle, 2003).

When specifically examining the WMC-attentional capture relationship, various studies have shown that high-WMC individuals are less likely to involuntarily orient attention to irrelevant information (Fukuda & Vogel, 2009) and take less time to recover from attentional capture (Fukuda & Vogel, 2011). Another reason to expect individual differences in WMC to predict reduced capture is the effect of working memory load on capture. Several studies have shown that when working memory is burdened, especially visual and spatial working memory, attentional capture effects increase (e.g., Burnham, Sabia, & Langan, 2014; Lavie & de Fockert, 2005). The conclusion from these studies is that working memory is required to exert control over attentional capture. Thus, it follows that individuals with greater WMC should be able to exert more resistance to capture. But given this evidence, recent examinations of the relationships among traditional measures of WMC, AC, and attentional capture have been less conclusive. Specifically, Stokes (2016) systematically examined several types of attention capture using well-established paradigms (e.g., temporal visual search, contingent spatial visual search, noncontingent spatial visual search, and involuntary spatial orienting) and found no relationship between operation span scores and the magnitude of attentional capture effects. Although the capture effects in the above-mentioned paradigms were reliable both within and across sessions, they did not correlate with one another (Stokes, 2016). A common assumption within the executive-attention account of WMC is that individuals with lower WMC will be more susceptible to irrelevant internal or external information that interferes with the current task goal (Conway & Kane, 2001; Engle, 2002; Kane & Engle, 2003). But Stokes (2016) showed that there may be little shared variance between WMC and attentional capture.

In addition to executive-attention abilities, another manner in which attentional capture may be mitigated is by top–down task approaches and strategic dynamics. For example, Leber and Egeth (2006) attempted to resolve some outstanding issues by inducing individuals to use specific search modes. Specifically, Leber and Egeth (2006) had two groups of participants each complete two different visual search tasks. In one condition, the task and instructions induced a singleton-detection mode. In the other condition, the task and instructions induced a feature-search mode. After a training session using these two tasks between conditions, all participants completed a testing session in which the task was identical between conditions. The testing session's task contained color singletons in some trials to create attentional capture. The critical finding showed that only participants in the singleton-training condition showed attentional capture during the testing session. Participants who had been using a feature-search mode during the training session carried this strategy over into the testing session. Therefore, the color singletons had no effect on their response times. Their top–down search strategy settings made them resistant to attentional capture. These results suggest that strategic approaches to a task can effectively eliminate attentional capture effects.

Recently, Cosman and Vecera (2013a, 2013b) used this same method to examine the role of long-term memory in guiding attention control. In one experiment, Cosman and Vecera (2013a) included irrelevant contextual features (background scenes) during the training task and associated these scenes with specific attentional sets (i.e., singleton-detection vs. feature-search). During the testing session, participants tended to adopt the search mode associated with the irrelevant contextual feature. When the encountered background was associated with the singleton-detection task during training, participants tended to show capture. When the encountered background was associated with the feature-search task during training, participants did not show capture (Cosman & Vecera, 2013a). These results suggest that as individuals learn a task, the contextual features of the task are rather automatically encoded in a long-term memory representation of the attentional set. When the task is encountered again the future, these contextual features activate particular attentional sets (Cosman & Vecera, 2013a; Leber & Egeth, 2006; Leber, Kawahara, & Gabari, 2009).

In a separate study, Cosman and Vecera (2013b) had individuals with damage to the medial-temporal lobe and healthy controls complete a training session and a testing session separated by a 5-min break. During the training session, participants completed a search task in which they identified a target circle among a heterogeneous set of nontarget shapes. On half of trials, one of the nontarget shapes was a different color. This task induces participants to employ a feature-search mode (i.e., "find the circle"), and participants are generally resistant to attentional capture from the color singletons when using this mode (Bacon & Egeth, 1994). During the testing session, participants completed the same task with the subtle change that the search array comprised a homogenous set of nontargets. Again, on half of trials, one of the nontargets was a different color than all other items. When completed in isolation, this task usually produces an attentional capture effect, as participants tend to employ a singleton-detection mode (Kawahara, 2010; Theeuwes, 1992, 2010). But when preceded by a task utilizing a feature-search mode, attentional capture effects are not observed (Leber & Egeth, 2006). Critically, only the amnesic individuals showed attentional capture during the testing session. This finding demonstrated that the amnesic individuals did not carry over the feature-search mode from the training session to the testing session. The healthy controls did carry over the feature-search mode, and this eliminated the capture effect. Therefore, not only can attentional capture be driven by differences in attention control, long-term memory plays a role in establishing and executing effective search modes. In addition to its relationship with AC, WMC also predicts long-term memory abilities (Rosen & Engle, 1997; Unsworth & Engle, 2007; Unsworth & Spillers, 2010). Therefore, we may observe WMC-related differences in attentional capture not because low-WMC individuals have poor AC, but rather because they do not effectively develop and employ search strategies, as was the case with individuals with medial-temporal lobe damage (Cosman & Vecera, 2013b).

Although the singleton-detection and feature-search strategies may be induced by various task parameters, Kawahara (2010) demonstrated that individuals may have little conscious control over their search mode (Cosman & Vecera, 2013a). When given no specific task instructions, people tend to adopt a singleton-detection mode, as this may be a more parsimonious approach to the task. Additionally, even when people explicitly state that they are using a feature-search mode, their behavior reflects a singleton-detection mode (Kawahara, 2010). However, Kawahara (2010) notes that the ability to control search in a top–down manner may be influenced by individual differences in cognitive abilities. So although singleton-detection may be the default mode of search into which people tend to fall given visual search tasks, individuals with greater WMC may be able to maintain and execute a feature-search mode given their superior cognitive abilities. Within the classic visual search tasks used to study attentional capture (see Theeuwes, 2010, for review), distractor trials are typically included on 50% of trials. Therefore, half the time the singleton-detection mode is a perfectly effective means of completing the task. In fact, it may be the only means of completing the task (e.g., “find the unique shape”). So low-WMC individuals may adopt this search mode, consciously or unconsciously, because it is effective at least half the time.

The present investigation attempted to resolve some discrepancies in the literature by examining individual differences in top–down strategic task approaches and their relationship with WMC. Some prior investigations have shown that high-WMC individuals tend to be more strategic in their approaches to various tasks (Bailey, Dunlosky, & Kane, 2008; Robison & Unsworth, 2017; Turley-Ames & Whitfield, 2003; Unsworth, 2016), and this partially explains why they tend to perform better on these tasks. So in addition to long-term memory abilities, strategic advantages among high-WMC individuals may make them more resistant to attentional capture.

