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Where to Start? Bottom-Up Attention Improves Working Memory by Determining Encoding Order

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The present study aimed to characterize the mechanism by which working memory is enhanced for items that capture attention because of their novelty or saliency—that is, via bottom-up attention. The first experiment replicated previous research by corroborating that bottom-up attention directed to an item is sufficient for enhancing working memory and, moreover, generalized the effect to the domain of verbal working memory. The subsequent 3 experiments sought to determine how bottom-up attention affects working memory. We considered 2 hypotheses: (1) Bottom-up attention enhances the encoded representation of the stimulus, similar to how voluntary attention functions, or (2) It affects the order of encoding by shifting priority onto the attended stimulus. By manipulating how stimuli were presented (simultaneous/sequential display) and whether the cue predicted the tested items, we found evidence that bottom-up attention improves working memory performance via the order of encoding hypothesis. This finding was observed across change detection and free recall paradigms. In contrast, voluntary attention improved working memory regardless of encoding order and showed greater effects on working memory. We conclude that when multiple information sources compete, bottom-up attention prioritizes the location at which encoding should begin. When encoding order is set, bottom-up attention has little or no benefit to working memory.

Keywords: working memory, attentional capture, short-term memory

Working memory (WM) has a limited capacity, and therefore it is critical to optimize the encoding and maintenance of information that is task-relevant. Selective attention is known to facilitate the effective use of WM by prioritizing the encoding of task-relevant information over irrelevant information (Awh, Vogel, & Oh, 2006). As a consequence, WM for attended items is better than unattended items, whether attention is guided voluntarily (Bays & Husain, 2008; Bollinger, Rubens, Zanto, & Gazzaley, 2010; Griffin & Nobre, 2003; Murray, Nobre, & Stokes, 2011; Schmidt, Vogel, Woodman, & Luck, 2002) or automatically (Bays & Husain, 2008; Fine & Minnery, 2009; Santangelo & Macaluso, 2013; Schmidt et al., 2002). Voluntary, or top-down, attention is thought to facilitate WM performance by prioritizing memory for items that match an internal task set. Similar to its role in perceptual tasks, voluntary attention aids selection for WM by enhancing neural activity in task-relevant regions of the brain and suppressing activity in regions that are irrelevant to the task (see Gazzaley & Nobre, 2012, for a review). In this manner, voluntary attention is thought to provide a stronger perceptual representation of attended stimuli because the quantity of information encoded and/or the rate of encoding are enhanced (Prinzmetal, Ha, & Khani, 2010).

In contrast, little is known about the source of enhanced WM performance for information that captures attention automatically. Novel or salient sensory information can capture attention in a bottom-up manner regardless of its relevance to task goals. As with voluntary attention, bottom-up attention has also been shown to enhance WM. Recent work has shown that WM performance is better for objects that are more visually salient (e.g., intensity contrast, color opponency) and thus presumably capture bottom-up attention (Fine & Minnery, 2009; Santangelo & Macaluso, 2013). WM performance is also better for items that are exogenously cued by a stimulus with a sudden onset (Bays & Husain, 2008; Schmidt et al., 2002). Schmidt et al. (2002), for example, presented six colored shapes simultaneously with one item preceded by a sudden onset cue. In the predictive condition, the cue indicated which item would likely be probed at recall, and in the nonpredictive condition, the cue was uninformative—a random item was probed. It was assumed that voluntary attention was engaged in the predictive condition, allocating resources to the items that were likely to be probed. However, in the nonpredictive condition, any benefit for WM was assumed to be because of bottom-up attention. The nonpredictive cue simply draws attention to the location of one of the six upcoming stimuli without providing any added information about what item will be probed; there is no reason to voluntarily attend that cued location. It is important that both predictive and

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nonpredictive cues enhanced WM performance for cued items (Schmidt et al., 2002).

While studies have demonstrated that bottom-up attention improves WM performance, the mechanism underlying this benefit remains unclear. Voluntary attention assumes an a priori task set that drives selection at encoding by modulating sensory processing relevant to the task. Enhancing sensory processing may result in the acquisition of more information at encoding which results in a stronger perceptual trace. Bottom-up capture to novel or salient features of a stimulus, however, can be unexpected and occur for items that are not task-relevant. Thus, modulation of sensory regions seems an unlikely explanation for the benefits of bottom-up attention because the stimuli that involuntarily captured attention are either unexpected or irrelevant to the task.

Instead, there is some evidence that bottom-up attention enhances WM through prioritizing selection at encoding. Items that capture bottom-up attention may be encoded first and, thus, show an advantage at recall because of the primacy effect in which initial items are more likely to enter into long-term memory (Waugh & Norman, 1965). It has been argued that items that have visual (Pedale & Santangelo, 2015; Santangelo & Macaluso, 2013) or contextual salience (Santangelo, Di Francesco, Mastrobe-rardino, & Macaluso, 2015) draw attention and, therefore, are more likely to enter WM at the expense of other items (Melcher & Piazza, 2011). Consistent with this hypothesis, Pedale and Santangelo (2015) found that salient items in a naturalistic scene are also more likely to be reported earlier than minimally salient items in a free-recall task, although this may have been because of a bias to report distinctive items first rather than to the item being encoded first.

While the benefits of bottom-up attention have been documented in previous studies, none have provided a strong test of the encoding-order hypothesis. The encoding-order hypothesis predicts that bottom-up attention should only help when multiple items are competing for attention. When encoding order is fixed as, for example, when stimuli are presented sequentially, bottom-up attention should have little or no effect on WM performance. In contrast, the benefit of voluntary attention should be observed regardless of the type of presentation (i.e., simultaneous or sequential). This is because voluntary attention not only increases the likelihood that an item will be encoded, but it also benefits from more effective encoding. The ability of voluntary attention to prepare sensory processing allows for a stronger representation of the attended item in WM.

