Journal of Memory and Language 69 (2013) 384–396

Contents lists available at SciVerse ScienceDirect

Journal of Memory and Language

journal homepage: www.elsevier.com/locate/jml

The benefits of stimulus-driven attention for working memory encoding

Susan M. Ravizza [a,*], Eliot Hazeltine [b]

[a] Department of Psychology, Michigan State University, United States
[b] Department of Psychology, University of Iowa, United States

ARTICLE INFO

Article history:
Received 18 July 2012
revision received 30 May 2013
Available online 22 June 2013

Keywords:
Verbal working memory
Attentional capture
Short term memory

ABSTRACT

The present study investigates how stimulus-driven attention to relevant information affects working memory performance. In three experiments, we examine whether stimulus-driven attention to items can improve retention of these items in working memory. Lists of phonologically-similar and dissimilar items were presented at expected or unexpected locations in Experiment 1. When stimulus-driven attention was captured by items presented at unexpected locations, similar items were better remembered than similar items that appeared at expected locations. These results were replicated in Experiment 2 using contingent capture to boost stimulus-driven attention to similar items. Experiment 3 demonstrated that stimulus-driven attention was beneficial for both similar and dissimilar items when the latter condition was made more difficult. Together, these experiments demonstrate that stimulus-driven attention to relevant information is one mechanism by which encoding can be facilitated.

Introduction

Working memory (WM) keeps information in an active state for a short period of time so that it can be readily accessed and manipulated in the service of immediate task goals. Given its limited capacity, WM must be used efficiently, maintaining only task-related information. Therefore, a large body of research has examined how the flow of information into WM is controlled in order to understand the limitations it places on human performance.

The benefit of voluntary attention for prioritizing task-related information at encoding is well-established (for reviews, see Awh, Vogel, & Oh, 2006; Gazzaley & Nobre, 2012); that is, WM performance improves when individuals exert control over what information is encoded and maintained in WM. However, the contents of WM are not entirely under voluntary control. This is primarily demonstrated in research examining the detrimental effects on WM performance when stimulus-driven attention is captured by irrelevant distractors (Anticevic, Repovs, Shulman, & Barch, 2009; Majerus et al., 2012; Olesen, Macoveanu, Tegner, & Klingberg, 2007; West, 1999). Stimulus-driven attention is an involuntary mechanism that is engaged by salient or novel properties of the environment. Rather than focusing on the detrimental effects of stimulus-driven attention to distracting information, the present study examines whether stimulus-driven attention can benefit WM performance.

Theories of WM widely embrace the notion that attention serves as a gate to resource-limited maintenance processes; however, there is little empirical work to verify that stimulus-driven attention results in better WM performance. On the theoretical side, the Embedded Process model (Cowan, 1988, 1999) posits that attention directed towards incoming stimuli will increase the activation level of these items in WM, and that attentional selection can be either voluntary or stimulus-driven. In particular, novel, salient, or personally-relevant stimuli will automatically

* Corresponding author. Address: Department of Psychology, Michigan State University, East Lansing, MI 48824, United States.
E-mail address: ravizzas@msu.edu (S.M. Ravizza).

0749-596X/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.jml.2013.05.007

recruit stimulus-driven attention compared to stimuli that have been habituated. A similar idea is incorporated in the serial-order-in-a-box (SOB) and the oscillator-based memory for serial order (OSCAR) models in which encoding strength is novelty sensitive in order to avoid the storage of redundant information (Brown, Preece, & Hulme, 2000; Farrell & Lewandowsky, 2002). The critical idea is that habituated or unchanged stimuli that do not capture attention will be strongly represented in WM only if they are voluntarily attended whereas novel stimuli will capture attention automatically and, thus, be encoded in WM (Cowan, 1988, 1999). Attention is assumed to modulate how strongly information is activated in WM. Thus, encoding benefits can be obtained by moving attention voluntarily via the top-down control or through stimulus-driven attention that is automatically directed toward novel or salient stimuli.