In general, the present study sought to identify and explain several ways in which attention and memory interact. In doing so, we attempted to answer several questions. When there is only one employable search strategy, will WMC predict reduced susceptibility to attentional capture? Subsequently, when a particular search strategy can be employed to eliminate capture, will participants learn this strategy and carry it forward to similar tasks? If so, will this carry-over effect differ as a function of WMC? Not only will the present set of experiments better inform how typical measurements of WMC and AC predict attentional capture, it will further examine how long-term memory mechanisms may be employed to adjust AC settings to meet current task demands. Because WMC involves both AC and long-term memory systems, we can leverage individual differences to examine how individuals form and employ learned control over capture.

Experiment 1

The aim of Experiment 1 was to examine the relation between WMC, AC, and attentional capture effects in a visual search task. The task induced a singleton-detection mode. A negative relationship between WMC and the magnitude of attentional capture effects would be consistent with the idea that individuals with greater WMC are less susceptible to attentional capture (Fukuda & Vogel, 2009), or take a shorter time to recover from attentional capture (Fukuda & Vogel, 2011). Furthermore, if AC mediates the relationship between WMC and attentional capture, this would suggest that differences are due to the executive-attention component of WMC. A null relationship between WMC and attentional capture would be consistent with the finding that these two abilities (or susceptibilities) are rather distinct (Stokes, 2016). If this is the case, it would suggest that the singleton-detection mode employed in the current task does not require significant goal maintenance. The goal in this case is to find the unique shape, and any failures to maintain that goal may result in longer response times, but not necessarily larger attentional capture effects. The goal is to employ the singleton-detection mode, and any capture effects caused by the presence of color singletons may simply be a consequence of searching in this mode. For that reason, we may observe no relationship between WMC and attentional capture. We selected measures of WMC and AC based on prior individual differences investigations of these constructs (Kane et al., 2001, 2016; Kane & Engle, 2003; Robison, Gath, & Unsworth, 2017; Unsworth & McMillan, 2014; Unsworth & Spillers, 2010; Unsworth et al., 2014).

Method

Participants and procedure. A total of 170 participants were recruited from the University of Oregon human subjects pool. Participants first completed three measures of WMC followed by three measures of AC and a visual search task. At the end of the tasks, participants completed a brief personality questionnaire (John, Naumann, & Soto, 2008). In total the session lasted about 1.5 hours. One participant was excluded from the final analyses because of high errors on the complex span tasks. Another 24 participants were excluded for accuracy at or below chance on the visual search task, which indicated they did not understand the task instructions. Because of computer errors, not all participants had data for all tasks. One participant was excluded from the analysis because of extremely long average RTs in the psychomotor vigilance task. This left a final sample of 137 participants. All participants were treated ethically according to the guidelines of the American Psychological Association and the protocol was approved by the Institutional Review Board of the University of Oregon.

Tasks All participants completed three complex span working memory tasks, three measures of attention control, and one attentional capture task. Every participant completed the tasks in the same order (as listed below).

Operation span. In this task, participants solved a series of math operations while trying to remember a set of unrelated letters. Participants were required to solve a math operation, and after solving the operation, they were presented with a letter for 1 s. Immediately after the letter was presented the next operation was presented. At recall participants were asked to recall letters from the current set in the correct order by clicking on the appropriate letters. For all of the span measures, items were scored correct if the item was recalled correctly from the current list in the correct serial position. Participants were given practice on the operations and letter recall tasks only, as well as two practice lists of the complex, combined task. List length varied randomly from three to seven items, and there were two lists of each length for a total possible score of 50. The score was total number of correctly recalled items in the correct serial position.

Symmetry span. Participants recalled sequences of red squares within a matrix while performing a symmetry-judgment task. In the symmetry-judgment task, participants were shown an 8 × 8 matrix with some squares filled in black. Participants decided whether the design was symmetrical about its vertical axis. The pattern was symmetrical half of the time. Immediately after determining whether the pattern was symmetrical, participants were presented with a 4 × 4 matrix with one of the cells filled in red for 650 ms. At recall, participants recalled the sequence of red-square locations by clicking on the cells of an empty matrix. Participants were given practice on the symmetry-judgment and square recall task as well as two practice lists of the combined task. List length varied randomly from two to five items, and there were two lists of each length for a total possible score of 28. We used the same scoring procedure as we used in the operation span task.

Reading span. While trying to remember an unrelated set of letters, participants were required to read a sentence and indicated whether or not it made sense. Half of the sentences made sense, and the other half did not. Nonsense sentences were created by changing one word in an otherwise normal sentence. After participants gave their response, they were presented with a letter for 1 s. At recall, participants were asked to recall letters from the current set in the correct order by clicking on the appropriate letters. Participants were given practice on the sentence judgment task and the letter recall task, as well as two practice lists of the combined task. List length varied randomly from three to seven items, and there were two lists of each length for a total possible score of 50. We used the same scoring procedure as we used in the operation span and symmetry span tasks. For graphical depictions of each complex span task, see Redick et al. (2012).

Psychomotor vigilance. The psychomotor vigilance task (Dinges & Powell, 1985) was used as the primary measure of sustained attention. Participants were presented with a row of zeros on screen and after a variable amount of time the zeros began to count up in 1-ms intervals from 0 ms. The participants' task was to press the spacebar as quickly as possible once the numbers started counting up. After pressing the space bar the response time was left on screen for 1 s to provide feedback to the participants. Interstimulus intervals were randomly distributed and ranged from 2 s to 10 s. The entire task lasted for 10 min for each individual (roughly 75 total trials). The dependent variable was the mean reaction time (RT) for the slowest 20% of trials. Thought probes were randomly presented after 20% of trials.

Antisaccade. In this task (Kane et al., 2001) participants were instructed to stare at a fixation point which was onscreen for a variable amount of time (200–2,200 ms). A white equals sign ("=") was then flashed either to the left or right of fixation (11.33° of visual angle) for 100 ms, followed by a 50-ms blank screen, then reappearing for another 100 ms. After a 50-ms blank interval, the target stimulus (a *B*, *P*, or *R*) appeared onscreen for 100 ms. This was followed by masking stimuli (an *H* for 50 ms followed by an 8 which remained onscreen until a response was given). The participants' task was to identify the target letter by pressing a key for *B*, *P*, or *R* (the keys *4*, *5*, or *6*) as quickly and accurately as possible. In the prosaccade condition the flashing cue (=) and the target appeared in the same location. In the antisaccade condition the target appeared in the opposite location as the flashing cue. Participants received, in order, 10 practice trials to learn the response mapping, 15 trials of the prosaccade condition, and 60 trials of the antisaccade condition. The dependent variable was proportion correct on the antisaccade trials. Thought probes were randomly presented after 17% of trials.