The current experiments were designed to demonstrate a boundary constraint on bottom-up attention to provide insight into the mechanism underlying its benefit to WM; namely, that WM will benefit from bottom-up attention only when items are presented simultaneously because of its effect on encoding order. Thus, the present set of studies will demonstrate when bottom-up attention enhances WM and, as importantly, when it does not help. Moreover, the present study provides a stringent test of the primacy effect by calculating the rate at which an item is being recalled in the first position of the list. Pedale and Santangelo (2015) observed that objects with maximal sensory salience were reported at earlier positions in the list than those that were minimally salient (Pedale & Santangelo, 2015), and this raises the possibility that improved WM performance may related to a primacy effect. If so, items that benefit from bottom-up attention should be recalled earlier in free recall. In order to overcome a potential bias in reporting distinctive items first, we assess whether items that capture bottom-up attention are recalled first when distinctiveness between items is equated.

Unlike previous studies that investigated bottom-up attention effects on WM by investigating low-level sensory salience, the present set of studies uses a spatial cue to capture attention to an item. Spatial cuing was used to disentangle the effects of bottom-up attention from the von Restorff (or distinctiveness) effect (von Restorff, 1933). It is well known that singleton items that are visually, auditorily, or semantically distinctive are better recalled (see Cimbalo, 1978, for a review). This phenomenon has been termed the von Restorff effect (1933) and is thought to be because of the distinctive item having an advantage at recall or in how it is stored rather than at encoding. For example, there is evidence that the von Restorff effect is because of distinctive items being placed in their own category (Bruce & Gaines, 1976; Schmidt, 1991) or because distinctive items are associated with more cues for recall (Kelley & Nairne, 2001). Moreover, the von Restorff effect is found for the first item of a sequence when its relative salience is unknown (Kelley & Nairne, 2001). While we cannot rule out an effect of bottom-up attention for distinctive items when items are presented simultaneously during encoding, the spatial cuing paradigm allows us to manipulate bottom-up attention while not changing the distinctiveness of the item itself.

To test the mechanism of bottom-up attention effects on WM, we modified the change detection task used in the Schmidt et al. (2002) paradigm that relied on spatial cuing. Experiments 1A and 1B will assess this effect for both nonverbal and verbal stimuli in a change detection task. Experiment 2 will then test whether serial presentation diminishes or eliminates the effect of bottom-up attention on WM performance. Experiment 3 tests whether the enhancement of bottom-up attention in simultaneous conditions is because of a primacy effect.

Experiments 1A and 1B

As a first step, we sought to replicate the results of Schmidt et al. (2002), who observed a benefit of bottom-up attention in a change detection task. Type of attention was manipulated between groups by varying the probability that a cue would correctly indicate which item would be probed at test. When all items are equally likely to be probed and the cue provides no information, there is no reason to preferentially remember items at the cued location. Any benefit for the recall of cued items is presumably because of bottom-up attention drawn by the sudden onset of the cue. In contrast, when the cued item is more frequently probed than the other items, voluntary attention should provide an additional benefit to WM performance.

Experiment 1A used colored squares as in Schmidt et al. (2002) and Experiment 1B used verbal stimuli. Experiment 1B assessed the generalizability of the effect across domains and had the additional benefit of testing the role of attention in verbal WM, which is relatively understudied (Awh et al., 2006). Based on the results of Schmidt et al., we predicted that both voluntary and bottom-up attention would enhance WM performance. Most critically, bottom-up attention should enhance WM performance because encoding order is undetermined when multiple items are presented simultaneously. Thus, we should see that cued items are better remembered than uncued items regardless of whether the cues are predictive.

Method

Participants. Twenty-eight undergraduates from Michigan State University participated in Experiment 1A for course credit. All participants provided informed consent. Half ($n = 14$) were randomly selected to form the nonpredictive cue group, and the remaining half ($n = 14$) formed the predictive cue group.

Thirty undergraduates from Michigan State University participated in Experiment 1B for course credit. Half ($n = 15$) were randomly selected to form the nonpredictive cue group, and the remaining half ($n = 15$) formed the predictive cue group. The sample size was chosen to be similar to the sample used in the Schmidt et al. (2002) study ($n = 24$) in which large cuing effects were observed for both predictive and nonpredictive cues.

Stimuli. Stimuli were presented using E-Prime 2.0 software and shown on a gray background with a continuously visible white fixation cross centered on screen. In Experiment 1A, the stimuli were six colored squares evenly spaced around fixation, such that the centers of the squares formed the corners of a regular hexagon. The color of each square was selected at random (without replacement) from a set of seven easily discriminable colors: blue, brown, green, magenta, off-white, red, and yellow.

The stimuli in Experiment 1B were six black letters evenly spaced around a continuously visible white fixation cross. Each letter was chosen from a set of seven visually distinguishable and nonrhyming letters: “F”, “H”, “J”, “M”, “Q”, “S”, “Z”. Letters were presented in Calibri font.

Both letters and shapes subtended 3.2° × 3.2° of visual angle and were presented at a distance of 8.8° from the center of the fixation cross. In both experiments, the cue was the outline of a white square that subtended 4.8° × 4.8°. The cue was presented in the same location as one of the items, also at a distance of 8.8° from the center of the fixation cross.

Task. Figure 1A depicts the sequence of events comprising each trial in both Experiment 1A and 1B. Each trial began with 2000ms of fixation and functioned as the intertrial interval (ITI). Next, a cue appeared for 50 ms at one of the six locations, selected at random. This was followed by 50 ms of fixation, and then the memory array of six items was presented for 100 ms. Fixation was again presented for 900 ms, and then the probe appeared until a response was recorded or for a maximum of 2,000 ms if no response was provided.