On the empirical side, investigations of the interaction between attention and WM have focused on the competition between voluntary and stimulus-driven attention when distraction is present (Anticevic et al., 2009; Majerus et al., 2012). For example, stimulus-driven attention to distracting information during the encoding or maintenance interval of a WM task reduces the accuracy and speed of recall (Anticevic et al., 2009; Majerus et al., 2012; Olesen et al., 2007; West, 1999). Other research has examined how items in WM may induce attentional capture to irrelevant items in a visual search task (see Soto, Hodsoll, Rotshtein, & Humphreys, 2008 for a review). Visual search is slower when stimulus-based attention is captured by distractors that are identical to or match the features of items held in WM (Olivers, Meijer, & Theeuwes, 2006; although see, Woodman & Luck, 2007). While these studies clearly demonstrate that stimulus-driven attention to irrelevant information disrupts performance, the current study investigates the potential benefits of stimulus-driven attention for encoding items into WM.

There is evidence that stimulus-driven and voluntary attention may have distinct consequences. For example, stimulus-driven attention does not appear to enhance perceptual encoding (Prinzmetal, Ha, & Khani, 2010; Prinzmetal, McCool, & Park, 2005). Prinzmetal et al. (2005) proposed that stimulus-driven attention shortens the decision stage through non-perceptual priming rather than an enhancing the quality of the perceptual representation (as when items are voluntarily attended). That is, stimulus-driven attention speeds processing because information is accumulated earlier for stimuli presented at the cued location. When response selection is modeled as a leaky accumulator model (e.g., Usher & McClelland, 2001), this results in faster, but not more accurate, responses to involuntarily attended information than unattended information (see Prinzmetal & Landau, 2008 for a review). Prinzmetal et al. (2005) showed in a series of experiments that just this pattern of results is observed when stimulus-driven attention is directed toward a stimulus whereas - both response accuracy and speed of perceptual identification improve when voluntary attention is directed towards a stimulus (Prinzmetal et al., 2005). Memory performance relies on accurate representations rather than speed of responding, however, and this casts doubt on whether stimulus-driven attention can improve WM recall in a similar manner to voluntary attention.

There is little data to indicate whether stimulus-driven attention affects WM performance. Involuntary cuing improves recognition accuracy in a visual change detection task due to the sudden onset of the cue (Schmidt, Vogel, Woodman, & Luck, 2002). Other studies have shown that visual salience (e.g., discontinuities in line orientation, intensity contrast, color opposition) improved memory for an object's location (Fine & Minnery, 2009; Santangelo & Macaluso, 2012). However, all of these studies presented items at multiple locations, simultaneously, making it unclear whether WM performance improved because the quality of information encoded in the memory trace increased or because environmental cues allowed this information to be entered into WM first. In other words, visual salience (Fine & Minnery, 2009; Santangelo & Macaluso, 2012) or the sudden onsets of involuntary cues (Schmidt et al., 2002) may have provided a starting point at which encoding could begin and so these items were prioritized (for a similar argument in perception, see Prinzmetal et al., 2010). It remains unclear whether stimulus-driven attention will have any effect on WM performance when selection is easy. In the present paper, we assess whether stimulus-driven attention will enhance memory when information is presented serially so there is no competition between items at encoding. In this way, we can assess whether stimulus-driven attention has similar benefits to voluntary attention in increasing the amount or quality of information encoded into WM or whether it merely prioritizes selection in a noisy environment.