Stroop. In a computerized color-word Stroop task (Stroop, 1935) participants were presented with a color word (red, green, or blue) presented in one of three different font colors (red, green, or blue). The participants' task was to indicate the font color via key press (red = 1, green = 2, blue = 3). Participants were told to press the corresponding key as quickly and accurately as possible. Participants received 15 trials of response mapping practice and 6 trials of practice with the real task. Participants then received 100 experimental trials. Of these Trials 67% were congruent such that the word and the font color matched (i.e., red printed in red) and the other 33% were incongruent (i.e., red printed in green). The dependent variable was the mean RT for accurate incongruent trials. Thought probes were randomly presented after 36% of incongruent trials.

Visual search. This task was modeled after typical attention capture tasks (Bacon & Egeth, 1994; Theeuwes, 1992). Each trial began with a 1,000-ms fixation screen in which a white dot appeared at the center of a black background. Six items then appeared around an invisible circle. Participants were instructed to find the unique shape (either a diamond or a circle) among a homogenous set of nontargets (all circles or all diamonds) and to report whether a line inside the shape was slanting to the right or left (see Figure 1). Participants made their response by pressing one of two keys labeled *L* and *R* on the keyboard (the */* and *Z* keys). The search array remained on-screen until the participant made a response. On half of trials, one of the nontargets was a different color (red, green, blue, or yellow) from all other items, which were always white. Trial types were randomly intermixed. Participants were instructed that the color singletons would appear on some trials and that they should do their best to ignore this item, as it would never be the target. The color singleton was equally likely to be adjacent to the target, two items away, or across the array from the target. Participants completed 10 practice trials with feedback prior to completing 144 scored trials without feedback. Thought probes were presented after 15 trials. The dependent variable for the visual search task was the mean RT after trimming extremely short (<200 ms) and extremely long (>3,000 ms) RTs

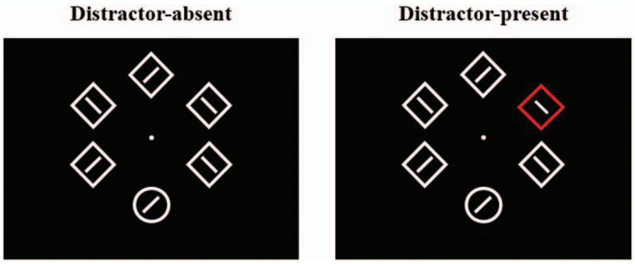

Figure 1. Trial types for Experiment 1. On distractor-present trials, the color singleton could be red, yellow, blue, or green, and located at any of the five nontarget locations. See the online article for the color version of this figure.

for each trial type. After removing inaccurate and extremely long and short RTs, we averaged each participant's RTs for each trial type.

Thought probes. Although they were not the focus of the present investigation, thought probes were included in the psychomotor vigilance, antisaccade, Stroop, and visual search tasks. Randomly after a certain percentage of trials (listed for each task above), thought probes would appear asking participants to report the current contents of their consciousness. Specifically, they saw a screen that said, "Please characterize your current conscious experience." Possible responses were (a) I am totally focused on the current task, (b) I am thinking about my performance on the task, (c) I am distracted by sights/sounds/physical sensations, (d) I am thinking about things unrelated to the task, which are positive in nature, (e) I am thinking about things unrelated to the task, which are negative in nature, and (f) I am not very alert/my mind is blank. Participants responded by pressing the appropriate key on the keyboard. These thought probes were included as part of a separate investigation involving mind-wandering and personality, and therefore we did not analyze those responses in the present study.

Results

Descriptive statistics and zero-order correlations among the WMC and AC measures are shown in Table 1. Descriptive statistics and correlations for the WMC and AC factors, as well as the various trial types in the visual search task are shown in Table 2. Data are only reported for the final sample of participants (N = 137). Scores on the three complex span working memory measures were entered into a factor analysis using principal axis factoring and factor scores were saved for each participant.[1] This single score is used in all subsequent analyses involving WMC. Accuracy on the antisaccade task, mean RTs for incongruent trials on the Stroop task, and the mean of the slowest 20% of trials on the psychomotor vigilance task were entered into a factor analysis using the same method.[2] These factors significantly correlated, $r = .31$, $p < .001$. After eliminating participants who performed at or near chance (~50% accuracy), mean accuracy was high across all trial types (95%, 94%, 95%, and 93% for distractor-absent, near-distractor, two-away-distractor, and across-distractor trials, respectively).

Table 1
Descriptive Statistics for WMC and AC Measures

Measure	1	2	3	4	5	6
1. OSpan	—					
2. SymSpan	.37*	—				
3. RSpan	.59*	.30*	—			
4. PVT	−.08	−.23*	−.13	—		
5. Antisaccade	.21*	.26*	.12	−.32*	—	
6. Stroop	−.35*	−.26*	−.13	.28*	−.31*	—
M	38.22	19.72	37.53	503	0.48	845
SD	8.43	5.03	8.55	101	0.14	156
Skew	−1.02	−0.68	−0.78	1.72	0.42	0.98
Kurtosis	1.37	0.34	0.23	4.75	−0.69	1.98
Reliability	.71	.65	.70	.93	.75	.85

Note. N = 137. Reliabilities for the operation span, symmetry span, and reading span tasks were computed as a Cronbach's alpha using mean accuracy for each set size. Reliabilities for psychomotor vigilance, antisaccade, and Stroop were computed using Spearman–Brown split-half coefficients. OSpan = operation span; SymSpan = Symmetry Span; RSpan = reading span; PVT = psychomotor vigilance.
* $p < .05$.

Table 2
Descriptive Statistics and Correlations for Factors and Visual Search in Experiment 1

Measure	1	2	3	4	5	6
1. WMC factor	—					
2. AC factor	.31*	—				
3. Absent RT	−.17*	−.52*	—			
4. Near RT	−.15	−.44*	.84*	—		
5. Two Away RT	−.18**	−.42*	.86*	.87*	—	
6. Across RT	−.17*	−.53*	.88*	.86*	.87*	—
M	.00	.00	1,122	1,254	1,222	1,188
SD	.89	.75	264	309	295	292
Skew	−1.01	−0.23	0.60	0.51	0.54	0.51
Kurtosis	1.07	−0.06	−0.34	−0.25	−0.03	−0.14
Reliability	—	—	.92	.86	.88	.90

Note. N = 137. Reliabilities were computed using Spearman–Brown split-half coefficients. RT = reaction time; WMC = working memory capacity; AC = attention control; Absent = mean RT for distractor-absent trials; Near = mean RT for trials with a singleton distractor adjacent to the target; Two Away = mean RT for trials with a singleton distractor two locations from the target; Across = mean RT for trials with a singleton distractor three locations (across the array) from the target.