On half of the trials, the probe item was the same color (Exp. 1A) or letter (Exp. 1B) as the memory array item that had previously been presented at the same location; participants were instructed to press “1” on the number pad for these match trials (Figure 1A on the top depicts a match trial for Exp. 1A). On the remaining trials, the probe was a different, randomly selected color or letter that did not match; for no-match trials, participants were instructed to press “2” on the number pad (Figure 1A on the bottom depicts a no-match trial for Exp. 1B).

For the subjects in the predictive cue group, the probe appeared at the cued location on two thirds of the trials and at a randomly selected uncued location on the remaining trials. For the subjects in the nonpredictive cue group, the probe appeared at the cued location on one sixth of the trials and at a randomly selected

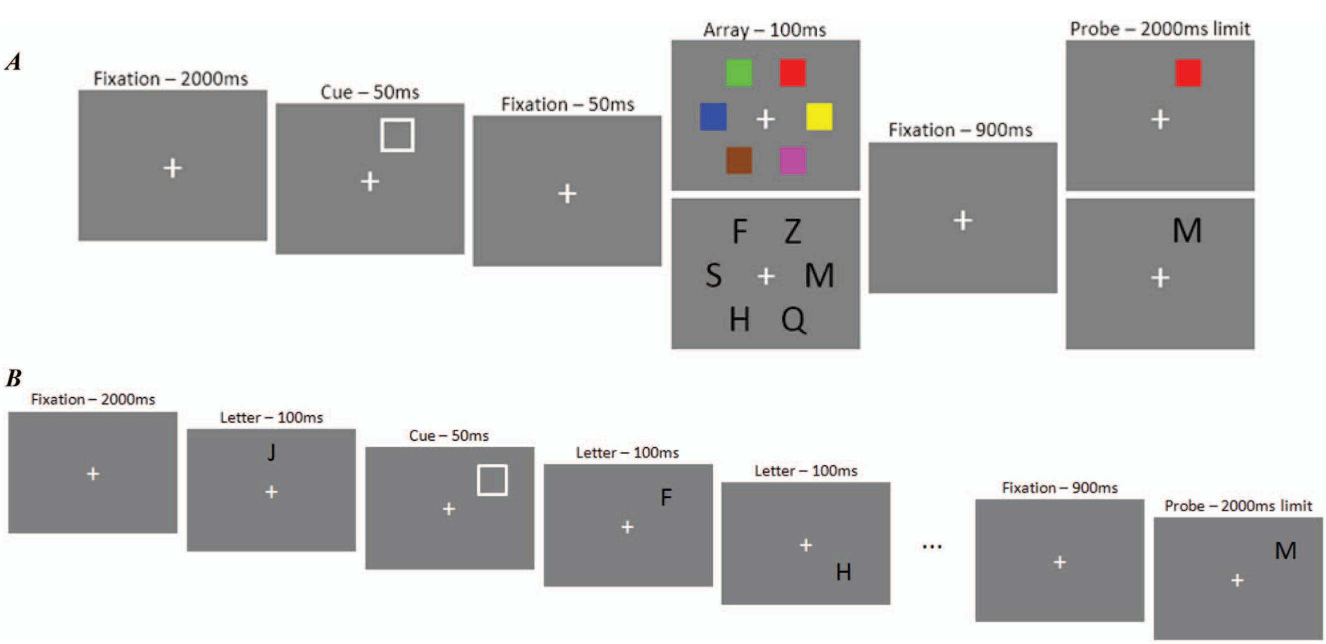

Figure 1. Timing schedules for (*A*) Experiment 1A (*top*) and 1B (*bottom*), and (*B*) the sequential blocks of Experiment 2 and Experiment 3. *Note.* (B) In between the presentation of each letter and the cue, a fixation cross was shown for 50ms. A total of 6 letters were displayed before the probe. Therefore, the . . . emits 3 letters that would continue around in a clockwise pattern. In this example, the second letter is cued, but any of the six letters could be cued. See the online article for the color version of this figure.

uncued location on the remaining trials. The participants were informed of these probabilities at the beginning of the task.

After 10 trials of practice, each participant completed five blocks of 90 trials. The number of trials per condition differed for predictive and nonpredictive cue conditions, but each condition had a minimum of 50 trials.

Results

To get a pure baseline, we excluded trials in which the cued item was used as a probe in a different location (no-match trial). If the cued item was better remembered than uncued items, participants may be better at knowing that the item was not presented at that location. This would, consequently, inflate accuracy at uncued locations.

For both verbal and nonverbal experiments, a mixed-factor analysis of variance (ANOVA) was performed on accuracy scores using cuing (cued/uncued) as a within-subjects variable and type of cue (predictive/nonpredictive) as a between-subjects variable (Figure 2). In Experiment 1A, a main effect of cuing was observed, $F(1, 26) = 66.17$, $p < .001$, reflecting the higher accuracy in cued (80.3%) compared with uncued locations (59.7%). It is important that accuracy was higher for cued items than uncued items for both the predictive, $t(13) = 6.66$, $p < .001$, and nonpredictive cues, $t(13) = 4.71$, $p < .001$. The type of cue did not have a main effect on accuracy, $F(1, 26) = 0.21$, $p = .65$; however, the significant interaction suggested that the effect of the cue was greater in the predictive than the nonpredictive condition, $F(1, 26) = 4.62$, $p = .041$. The cue effect (cued − uncued accuracy) was larger in the predictive condition (26%) than in the nonpredictive (15%) condition, $t(26) = 2.15$, $p = .041$. The larger cuing effect in the predictive condition compared with the unpredictive condition was because of lower accuracy for uncued items, $t(26) = 2.19$, $p = .038$; the greater accuracy for cued items was not reliable, $t(26) = -.75$, $p = .462$.