The interaction of stimulus-driven and voluntary attention

Our hypothesis is that stimulus-driven and voluntary attention can act cooperatively as well as competitively to enhance memory encoding. Stimulus-driven attention may facilitate the encoding of items into WM by reorienting attention to novel or salient information that is task-relevant. Thus, stimulus-driven attention may be important when information is unlikely to be brought into the focus of attention through voluntary effort. For example, the ability to sustain voluntary attention may diminish as a function of time and memory for items at the end of a list of items might be especially vulnerable. This idea is in line with the claims of several WM models which posit a primacy gradient in which the strength of the memory trace declines for each successive item in a list (Brown et al., 2000; Farrell & Lewandowsky, 2002; Page & Norris, 1998). This primacy gradient may be due to declining voluntary attention to a relatively homogenous lists of items (; Farrell & Lewandowsky, 2002). Brown et al., 2000 argue that this idea is consistent with the lack of a primacy effect in incidental memory tasks in which attention may not be voluntarily deployed at encoding.

If stimuli are novel or salient, stimulus-driven attention may alleviate the attenuation and boost the activation of these items' representations. Critically, the benefit of stimulus-driven attention to memory encoding should only be observed for items that are unlikely to be brought into the focus of attention voluntarily. Items that are brought into the focus of attention through voluntary mechanisms are unlikely to benefit any further by boosting attention through stimulus-based mechanisms. Thus, increasing stimulus-driven attention to items should improve memory for items at the end of a list but not for items presented earlier in the list.

Items that are highly similar to previous items in a list may also be unlikely to be brought into the focus of attention because attention will not be moved either via stimulus-driven or voluntary means. Items that share perceptual features are more likely to become habituated and, thus, are less likely to capture stimulus-based attention during encoding. If so, then boosting stimulus-driven attention should be more beneficial for similar than dissimilar items presented at the end of the list. In fact, a loss of stimulus-driven attention may be one factor contributing to the well-established finding that items that sound alike are remembered less well than items that do not sound alike (phonological similarity effect, PSE; Lewandowsky & Farrell, 2008). To assess this possibility, we investigated the effectiveness of engaging stimulus-driven to overcoming the PSE.

To test whether stimulus-driven attention can facilitate encoding, we engaged stimulus-driven attention to similar- and dissimilar-sounding items in Experiment 1 by presenting them at unexpected locations using a modified Posner cuing paradigm (Posner, 1980). Rather than predicting a performance benefit for validly-cued letters, we predicted the opposite; that is, memory should improve for items at the end of the list when they are invalidly cued because stimulus-driven attention is necessary to detect such items (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Corbetta, Kincade, & Shulman, 2002). In contrast, items in the middle of the list should not benefit from an increase in stimulus-driven attention because these items are more likely to be in the focus of attention through voluntary attention.

In Experiment 2, we tested the generality of this approach by employing a different manipulation of stimulus-driven attention, contingent capture, to test the effect of stimulus-driven attention on memory encoding of phonologically-similar items. This task capitalized on the finding that irrelevant items that share a feature with a target are more likely to capture attention. For example, red distractors (colored number signs) are more likely to produce an attentional blink when participants' task is to identify red letters (Folk, Leber, & Egeth, 2002; Serences & Yantis, 2007). This paradigm was adapted such that participants had to remember multi-colored letters while detecting red number signs. In this case, the contingent-based capture of stimulus-driven attention should occur for red letters because these letters share a feature with the target detection task. Similar to the prediction of Experiment 1, recall of letters at the end of the list should be enhanced if they are presented in a task-relevant color compared to letters of a different color.

Experiment 3 assessed whether phonologically similar items benefitted to a greater degree from stimulus-driven attention than dissimilar items by making the latter condition more difficult. This study used the contingent capture paradigm described in Experiment 2. If a loss of stimulus-driven attention is one explanation of the PSE, then performance for similar items at the end of the list should improve more by contingent capture than dissimilar items.

Experiment 1

In the current study, we tested whether stimulus-based attention can facilitate the encoding of items into WM. Thus, we asked participants to encode lists of letters into WM and determined whether the increased stimulus-based attention improved memory performance. We predicted an interaction: the benefit of stimulus-based attention for items at the end of the list should be greater than for items earlier in the list.