For the visual search task, we excluded trials with RTs longer than 3,000 ms or shorter than 200 ms (3% of trials). These cutoffs were determined by referring to prior studies with similar measures (e.g., Folk, Remington, & Johnston, 1992; Theeuwes, 1992; Bacon & Egeth, 1994).[3] We entered RTs into a repeated measures analysis of variance (ANOVA) with color (red, yellow, green, blue) and distractor location (absent, near, two away, across) as within-subjects factors. Because there was no main effect of distractor color on RTs ($F < 1$), we collapsed across all distractor colors. There was a main effect of distractor type such that RTs were shortest for distractor-absent trials and progressively lengthened as the distractor approached the target location, $F(3, 408) = 36.37$, $p < .001$, partial $\eta^2 = 0.21$. Bonferroni-corrected follow-up comparisons indicated that distractor-absent trials were significantly faster than all other trials (all ps $< .001$). Near-distractor trials and two-away distractor trials were not significantly different ($p = .11$). Distractor trials in which the singleton was across the array from the target were significantly faster than near-distractor ($p < .001$) and marginally faster than two-away-distractor trials ($p = .059$).

Adding WMC and AC as covariates to the model revealed a main effect of AC, $F(1, 134) = 39.51$, $p < .001$, partial $\eta^2 = .23$,

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[1] Factor loadings for operation span, symmetry span, and reading span on the WMC factor were 0.85, 0.43, and 0.69, respectively.

[2] Factor loadings antisaccade, Stroop, and psychomotor vigilance on the AC factor were .59, −.54, and −.52, respectively.

[3] RTs can also be trimmed by computing each participant's mean and standard deviation and eliminating any trials that fall +/− three SDs away from the mean. We also performed this procedure and reran all analyses for Experiments 1 and 2 and produced identical patterns of findings. Therefore, we only report analyses using the trimming procedure described above.

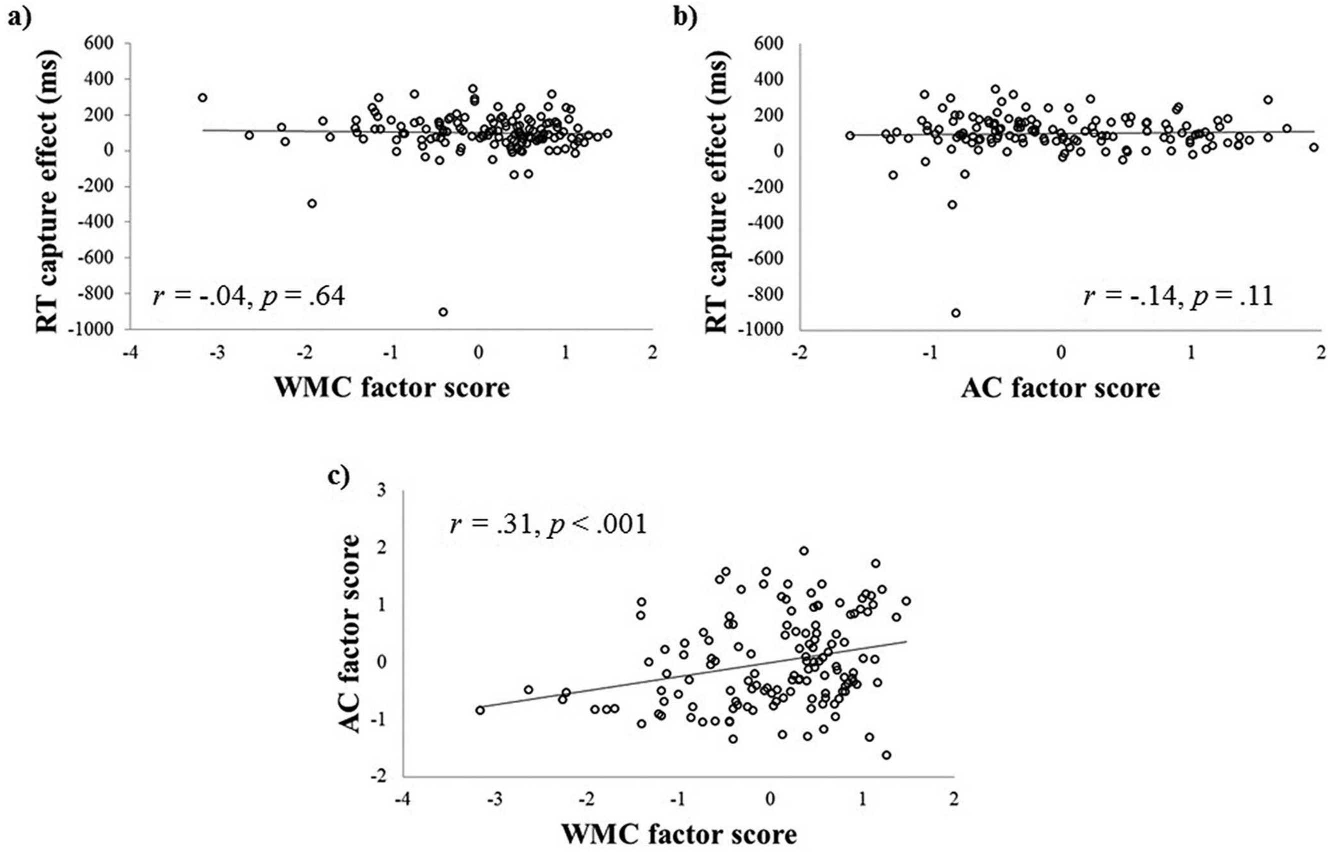

Figure 2. Scatterplots showing relationships between (a) working memory capacity (WMC) and capture effects, (b) attention control (AC) and capture effects, and (c) WMC and AC.

such that individuals with better AC tended to have shorter RTs overall ($r = -.50$). WMC also correlated with shorter RTs, $r = -.18$, $p = .02$, but the main effect of WMC was not significant ($F < 1$). So this effect was primarily driven by AC. Importantly, neither WMC nor AC interacted with the effect of trial-type (both Fs < 2). Therefore, AC and WMC did not offer a specific advantage on distractor-present trials. We also computed capture effects at each of the three target-distractor distances by subtracting each participant's mean distractor-absent trial RT from the mean RT of the other three trial types individually. This gave us an estimate of the magnitude of the capture effects at each of the target-distractor distances for each participant. None of the capture effects at the various target-distractor distances significantly correlated with WMC (all ps $> .53$), nor did they correlate with AC (all ps $> .14$). Averaging RTs for all distractor-present trial types and subtracting mean RTs on distractor-absent trials gave each participant a distractor effect. This effect did not significantly correlate with WMC, $r = -.04$, $p = .68$ or AC ($r = -.14$, $p = .11$). To see if specific attention control mechanisms tapped by the three AC tasks (response inhibition, conflict resolution, sustained attention) correlated with capture, we also ran correlations between antisaccade, Stroop, and psychomotor vigilance and capture. Antisaccade, $r = -.04$, $p = .64$ and psychomotor vigilance, $r = .09$, $p = .31$ did not correlate with capture. But incongruent RTs on Stroop did significantly correlate with larger capture, $r = .19$, $p = .02$. So if anything, there may be a relationship between conflict resolution in Stroop and attentional capture. But this result should be interpreted with caution, as neither of the other two attention control tasks predicted smaller capture. Scatterplots demonstrating the relationships among WMC factor scores, AC factor scores, and capture effects are shown in Figure 2. The capture effects in Figure 2 were computed as the difference between mean RT on distractor-absent trials and all distractor-present trials (collapsed across target-distractor distance). Together these results suggest that WMC and AC were faster on the search task overall. However, these abilities did not predict reduced susceptibility to attentional capture.