A main effect of cuing was also observed in Experiment 1B for verbal stimuli, $F(1, 28) = 156.70$, $p < .001$ (Figure 2). Again, accuracy was higher for cued items than uncued items for both the predictive, $t(14) = 10.89$, $p < .001$, and nonpredictive cues, $t(14) = 6.54$, $p < .001$. Thus, both types of cue, voluntary and bottom-up, enhanced WM performance. There was no main effect of cue type, $F(1, 28) = 0.01$, $p = .92$. Similar to Experiment 1A, larger cue benefits were observed in the predictive condition (36%) compared with the nonpredictive (19%) condition, $t(28) = 3.97$, $p < .001$, which was confirmed by a significant interaction effect, $F(1, 28) = 15.79$, $p < .001$. The larger cuing effect in the predictive condition compared with the unpredictive condition was because of lower accuracy for uncued items, $t(28) = 2.42$, $p = .022$, and the greater accuracy for cued items, $t(28) = -2.94$, $p = .006$.

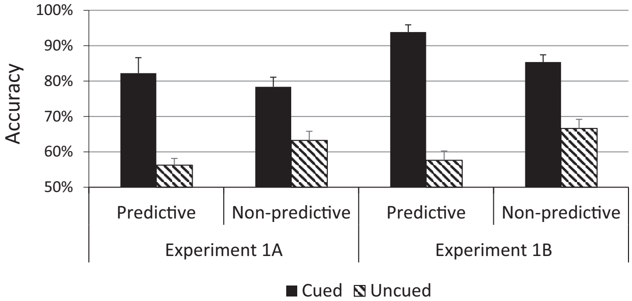

Figure 2. Means for accuracy in Experiment 1A and 1B with *SE* bars, separated by cuing and type of cue.

Discussion

These results replicate those reported by Schmidt et al. (2002). Automatic capture to a sudden onset enhanced WM performance both when the cue predicted and when it did not predict whether the item at that location would be probed. The better recall for cued items regardless of whether the cue was predictive suggests that bottom-up attention is sufficient for enhancing WM. Moreover, Experiment 1B demonstrates that the effect of bottom-up attention generalizes to verbal stimuli.

The effect of the cue was greater for predictive than nonpredictive cues, implying that voluntary attention to the cued location aids recall over and above bottom-up attention effects associated with the sudden onset of the cue. This was not because of greater overall performance in the predictive condition. Instead, uncued items were remembered better in the nonpredictive cue condition than when the cue was predictive. Thus, the greater benefit for cued items in the predictive condition was offset by decrements in recall for uncued items. This is consistent with findings of Melcher and Piazza (2011) showing that as salience increased, memory for other items decreased.

Experiment 2

Experiment 1 demonstrated that both voluntary and bottom-up attention produced benefits for recalling both verbal and nonverbal items stored in WM. In Experiment 2, we turn to the primary aim of the study: to understand how bottom-up attention enhances WM performance. We consider two hypotheses. First, bottom-up attention may work in a similar way to voluntary attention and enhance the perceptual trace. Alternatively, when multiple stimuli are presented, bottom-up attention may cause the cued stimulus to be encoded first and thereby benefit from increased probability of entering memory. To test these hypotheses, the effects of top-down and bottom-up attention were assessed under sequential presentation. If bottom-up attention affects the order of encoding, it should not affect WM performance in the sequential condition in which the order of encoding is fixed. In contrast, if bottom-up attention affects the perceptual trace, then benefits should be observed.

Given that bigger differences were observed between voluntary and bottom-up attention for verbal stimuli when compared with nonverbal stimuli, we modified Experiment 1B to create conditions in which letters were sequentially presented. Of course, the opportunity to rehearse is greater for sequential displays, but the delay between encoding and retrieval is longer for every position except the last. Therefore, we include the voluntary attention condition to control for differences between modes of display not related to attention effects. This will also allow for an additional test of the hypothesis that voluntary attention benefits recall even when encoding order is fixed.

If bottom-up attention affects the sequence of encoding, then the cueing effect should be greatly reduced or eliminated for nonpredictive cues in the sequential condition. There should be little ambiguity about where to start encoding information given that only one item is presented at a time in the sequential condition; thus, nonpredictive cues should provide no additional information. However, predictive cues should still be helpful in the sequential condition, because voluntarily attended items should benefit from enhanced sensory processing.

Method

Participants. Forty-one undergraduates from Michigan State University participated in this experiment for course credit. Half ($n = 21$) formed the nonpredictive cue group, and the remaining half ($n = 20$) formed the predictive cue group.

Stimuli. The same stimuli from Experiment 1B were again used for this experiment.

Task. The task consisted of two blocks, each containing 90 trials with a minimum of 25 trials per condition. The sequence of events is shown in Figure 1B. Each trial began with 2, 000ms of fixation. Then, the six letters were presented sequentially, each for 100 ms with 50 ms of fixation between each letter. The letters were presented in a clockwise fashion, starting at the topmost position. The white cue appeared for 50 ms before a randomly selected letter in the sequence of six letters, showing where the next letter would appear after 50 ms of fixation. After all six letters were presented, fixation was shown for 900 ms, and then the black probe letter appeared until a response was recorded or for a maximum of 2,000 ms if no response was provided.[1]

Half of the trials throughout the entire experiment were match trials, requiring a "1" response on the number pad; the other half were no-match trials, requiring a "2" response. The cue for the predictive cue group was accurate in two thirds of the trials while the cue for the nonpredictive cue group was only accurate in one sixth of the trials. The subjects were informed of these probabilities at the beginning of the task. The task began with five trials of practice.