We also varied the similarity of the letters in the list in order to increase our chance of finding an effect. Stimuli that are similar to each other will become habituated and, thus, are less likely to capture stimulus-driven attention. As a list of items progresses, the ability to sustain voluntary attention to incoming stimuli may also diminish. A lapse of voluntary attention on performance may not be noticeable for dissimilar lists because stimulus-driven attention to their sensory novelty may bring these items into the focus of attention. In contrast, similar items toward the end of the list may not receive much attention because neither voluntary nor stimulus-based processes are directing attention to those items. Boosting stimulus-driven attention to habituated items at the end of the list may allow those items to enter the focus of attention and, thus, improve their recall.

Materials and methods

Participants

Thirty undergraduates (average age: 19.3 years, 25 F) from Michigan State University participated in this experiment for course credit. All participants provided informed consent.

Stimuli

Nine letters formed the set of dissimilar (A, F, H, L, M, O, R, U, Y) and similar (B, C, D, E, G, P, T, V, Z) items.

Procedure

Six letters were drawn from either the similar or dissimilar letter set and were presented serially for 500 ms (Fig. 1). List type was chosen at random with an equal likelihood of occurrence. Each letter appeared in one of two boxes located on either side of a central point, and one of the boxes would brighten 500 ms before each letter appeared. This brightening predicted the location of where the letter would be presented 57% of the time. The letter appeared on the uncued side 29% of the time and a catch trial in which the box would brighten but no letter subsequently appeared occurred 14%. Cue types were interleaved within a list of letters. Catch trials occurred once in every list, but the proportion of valid and invalid cues was probabilistic. The onset interval between successive letters was 4 s. Participants were instructed to press the space bar as soon as they detected a letter. After all six

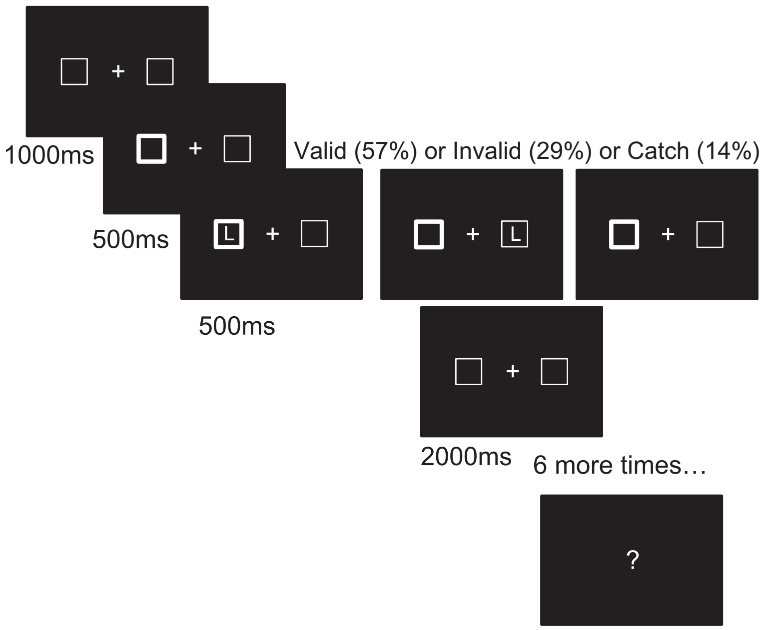

Fig. 1. The modified Posner cuing paradigm used in Experiment 1. Participants were instructed to respond to letters by pressing a key when they appeared while simultaneously memorizing the sequence of the letters for later recall.

letters were presented, there was a 2 s delay in which a fixation cross appeared before participants were asked to recall the letters in serial order by typing them on a standard keyboard. As they typed, the letters were displayed at the top of the screen. If they did not remember the letter in a certain position of the list, they were instructed to insert a period in the list to indicate the missing item. Participants performed 6 blocks composed of 12 lists of 6 letters each. In the least frequent condition (i.e., invalid trials for letters at the end of the list), participants performed an average of 18 trials.