Discussion

Although participants with greater WMC and AC were faster overall on the visual search task, they did not show reduced susceptibility to attentional capture by the color singletons. The singletons had the greatest effect on RTs when they were closest to the target, and as the singleton got further away from the target the effect on RTs monotonically diminished. However, at none of the target-distractor distances did the magnitude of the effect of the singleton correlate with WMC or AC. These results suggest that attentional capture effects, as measured by increased RTs on trials including color singletons in a visual search task, do not correlate with traditional measures WMC and AC.

Presumably, all participants were using a singleton-detection mode to find the target, as the instructions explicitly told participants to do so (i.e., "find the unique shape.") Because the unique shape was unpredictable (i.e., either a circle or a diamond), participants could not employ a feature-search mode to find the target. Therefore, we observed a robust distractor effect on trials including a color singleton (Kawahara, 2010; Theeuwes, 1992, 2010). When all participants were induced to use such a search mode, we did not observe any relation between WMC and the magnitude of attentional capture effects. In other words, the costs associated with the presence of a color singleton were not greater for low-WMC or low-AC participants. Therefore, rather than reflecting a failure of goal maintenance as low AC and low WMC typically predict, this type of capture may be an unintended consequence of executing the appropriate task goal. When looking for a unique item, the color singletons are particularly salient because of their uniqueness. So capture by the singleton may not reflect a failure of goal maintenance, but rather an unintended consequence of goal maintenance and execution. In the present situation, failures of goal maintenance may be primarily related to WMC in the fact that individuals with low WMC and AC were slower overall. Of all the other measures, Stroop was the only significant predictor of capture. It may be the case that conflict resolution in Stroop is similar to the distractor inhibition in the visual search task. However, because the AC factor, WMC factor, and other zero-order correlations were not significant, this finding should be interpreted with caution. But when learned search modes can mitigate attentional capture, we may be able to observe WMC-related variation in capture. That hypothesis is tested in Experiment 2.

Experiment 2

Although we did not observe a relationship between WMC or AC and attentional capture in Experiment 1, we decided to follow-up with a set of tasks in which learned control can mitigate the effects of capture. Specifically, participants completed a similar set of tasks to the amnesic individuals and healthy controls in Cosman and Vecera's (2013b) study and the feature-search condition in Leber and Egeth's (2006) study. During the first visual search task (the training session), participants searched for a target (always a circle) among a heterogeneous set of nontargets (squares, diamonds, and triangles). This task attempted to induce a feature-search mode, and there should be no effect of color singletons on RTs. During the second visual search task (the testing session), participants searched for a circle among a homogenous set of nontargets (all diamonds, all squares, or all triangles). This task allowed participants to employ either a feature-search mode or a singleton-detection strategy. For both tasks, half of trials included a red singleton nontarget. All other items were green. If participants continue to use the feature-search mode, there will be no effect of the color singleton during the testing session. However, if participants revert to using a singleton-detection mode, there will be an effect of the color singleton during the testing session. Finally, if learned control differs as a function of an individual's WMC, individuals with lower WMC will be more likely to shift back to the singleton-detection mode during the testing session, thus showing a greater attentional capture effect. Further, if this effect is mediated by individual differences in AC, this relation can be attributable to executive-attention. However, if the effect is unrelated to AC, the relation can be attributable to WMC-related long-term memory processes that are independent of executive-attention abilities.

Method

Participants and procedure. A total of 187 participants were recruited from the University of Oregon human subjects pool in exchange for partial course credit. None of the participants in Experiment 2 had participated in Experiment 1. Participants first completed the same three complex span working memory measures and AC tasks as in Experiment 1 followed by a similar, but critically different visual search task. Between two versions of the visual search task, participants completed a brief (~5 min) filler task (the Cognitive Reflection Test; Frederick, 2005). The complex span tasks, three AC tasks, two visual search tasks, and filler task comprised about one hour of a 2-hr session during which participants completed other measures that were irrelevant to the present study. All other measures were completed after the measures of interest in the present study. After excluding participants for accuracy at or below chance and missing data due to computer errors, the final sample included 156 participants.

Tasks.

Operation span. See Experiment 1.

Symmetry span. See Experiment 1.

Reading span. See Experiment 1.

Psychomotor vigilance. See Experiment 1.

Antisaccade. See Experiment 1.

Stroop. See Experiment 1.

Visual search. The series of tasks was modeled after Cosman and Vecera (2013a, 2013b) and Leber and Egeth (2006). During the training session, participants searched for a target circle among a set of heterogenous nontargets (diamonds, squares, and triangles; Figure 3). Participants reported the direction of a slanted line inside the circle by pressing one of two keys labeled R and L (the / and Z keys) on the keyboard. The trial started with a 1000-ms fixation screen on which a white dot was centered on a black screen. Six items then appeared around an invisible circle. The search array remained onscreen until the participant made a response. Participants completed five blocks of 56 trials each. The testing session task was identical to the first with the exception of one critical difference. During testing, the set of nontargets was homogenous (all squares, all diamonds, or all triangles). For both tasks, all items were colored green except on distractor-present trials. On distractor-present trials, one nontarget item was colored red. In both tasks trial types were randomly intermixed. Participants completed five blocks of 56 trials (280 total) during the training task and three blocks of 56 trials (168 total) during the testing task. Each task also included 10 practice trials with feedback before the experimental blocks. The dependent variable for the visual search task was the mean RT after trimming extremely short (<200 ms) and extremely long (>3000 ms) RTs for each trial type.

Thought probes. Thought probes were again included in the three AC tasks, but they were not included in the visual search task. Just as in Experiment 1, these probes were part of a different experiment and thus were not analyzed in the current study.