Results

As in Experiment 1, trials in which the cued item was used as a probe in a different location were excluded. A 2 (cue/uncued) × 2 (predictive/nonpredictive) mixed-design ANOVA was used to analyze memory accuracy (Figure 3). A main effect of cuing was observed, $F(1, 39) = 30.15$, $p < .001$, as well as a significant interaction effect, $F(1, 39) = 20.51$, $p < .001$. Consistent with our hypothesis, a cuing effect was observed when the cue was predictive, $t(19) = 5.55$, $p < .001$, but not when it was nonpredictive, $t(20) = 1.04$, $p = .31$. There was no main effect of cue type, $F(1, 39) = 1.58$, $p = .22$. Although performance for cued letters was better in the predictive condition than the nonpredictive condition, $t(39) = 3.24$, $p = .002$, the opposite tended to be true for uncued letters, $t(39) = -1.88$, $p = .068$, but this effect narrowly missed significance.

Both Experiments 1 and 2 found that accuracy for uncued letters suffered when cues were predictive. We wondered if this was because of attention being focused on the cued item at the expense of other items in the list or if it might be because of a form of the attentional blink in which items after the cued letter were missed. A mixed-factor ANOVA with uncued letter position (before/after cue) as a within-subject factor and cue type (predictive/nonpredictive) was performed on accuracy scores. The results supported a focusing of attention on the cued item at the expense of all other items rather than to attentional blink. There were no difference in accuracy for uncued letters presented before (58%) or after (60%) the cued letter, $F(1, 39) = 1.89$, $p = .178$, nor did position interact with cue type, $F(1, 39) = 0.03$, $p = .866$.

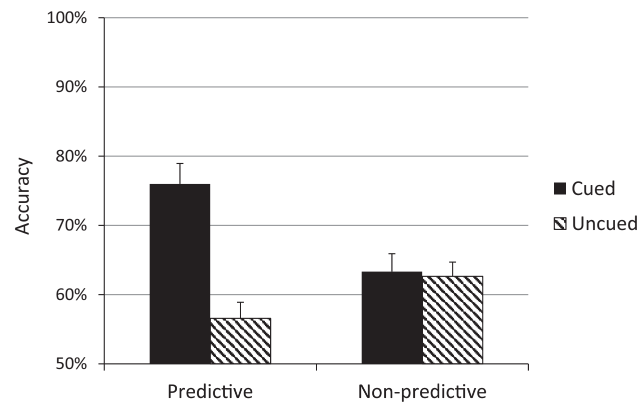

Figure 3. Means for accuracy in Experiment 2 with *SE* bars, separated by cuing and type of cue.

Discussion

When letters were presented sequentially, nonpredictive cues had no effect on subsequent memory for those items, whereas predictive cues enhanced memory performance. This suggests that voluntary and bottom-up attention affect the memory representation in different ways. Bottom-up attention most likely increases the probability that an item is encoded into WM by influencing the order of encoding. Voluntary attention affects WM beyond influencing which items enter WM, most likely by improving the attended item's perceptual trace.

These results are inconsistent with the idea that cued items are made more distinctive than uncued items. The von Restorff effect (von Restorff, 1933) predicts that unusual or distinctive items in a list are better recalled than standard items (e.g., one word in color and the rest in black font). In the nonpredictive condition, the cued item showed no advantage over uncued items even though the cue might be thought to have made it distinctive.

One limitation of our design is the use of recognition rather than recall. A recognition task may induce strategic differences in how the cue is used. For example, it was not advantageous to preferentially encode the cued item in the nonpredictive conditions. Rather than a difference in the type of attention per se, the results may be because of strategic differences in controlled processing; for example, participants might try to inhibit a preferential effect of

[1] In addition to the condition described here, each participant also completed two blocks in which stimuli were displayed sequentially at a random location (counterbalanced with clockwise). While the results were similar to the clockwise condition, uncertainty about the location of the next item made the nonpredictive cue informative and, thus, provided a reason to voluntarily attend the cue. This random location condition was not exclusively measuring bottom-up attention and so is not considered further.

bottom-up attention because cued items will only be probed one sixth of the time. In Experiment 3, a free recall paradigm is used in which every item must be recalled so that there is no strategic benefit in trying to inhibit the cued item.

Using free recall also allows us to directly test whether the benefit of nonpredictive cues is because of those items being encoded first in simultaneous condition. This may give the cued item a further advantage in that first items benefit from a primacy effect. The prediction is that the cued item will be reported first in simultaneous displays but not in sequential presentations.

Experiment 3

In Experiment 3, we directly examine how bottom-up attention affects the order of encoding in simultaneous displays by assessing the order in which items are reported. Previous work has shown that items are reported in the order in which they were presented even in free-recall tasks (for a review, see Tan, Ward, Paulauskaite, & Markou, in press). If the benefit of the nonpredictive cue is because of the increased likelihood of encoding those items first, cued items should also be reported first in the simultaneous condition. In the sequential condition, the order of encoding is fixed so the cue should provide no benefit to WM performance. Instead, the item presented first should be better recalled than the cued item. All items had to be recalled, thereby making the cue not predictive of the probe. This should eliminate potential strategies for inhibiting cued items in the nonpredictive condition. Thus, any benefit of cued items in simultaneous displays is expected to be a product of bottom-up attentional capture to the location of the cued item.

Method

Participants. Thirty participants from Michigan State University participated in this experiment for course credit.

Stimuli. The stimuli, presented on a black background, were six white letters evenly spaced around a centered and continuously visible gray fixation cross. The six letters were randomly chosen each trial from a set of possible letters that included all letters in the English alphabet with the exception of vowels. The size and spacing of the letters were identical to Experiments 1 and 2. Cues were always nonpredictive in this experiment.

Task. The task consisted of four blocks, each containing 30 trials. Half of the blocks presented the six letters simultaneously and the other half presented the six letters sequentially. The sequential letters were presented in a predictable clockwise order. The blocks types were ABBA/BAAB counterbalanced between participants.