An item was scored as correct if it was recalled in the same serial position as it was presented regardless of the order relative to other items in the list. Trials in which participants failed to respond to a letter when it appeared (2% of trials) were excluded from the analysis. Data from three participants were discarded because the participants did not manually respond to the letters as they appeared. Another participant's data were discarded because the participant scored 3 *SD*s below average performance. This left 26 participants whose data were analyzed.

Results

To ensure that cues were used to direct voluntary attention, we verified that participants were responding more quickly to validly-cued letters. A 2 (cue type) × 2 (list type) repeated-measures ANOVA on letter-detection RT produced a main effect of validity ($F(1,25) = 203.02$, $p < .05$). Participants were slower to detect invalidly-cued letters (517 ms, $SE = 25.58$) than validly-cued letters (435 ms, $SE = 23.16$). List type ($F(1,25) = 1.21$, $p = .28$) and the interaction of cue and list type ($F(1,25) = .38$, $p = .54$) were not significant. Failure to respond to the letter when it appeared was very rare and occurred less than 2% of the time. Misses were equivalent in each condition (list: $F(1,25) = .49$, $p = .49$; validity: $F(1,25) = .19$, $p = .67$; list × validity: $F(1,25) = .36$, $p = .55$). False alarms in catch trials were also rare (4%) and did not differ by condition ($t(1,25) = .14$, $p = .89$).

After confirming a validity effect in the target detection data, we then assessed whether a similarity effect was present in memory recall. The presence of a PSE on memory accuracy was confirmed by a 2 (list type) × 6 (position) repeated-measures ANOVA, which revealed a main effect of list type ($F(1,25) = 17.49$, $p < .05$) as well as a main effect of position ($F(5,125) = 35.41$, $p < .05$). The interaction was also significant and indicated that items near the end of similar-sounding lists were remembered less accurately than items at the end of dissimilar-sounding lists (list type × position: $F(5,125) = 6.52$, $p < .05$; Fig. 2A). Two-tailed *t*-tests confirmed that the PSE at positions 5 and 6 was greater than at the other four positions (all *p*-values < .05).

To evaluate the effects of stimulus-driven attention, accuracy for items at the end of the list (positions 5 and 6) was compared to items in the middle of the list (positions 3 and 4). Items at the beginning of the list were not analyzed because accuracy for these items was near ceiling (position 1: 96%; position 2: 92%). A 2 (position) × 2 (cue type) × 2 (list type) repeated-measures ANOVA was conducted. Critically, the 3-way interaction between position, list type and cue type was significant ($F(1,25) = 5.21$, $p < .05$) (Fig. 2B). To interpret these findings, separate 2 (cue type) × 2 (list type) repeated-measures ANOVAs were run on accuracy for the middle and end positions. A significant interaction of cue and list type was observed for the end positions ($F(1,25) = 4.83$, $p < .05$) but not the middle