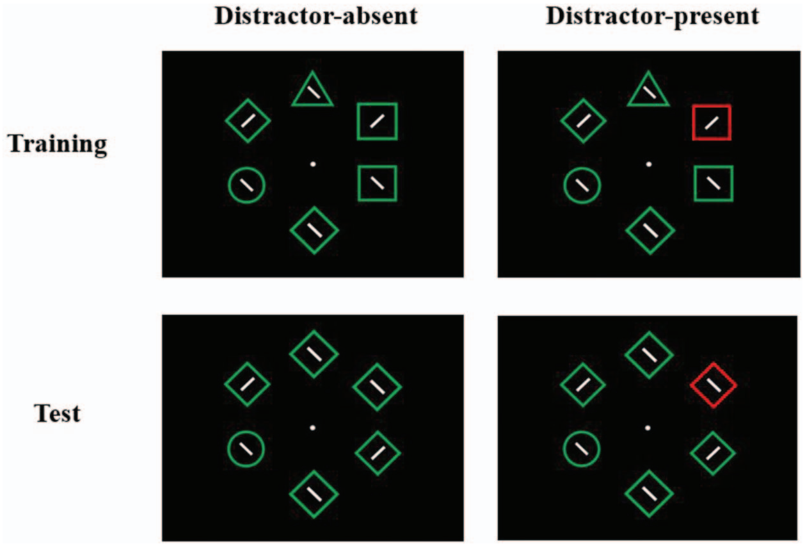

Figure 3. Trial types for Experiment 2. During the training task, the target was always a circle and the nontargets were a homogenous set of different shapes. During the testing task, the target was always a circle and the nontargets were a homogenous set of a different shape. Targets and nontargets were always green, and color singletons were always red. See the online article for the color version of this figure.

Results

Descriptive statistics and correlations for the WMC and AC measures are shown in Table 3. Descriptives and correlations for the WMC factor, AC factor, and visual search tasks are shown in Table 4. We again computed a WMC factor score by entering scores from operation span, symmetry span, and reading span into a factor analysis and saving each participant's factor score. We also computed a factor score for AC using the same procedure.[4] Only accurate RTs were analyzed. We then trimmed the data by eliminating any RTs longer than 3,000 ms or shorter than 200 ms. Data are reported only for participants who were included in the final sample ($N = 156$). After eliminating participants who performed at or near chance (50% accuracy), mean accuracy rates in the two tasks were high. In the training task, mean accuracies for distractor-absent and distractor-present trials were 95.4% and 95.2%, respectively. In the testing task, mean accuracies for distractor-absent and distractor-present trials were 95.8% and 96%.

Table 3
Correlations and Descriptive Statistics for WMC and AC Measures in Experiment 2

Measure	1	2	3	4	5	6
1. OSpan	—					
2. SymSpan	.37*	—				
3. RSpan	.55*	.25*	—			
4. PVT	−.14	−.22*	−.14	—		
5. Antisaccade	.15	.27*	.16	−.26*	—	
6. Stroop	−.06	−.17*	−.16	.36*	−.36*	—
M	38.75	19.35	37.24	492	0.51	832
SD	7.89	4.86	8.72	123	0.15	169
Skew	−1.02	−0.36	−0.59	2.00	0.33	1.45
Kurtosis	1.34	−0.33	−0.37	4.73	−0.29	4.45
Reliability	.72	.53	.74	.98	.75	.91

Note. $N = 156$. Reliabilities for the operation span, symmetry span, and reading span tasks were computed as a Cronbach's alpha using mean accuracy for each set size. Reliabilities for all other tasks were computed using split-half Spearman–Brown correlations. OSpan = operation span; SymSpan = symmetry span; RSpan = reading span; PVT = psychomotor vigilance; AC = attention control; WMC = working memory capacity.
* $p < .05$.

A repeated measures ANOVA with within-subjects factors of task (training vs. test) and trial-type (distractor-present vs. distractor absent) on RTs revealed a main effect of task, $F(1, 155) = 312.97$, $p < .001$, partial $\eta^2 = .67$, but no main effect of trial-type ($F < 1$), nor a task by trial-type interaction ($F < 2$). So although participants were faster during the testing task overall, there was no evidence for an effect of color singletons for either task at the group level. This replicates prior research that has used this series of tasks (Leber & Egeth, 2006; Cosman & Vecera, 2013b). But there was considerable variability in the magnitude of capture across participants. To see if these effects changed as a function of WMC and AC, we added these variables as covariates to the model. This analysis revealed a main effect of WMC, $F(1, 153) = 3.74$, $p = .05$, partial $\eta^2 = .02$, and a main effect of AC, $F(1, 153) = 42.24$, $p < .001$, partial $\eta^2 = .22$, such that individuals with greater WMC and better AC were faster overall. This effect was qualified by interactions between AC and task, $F(1, 153) = 12.92$, $p < .001$, partial $\eta^2 = .08$, and WMC and trial-type, $F(1, 153) = 7.33$, $p = .008$, partial $\eta^2 = .05$. Further investigation of the task by AC interaction revealed that high-AC participants showed a sharper drop in RTs from the training task to the testing

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[4] The loadings on the WMC factor for operation span, symmetry span, and reading span were .86, .43, and .66, respectively. The loadings on the AC factor for antisaccade, Stroop, and psychomotor vigilance were .51, .70, and .51, respectively.

Table 4
Descriptive Statistics and Correlations for Factors and Visual Search in Experiment 2

Measure	1	2	3	4	5	6
1. WMC factor	—					
2. AC factor	.18*	—				
3. Training—Absent	−.12	−.40*	—			
4. Training—Present	−.14*	−.39*	.99*	—		
5. Testing—Absent	−.15	−.42*	.61*	.60	—	
6. Testing—Present	−.21*	−.44*	.64*	.64*	.96*	—
M	−0.01	0.00	843	844	672	668
SD	0.92	0.79	187	190	109	111
Skew	−0.96	−0.96	1.47	1.29	0.99	1.13
Kurtosis	1.23	1.42	2.87	2.04	1.04	2.08
Reliability	—	—	0.85	0.74	0.76	0.78

Note. AC = attention control; WMC = working memory capacity.
* $p < .05$.

task than low-AC participants, $r = -.30$, $p < .001$.[5] The WMC by trial-type interaction revealed that WMC did not correlate with the magnitude of the attentional capture effects during the training task, $r = -.09$, $p = .24$, but greater WMC related to significantly smaller attentional capture effects in the testing task, $r = -.23$, $p = .004$. Scatterplots demonstrating the relationships among WMC factor scores, AC factor scores, and capture effects are shown in Figure 4. Just as in Experiment 1, capture effects were computed by subtracting mean RT on distractor-absent trials from mean RT on distractor-present trials for each participant.