The simultaneous block mirrored Experiment 1B (Figure 1A): the trial began with 2,000 ms of fixation, followed by the cue for 50 ms, then after 50 ms of fixation, the memory array in which six letters were presented simultaneously was shown for 100 ms. After 900 ms of fixation, the participants were brought to test.

The other two blocks presented the six letters in a sequential clockwise fashion, starting at the topmost position and mirrored the trial sequence of Experiment 2 (Figure 1B). Each trial began with 2,000 ms of fixation; the six letters were then presented sequentially, each for 100 ms with 50 ms of fixation between each letter. The first letter was shown at the topmost position, and each following letter was presented in the next clockwise position. A white cue appeared for 50 ms before a randomly selected letter in the sequence of six letters, showing where the next letter would appear after 50 ms of fixation. After all six letters were presented, fixation was shown for 900 ms, and then the participants were brought to test.

Unlike Experiments 1 and 2, there was a free recall test rather than a probed response. At the end of the trial, participants saw a "?" on screen and were instructed to type in as many letters as they remembered seeing in that trial. Only six letters were allowed to be typed, and responses could be given in any order—not necessarily the order of presentation. Trials were graded such that if a presented letter appeared anywhere in the string of participants' responses, it was marked as correct. Each position was cued an equal number of times each block.

Results

For each position, we first examined whether we replicated our findings of reduced cue effects in the sequential condition. In the simultaneous condition, position denotes the location on the screen of the item whereas in the sequential condition, it denotes the position and the order of presentation. A repeated measures ANOVA with position (6) $\times$ presentation mode (simultaneous/sequential) $\times$ cuing (cued/uncued) was performed with accuracy data. Overall accuracy between simultaneous and sequential conditions was equivalent, $F(1, 29) = 0.28$, $p = .60$. A main effect of cue, $F(1, 29) = 44.33$, $p < .001$, and the predicted interaction of presentation $\times$ cue, $F(1, 29) = 22.24$, $p < .001$, were observed. The cuing effect was larger with simultaneous presentation (16.4%) than with sequential presentation (3.8%), $t(29) = 4.72$, $p < .001$ (Figure 4). Although reduced, a significant cuing effect occurred with sequential presentation, $t(29) = 3.48$, $p = .002$. Thus, the cuing effect was reduced but not completely eliminated when items were presented sequentially, presumably because of the reduction of strategic effects of using the cue when all items had to be remembered.

The interaction between presentation mode and position was also significant, $F(5, 145) = 4.85$, $p < .001$. Regardless of cuing, accuracy for items presented at the top (i.e., positions 1 and 6) was higher than at the other positions (Figure 5). In the sequential

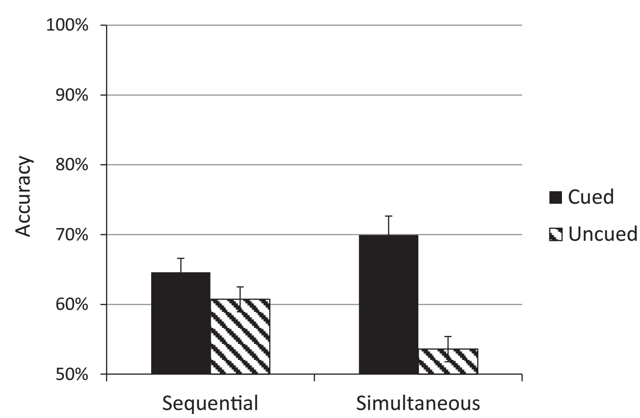

Figure 4. Means for accuracy in Experiment 3 with *SE* bars, separated by cuing and presentation style.

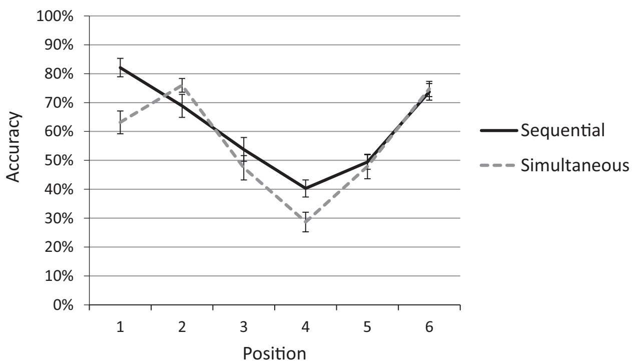

Figure 5. Means for accuracy in Experiment 3 with *SE* bars, separated by position and presentation style.

conditions, this also corresponded to a primacy and recency effect as these items were presented first and last. The interaction was accounted for by significantly greater accuracy at positions 1, $t(29) = 5.22$, $p < .001$, and 4, $t(29) = 3.69$, $p = .001$, in the sequential condition than the simultaneous condition. Conversely, accuracy at position 2 was higher in the simultaneous condition, $t(29) = -2.11$, $p = .044$. These results show that, in addition to an advantage in the location at the top of the screen, there was an advantage of position 1 in the sequential condition because of a primacy effect. The lower accuracy at position 4 in the simultaneous condition is unclear, but may reflect the verbal nature of the stimuli; this might bias the encoding of the upper left-hand part of the display as when initiating reading.

Our main research question concerned whether cued items were reported first more often in the simultaneous than the sequential condition. To answer this question, we calculated the proportion of trials in which the letter was reported first in the list. Separate Position (6) × Cue (2) repeated-measures ANOVAs were performed on these proportions. Consistent with our prediction, the cue did not determine whether an item was reported first in the sequential condition, $F(1, 29) = 0.08$, $p = .785$ (Figure 6). Instead, items presented first in the list were also more likely to be reported first, $F(5, 145) = 152.51$, $p < .001$. The interaction effect was not significant, $F(5, 145) = 1.13$, $p = .349$. In contrast, cued items were more likely than uncued items to be reported first, $F(1, 29) = 26.11$, $p < .001$ (Figure 7). There was also a significant main effect of position that mirrored the accuracy data, $F(5, 145) = 22.39$, $p < .001$; that is, items at the top of the screen tended to be reported first more often than those at the bottom of the screen. The interaction was not significant, $F(5, 145) = .45$, $p = .814$. This pattern is consistent with the proposal that bottom-up attention improves WM for cued items by imposing a primacy effect on the cued item. These results confirmed that the primacy effect was driven by the order of presentation in the sequential condition and by bottom-up attention in the simultaneous condition.