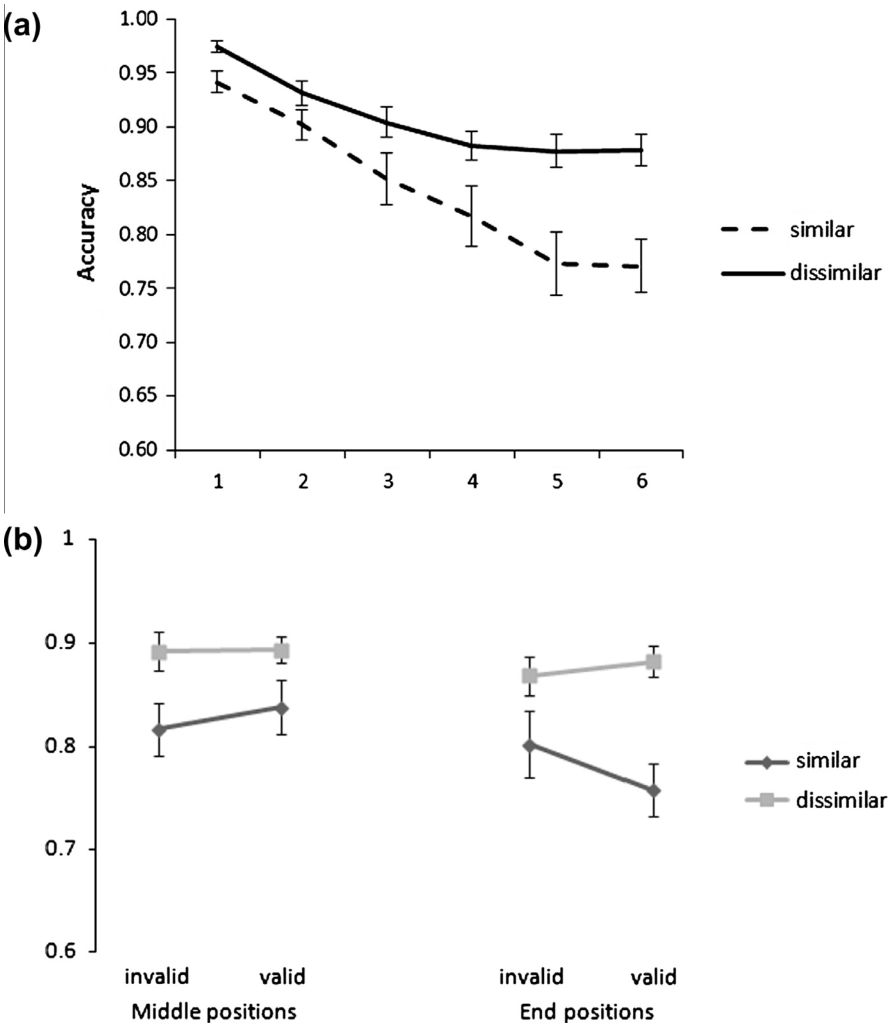

Fig. 2. Serial recall accuracy for (a) similar and dissimilar letters in each position and (b) at middle or end positions of the list when validly- or invalidly-cued in Experiment 1. Error bars indicate the standard error of the mean.

positions ($F(1,25) = .87$, $p = .26$). For items at the end of the list, the PSE was almost twice as large in the valid condition (12.4%) than the invalid condition (6.5%) ($t(25) = 2.2$, $p < .05$). Simple comparisons showed that the PSE was observed for valid items ($t(25) = 5.34$, $p < .05$), but was not significant for invalidly-cued items ($t(25) = 1.84$, $p = .078$). Moreover, similar items were more accurately recalled when they were invalidly-cued than validly-cued ($t(25) = 2.15$, $p < .05$). Cuing did not affect dissimilar-sounding letters ($t(25) = .86$, $p = .4$) and the cue effect was in the opposite direction compared to similar-sounding letters.

Discussion

Experiment 1 demonstrated that stimulus-driven attention can enhance encoding. Items at the end of the list were affected by the manipulation of stimulus-driven attention whereas accuracy for the middle positions showed no such benefit. We interpret this pattern as reflecting failures of voluntary attention during encoding for items at the end of the list. By presenting items at unexpected locations, we were able to re-engage attention to information presented later in the list so that they were more likely to be encoded. Thus, stimulus-driven attention can facilitate encoding if the information is task-relevant.

We found that the PSE was modulated by stimulus-driven attention; although similar-sounding items were consistently remembered less well than dissimilar-sounding items, the differences were much smaller for items that appeared in unexpected locations. These findings indicate that stimulus-driven attention at encoding can be beneficial in cases where items have lost sensory novelty as in the case of the PSE. Memory for dissimilar-sounding items did not become better when they were invalidly-cued, suggesting that this manipulation selectively addressed a specific aspect of processing relating to habituation. However, performance for dissimilar items was close to ceiling which, perhaps, obscured potential improvements in recall from stimulus-driven attention.