There are two possible reasons for the association between WMC and capture in the testing task. On the one hand, low-WMC participants may show larger (positive) capture effects in which they took longer to respond on distractor-present trials. On the other hand, high-WMC participants may show negative capture effects, which would reflect faster responding on distractor-present trials. To rule out the possibility that the relationship was driven by negative capture among high-WMC individuals we categorized a subset of participants as high-WMC using the upper quartile of the WMC distribution. These participants showed a slightly negative, but nonsignificant capture effect ($M = -2.07$ ms, $SD = 31.31$), $t(38) = -.41$, $p = .68$. In a separate analysis, we restricted the analysis to participants who showed a positive capture effect. We then reran the correlation between WMC and capture, and it remained largely unchanged, $r(88) = -.21$, $p = .05$. So the relationship does not appear driven primarily by a tendency toward negative capture effects among high-WMC individuals. But rather, low-WMC individuals appeared more likely to show larger positive attentional capture effects during the testing task, which we argue represents a shift back to a singleton-detection strategy among these individuals.

In our final analysis, we wanted to see whether the relationship between WMC and capture was driven by AC. To do so, we entered AC and WMC into a regression predicting the attentional capture effect in the testing task (see Table 5). The regression revealed that variance in attentional capture was largely driven by differences in WMC, not AC. So, even after controlling for individual differences in the ability to control attention, WMC significantly predicted smaller attentional capture effects.

Discussion

The results of Experiment 2 revealed several interesting findings. First, consistent with Leber and Egeth (2006), at the group level, participants did not show a distractor effect when the search set contained a heterogenous set of nontarget items (training task) and when instructed to search for the target using a feature-search mode (i.e., “find the circle”). Second, the results replicate Leber and Egeth (2006) in that participants did not show a distractor effect when asked to complete the same task with a homogenous set of nontarget items (testing task). So in general, participants appeared to employ a feature-search strategy during the testing task, which mitigated attentional capture by singletons. However, there was variation in the degree to which participants carried over the learned feature-search strategy, demonstrated by variation in the magnitude of the capture effect. Importantly, this variation significantly correlated with WMC. That is, participants with lower WMC tended to show larger attentional capture effects during the testing task only. These results suggest that participants with lower WMC were less likely to carry over the feature-search mode from the training session to the testing session. Because the effect was largely driven by WMC and not AC, as reflected by the regression in Table 3, this effect is most likely due to differences in long-term memory rather than executive-attention. As we address more thoroughly in the General Discussion, this WMC-related effect may be due to an inability to form a representation of the appropriate task approach in long-term memory or an inability to access that representation when they encounter a similar task again in the future.

General Discussion

Across two experiments, we examined how individual differences in WMC predicted the magnitude of attentional capture effects within visual search tasks. Prior research has shown that attentional capture, despite being a rather robust finding within many visual search paradigms (Theeuwes, 2010), does not always correlate with measures of WMC and AC (e.g., Stokes, 2016). We attempted to explain this rather surprising lack of covariance by examining task approaches and learned control over capture.

Attentional capture effects often manifest because participants are using a singleton-detection mode to find the target item. Even though the target may be unique in its shape, rendering color a meaningless dimension of the item, many individuals are slowed by the presence of a color singleton in the array. We observed this effect in Experiment 1, especially when the color singleton was in a location adjacent to the target. However, the magnitude of this effect did not correlate with individual differences in WMC. Traditionally, the covariance between complex span measures of working memory and measures of AC (e.g., Stroop, antisaccade) is explained by a shared executive-attention mechanism in which individuals must keep task goals active in mind. Any failure of goal maintenance will result in poor performance (e.g., poor memory maintenance, errors, long RTs). Within the context of the

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[5] Just as in Experiment 1, we correlated the magnitude of the capture effects for the training and testing tasks with each AC task individually. None of the tasks were significantly correlated with capture for either the training task or testing task (all $ps > .14$).

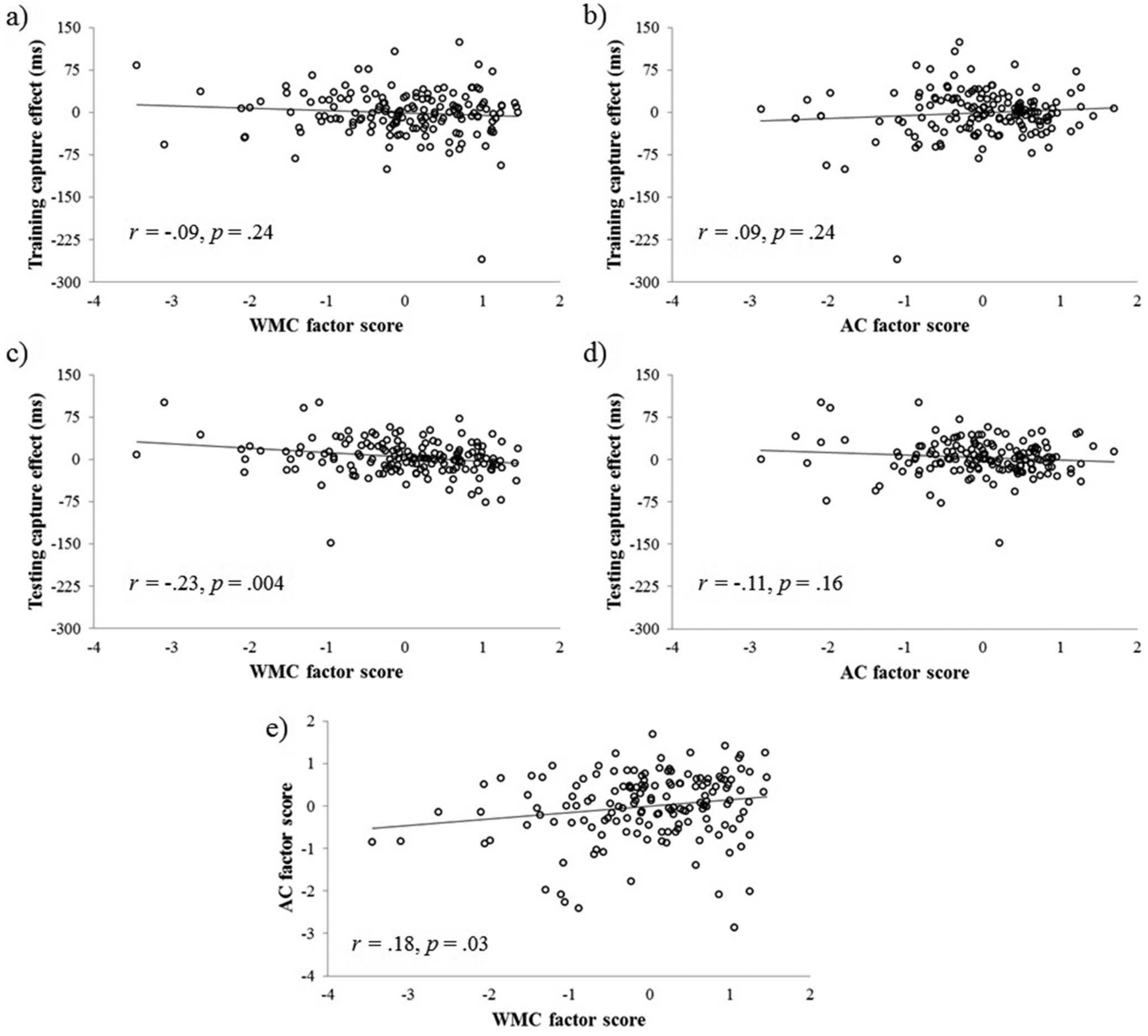

Figure 4. Scatterplots of relationships between (a) working memory capacity (WMC) and training task capture effects, (b) attention control (AC)and training task capture effects, (c) WMC and testing task capture effects, (d) AC and testing task capture effects, and (e) WMC and AC.