Discussion

Experiment 3 examined whether the benefit of nonpredictive cues was because of a primacy effect when items were presented simultaneously. We obtained evidence that this was the likely mechanism for the advantage of bottom-up attention to cued items: Cued items tended to be reported first more often in the simultaneous condition than in the sequential condition. This suggests that bottom-up attention prioritizes encoding order such that items that capture attention are more likely to be encoded first. Thus, bottom-up attention may not only increase the likelihood that an item gets encoded at all, but it is likely to be encoded before all other items. As a consequence, the cued item benefits from a primacy effect, which is conferred on items presented first in a sequence.

A primacy effect was observed for initial items (both cued and uncued) in the sequential condition. Primacy effects, however, have been absent in several studies of visual working memory (Broadbent & Broadbent, 1981; Phillips & Christie, 1977a, 1977b; Woodman, Vogel, & Luck, 2012). The difference between these studies and the present study may be because of the use of verbal stimuli in the present experiment which is amenable to articulatory rehearsal strategies in comparison to the nonverbal stimuli used in previous studies (e.g., abstract patterns, colored squares). The ability to rehearse via articulation may produce a primacy effect in which initial items are more likely to enter long-term memory (Waugh & Norman, 1965). While this may explain the primacy effect in the sequential condition, it is an unlikely explanation for the effect of cuing in the simultaneous condition. Cued items are most likely encoded first, but the relatively short encoding time does not allow for extensive rehearsal. More likely, the prioritiza-

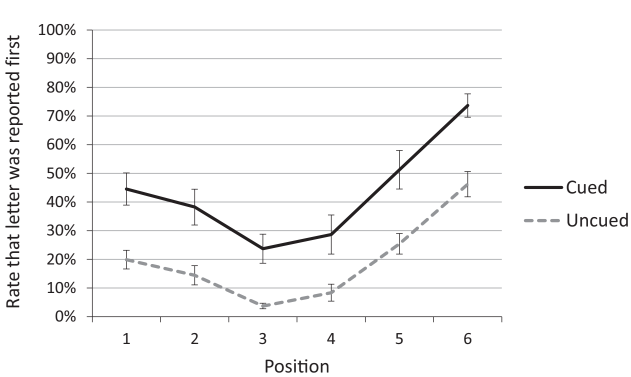

Figure 6. Means for accuracy in the sequential condition of Experiment 3 with *SE* bars, separated by position.

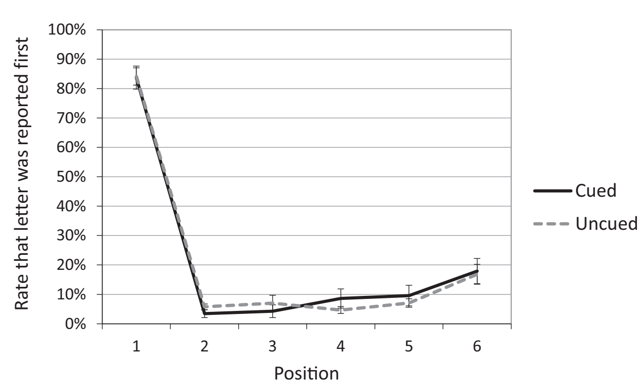

Figure 7. Means for accuracy in the simultaneous condition of Experiment 3 with *SE* bars, separated by position.

tion of cued items at encoding prevents other items from entering WM. Indeed, Experiment 1B demonstrated that the superior memory for cued items came at the expense of memory for uncued items. When items compete for selection at encoding, bottom-up attention helps to determine where to start the encoding process.

It is important to note that the difficulty between the simultaneous and sequential conditions was matched. Thus, the longer encoding time in the sequential condition did not result in more items being store in WM. The shorter encoding time in the simultaneous condition reduced the potential for strategic encoding such as moving attention back to some items more than others. This allowed us to get a more pure measure of attentional selection.

Bottom-up attention to cued items in the sequential condition had less effect on memory for those items than in the simultaneous condition. However, a residual cuing effect was apparent in the sequential condition unlike Experiment 2. The difference between Experiments 2 and 3 was in the method used to probe memory. In Experiment 2, the nonpredictive cue was unrelated to the likelihood that the item would have to be remembered. Participants may have implemented a strategy whereby items that were nonpredictively cued were inhibited so as to not give an advantage over that item compared with all others. Indeed, uncued items were better remembered in the nonpredictive cue condition than the predictive condition in Experiments 1 and 2. Once it was advantageous to remember all items, the nonpredictive cue showed a small residual benefit to WM in the sequential condition. Thus, the primary advantage of bottom-up attention to WM is in determining encoding order, however, we cannot rule out the possibility of a small benefit to the perceptual trace.

General Discussion

The purpose of these experiments was to characterize the mechanism by which WM is enhanced for items that capture attention. We considered two possibilities: First, automatic capture might function similarly to voluntary attention by enhancing sensory processing of attended stimuli (Gazzaley & Nobre, 2012). As an alternative, the benefits of bottom-up attention in WM may be because of its ability to bias encoding order. This latter hypothesis implies that the benefit of bottom-up attention to WM performance is because of how item encoding is prioritized rather than the perceptual trace. Bottom-up attention, therefore, increases the likelihood that the attended item is encoded and, further, that it is encoded before other items.