visual search task in Experiment 1, attentional capture may not reflect a failure of goal maintenance. If the goal is to find the unique item, as it was in Experiment 1, then attending to a unique item (even if it is unique because of an irrelevant feature) is not necessarily a failure of goal maintenance. Rather, attending to the color singleton, albeit briefly, may simply be an unintended consequence of successful goal execution. Although color is an irrelevant feature of the items in the search array, the use of a singleton-detection strategy encourages attention to unique items. That may explain why WMC was unrelated to the magnitude of attentional capture in this context.

In Experiment 2, the task goal shifted slightly. Despite the many task similarities, the training task in Experiment 2 induced participants to use a feature-search mode rather than a singleton-detection mode. The instruction to find the circle among the heterogenous set of items rendered the color singletons irrelevant. Indeed, there was no significant difference in response times between distractor-present and distractor-absent trials in that task at the group level. But when the task parameters changed slightly in the testing session, the color singletons again became a possible source of distraction. However, it was only a source of distraction if participants abandoned the feature-search mode and used a singleton-detection mode instead. Although there was no significant capture effect at the group level, there was variation in the effect between participants. Individuals with lower WMC showed larger attentional capture effects in the testing task only. This

Table 5
Regression on Attentional Capture Effect in Testing Task

Factor	β	*t*	*p*
AC	.07	.93	.35
WMC	−.22	−2.73	.004

Note. $N = 156$. The dependent variable was the capture effect in the testing task. AC = attention control; WMC = working memory capacity; β = standardized beta.

suggests that these individuals were more likely to abandon the feature-search approach in favor of the singleton-detection mode. Further, a regression showed that variance in capture was largely due to differences in WMC, not AC.

The fact that WMC-related differences in capture effects during the testing session were completely independent of variation in AC is a rather striking finding. Traditionally, the covariation between WMC and other forms of cognition has been attributed to an executive-attention mechanism (Engle, 2002). However, we also know the complex span working memory measures used in the present study correlate well with long-term memory measures (Robison & Unsworth, 2017; Rosen & Engle, 1997; Unsworth, 2016; Unsworth & Spillers, 2010; Unsworth et al., 2014). Therefore, the finding that high-WMC participants were more likely to carry over the feature-search mode from the training session to the testing session may be a manifestation of superior long-term memory abilities among high-WMC individuals. Despite the intuition that variation in attentional capture would be driven by executive-attention, we propose that the WMC-related differences were due to long-term memory representations. In fact, this interpretation is entirely consistent with the findings of Cosman and Vecera (2013a, 2013b), who propose that sufficient task experience leads to the formation of long-term memory representations that link the internal state of the attentional system to the attributes of a task at hand. When similar tasks are encountered again in the future, these memory representations are activated in service of goal-directed behavior (Logan, 2002). Extending this logic, we argue that the low-WMC individuals in the present study were less likely to continue use of the feature-search mode during the testing phase because of a relative inability to either 1) form an accessible and appropriate memory representation of the optimal task approach, or 2) retrieve this representation from long-term memory in service of successful task completion. This explanation is derived from findings that WMC-related differences in long-term memory are caused by differences in both effective encoding and successful retrieval (Rosen & Engle, 1997; Robison & Unsworth, 2017; Unsworth, 2016).

We should note that our findings might seem at odds with previous studies of similar relationships. For example, Fukuda and Vogel (2009, 2011) showed that low-WMC individuals take longer to recover from attention capture than high-WMC individuals. However, there were some critical differences between the present study and the studies by Fukuda and Vogel (2009, 2011). First, Fukuda and Vogel (2009, 2011) measured WMC with a colored-squares change-detection task. Although complex span measures, change-detection measures, and AC measures correlate, they seem to tap distinct cognitive abilities (Unsworth et al., 2014). Further, the attention capture effects were measured during similar visual working memory tasks. Therefore, the high degree of task overlap may account for some of the covariation between WMC and capture in those studies. It is possible that change-detection estimates of visual WMC would predict attention capture with the present paradigm, but follow-up work would be required to determine if that is the case. Second, Fukuda and Vogel (2011) measured capture with relevant and irrelevant flankers presented at various stimulus-onset asynchronies (SOAs) before a target array. High- and low-WMC individuals only differed at an intermediate SOA (150 ms). No differences emerged at the shortest SOA (50 ms), and there was no simultaneous presentation, which would be most relevant to the present study. Further, the task was modified for each individual participant using a staircasing procedure, so arrays appeared on-screen for different times between participants. For these reasons, it is hard to directly compare the present findings to those of Fukuda and Vogel (2011). To examine whether or not the relationship between capture in the testing effect was driven by the modality of the task (verbal vs. visual), we examined the correlations for each complex span task individually with capture. Operation span had the strongest correlation, $r = -.22$, $p = .006$, followed by symmetry span, $r = -.15$, $p = .06$ and reading span, $r = -.11$, $p = .18$. So it does not seem like the visuospatial nature of symmetry span drove the relationship. Future research will be necessary to integrate our findings with those of Fukuda and Vogel (2009, 2011).

Conclusions

Rather surprisingly, the robust attentional capture effects observed in visual search tasks sometimes do not correlate with other measures of conceptually related effects. In the present study, we argue that attentional capture may not necessarily reflect failures of goal maintenance, which are often the source of covariance among measures of WMC and AC. However, when the task goal includes a search mode that can be abandoned in favor of a less effective but perhaps more easily employable mode, low-WMC participants may be more likely to use the less-effective search mode. Mechanistically, low-WMC individuals may be unable to form a long-term memory representation of the effective task approach. Or rather, they may be unable to retrieve this representation when they encounter a similar task in the future. This finding helps to resolve some of the discrepancies in the literature surrounding the nature of individual differences in WMC and attentional capture, and it is consistent with the idea that that long-term memory representations exert an influence on attention control. Overall, the present study helps us further understand the nuanced ways in which memory and attention interact.

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