To adjudicate between these two explanations, we assessed the effects of voluntary and bottom-up attention when encoding order was fixed (serial presentation) or open-ended (simultaneous presentation). If bottom-up attention directly affects the WM representation by prioritizing encoding order, bottom-up attention should have greater effects on items presented simultaneously than serially. Our results primarily support the latter hypothesis. Bottom-up attention had little effect on WM when items were presented sequentially in a predictable location (Experiments 2 and 3). In contrast, voluntary attention improved WM performance for attended items regardless of presentation mode (Experiments 1A, 1B, and 2). These results are consistent with the hypothesis that bottom-up attention enhances WM performance because it influences the order of encoding when information is presented simultaneously.

The idea that voluntary and bottom-up attention enhance performance in different ways is supported by evidence from perceptual tasks without a strong memory component. In spatial cuing tasks, for example, bottom-up attention is thought to facilitate the speed of target detection because information is accumulated earlier for stimuli presented at the cued location (for a review, see Prinzmetal & Landau, 2008). In contrast, voluntary attention is thought to enhance the perceptual representation, which would affect both accuracy and processing speed. In a difficult face discrimination task, for example, accuracy is better for cued faces when spatial cues are predictive of the location but is unaffected when cues are not predictive (Prinzmetal, McCool, & Park, 2005).

Similarly, salient or novel items that capture bottom-up attention are more likely to be selected before all others in visual search tasks. In pop out search, bottom-up attention is drawn first to the unique item as demonstrated by the well-known observation that the speed of responding remains constant regardless of how many other items are in the search array (Treisman & Gelade, 1980). Thus, bottom-up attention affects whether perceptual encoding occurs or how early it begins but not necessarily the quality of the representation (Prinzmetal et al., 2010; Prinzmetal et al., 2005).

Imaging and neural recording studies have demonstrated that voluntary attention modulates processing in sensory regions (Gazzaley, Cooney, McEvoy, Knight, & D'Esposito, 2005; Kastner, DeWeerd, Desimone, & Ungerleider, 1998; Polk, Drake, Jonides, Smith, & Smith, 2008). This modulation is thought to enhance memory and perception of attended items by improving neural efficiency of stimulus processing. Furthermore, voluntary attention is thought to impact storage processes as well by keeping items refreshed during maintenance (Cowan, 1995) and by preventing interference from distractors (Clapp, Rubens, & Gazzaley, 2010; Hakun & Ravizza, 2016). Our results suggest that this may not occur for items that capture bottom-up attention. In this case, attention that is automatically directed to items benefits memory by prioritizing encoding of that item but has no further effects when the order of encoding is fixed and there is low competition from other stimuli. The neural consequence of bottom-up attention on processing in sensory regions would be an interesting avenue for further research.

Why is WM accuracy unaffected by bottom-up attention apart from initiating encoding order? One possibility is that there is typically no benefit from enhanced sensory processing or storage for these items compared with other items. This was directly manipulated in Experiments 1 and 2 in which the cue varied in how well it predicted the probe item. No benefit was observed to WM from nonpredictive cues when encoding order was fixed (Experiment 2). The effects of bottom-up attention, however, are not restricted to situations in which the cue has low predictability. Importantly, we found little to no effect of bottom-up attention even when all items were to be recalled in Experiment 3. This suggests a more general effect on WM performance when attention is directed automatically rather than voluntarily. When attention is directed in a bottom-up manner, further sensory or storage-related processing does not appear to be triggered. Perhaps enhanced processing is only triggered as the result of a high overlap in what is being perceived and the contents of the task set, as would be the case for voluntary attention. Enhanced sensory processing to novel or salient items may not be advantageous in most situations because task-relevance is typically more beneficial to goal-directed behavior than mere novelty. As a consequence, the cognitive control system may only minimally process such information.

The benefit of the cue in the nonpredictive condition was much smaller than when the cue was predictive. We hypothesized that the cue would have no effect on accuracy when encoding order was fixed. A small, but reliable, effect was observed, however, in the sequential condition of Experiment 3. This suggests that there may be an additional advantage because of bottom-up attention. Future research assessing effects of voluntary and bottom-up attention on the precision of the WM representation would be helpful in determining whether bottom-up attention affects the quality of the perceptual trace in the same way as voluntary attention.

These results also demonstrate that attention has similar effects on both visual and verbal WM. Much previous work on attention and WM has used nonverbal stimuli (Bays & Husain, 2008; Fine & Minnery, 2009; Santangelo & Macaluso, 2013; Schmidt et al., 2002), and this is the first demonstration that attentional capture also improves WM for verbal items. This result is consistent with the domain-general effects of voluntary attention on WM, although a stronger test would ensure that items were encoded verbally.

These results may have implications for using attentional capture to increase memory for information in settings such as a classroom. Drawing attention to the location of important information in a PowerPoint slide, for example, via sudden onsets or animations will increase the chance that students will encode that information first. Bottom-up attention directed to that information may ultimately result in better retention of that information compared with information presented at the same time. On the other hand, capturing attention to an item when there is little other competing information should not enhance memory for the attended item. This research suggests that trying to make items novel or salient to improve memory for those items will not be effective unless there are multiple sources competing for attention. Moreover, voluntary attention had much greater effects on WM than attentional capture. The implication is that it may be more effective to direct students' attention explicitly to important information rather than using attention-grabbing features.

In conclusion, bottom-up attention to the location of an item improved WM performance by influencing the order of encoding. Thus, attentional capture will primarily be effective in situations when there is competition for attentional resources. Attentional capture improves WM by increasing the likelihood that novel or salient items are encoded before other items. In contrast, voluntary attention improves WM regardless of whether encoding order is fixed or open-ended.

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