As more items in the list are presented, similar-sounding items may be more difficult to encode because voluntary attention may diminish over time. Thus, the encoding of items near the end of the list may rely more on stimulus-driven attention. In this way, stimulus-driven attention does not provide a universal advantage to memory performance. Instead, its benefits are primarily observed in situations in which stimuli have been habituated or voluntary attention has failed.

Stimulus-driven attention is necessary to detect items presented at unexpected locations (Corbetta et al., 2000, 2002) and encoding was facilitated by engaging stimulus-driven attention at that location. Intriguingly, this was true even though the standard validity effect was observed; that is, responses to invalidly-cued letters were slower. Consequently, invalidly cued items had shorter encoding times because of the additional time needed to re-orient attention to the proper location. It is possible, then, that the facilitation effect of stimulus-driven attention is underestimated because the shorter encoding time may have reduced performance in the invalidly-cued condition.

One limitation of this study is that invalidly cued trials were also less frequent, and thus more distinctive, than validly-cued trials. It is possible that items at infrequent locations are more likely to be recalled because of better source memory for those items. This explanation seems unlikely given that the recall of invalidly-cued dissimilar letters was not better than validly-cued dissimilar letters. However, it could be argued that participants used location as a strategy only for the more difficult, similar items. In the Posner cuing paradigm, the valid condition is more frequent in order to ensure that participants direct voluntary attention toward the location indicated by the cue. The higher probability of valid cues ensures that stimulus-based attention is necessary for moving attention towards letters in unexpected locations. In the next experiment, a different means of manipulating stimulus-based attention is employed that does not confound greater stimulus-based attention with less probable events.

Experiment 2

Infrequent items are generally easier to remember; in fact, this idea is the basis of the von Restorff effect in which items are better recalled if they are distinctive in some way (von Restorff, 1933; for a review see Wallace, 1965). The goal of Experiment 2 is to assess stimulus-based attention on recall while controlling for the frequency of potential retrieval cues. To do this, we capitalized on the finding that irrelevant distractors that share a feature with a relevant target are more likely to capture stimulus-driven attention (Folk et al., 2002; Serences & Yantis, 2007). Target detection is slower and less accurate when distractors that match a feature of an attentional set are present (see Soto et al., 2008 for a review). While the effect is partially due to voluntary attention to a target feature, it is the occurrence of the feature when the stimulus is present that captures stimulus-driven attention (Serences & Yantis, 2007). Given that the location and/or time or target presentation is unpredictable, stimulus-driven factors help to determine attentional priority.

While previous studies have focused on the detrimental effects of contingent capture to distractors, in the present experiment, we employ this paradigm in a novel way to assess whether contingent capture to task-relevant information can facilitate performance. Participants were asked to respond to a red number sign (#) while also remembering a series of multi-colored letters. Importantly, the task-relevant color is just as probable as any other color in the list. Letters presented in the task-relevant color should capture stimulus-driven attention and, consequently, improve memory for items at the end of the list. In this way, we used converging methods to demonstrate that manipulations of stimulus-based attention moderate encoding.

Materials and methods

Participants

Forty-three undergraduates (average age: 19.5, 36 F) from Michigan State University participated in this experiment for course credit. All participants provided informed consent.

Stimuli

The set of similar- and dissimilar-sounding letters was identical to Experiment 1. The set of stimulus colors was red, cyan, yellow, lime, magenta, gray, and blue.

Procedure

Seven stimuli (six letters and a number sign) were presented serially in the center of the screen for 1 s followed by 2 s in which a fixation cross was displayed (Fig. 3). Participants were asked to monitor the stream of incoming information for a red # while concurrently remembering the letters in order. When a red # appeared they were asked to press the space bar.

Each letter in a list was presented in a different color which was chosen at random. The position of the letter in the task-relevant color (red) was also selected randomly with an equal likelihood of occurrence at any point in the list. After a 1 s delay, participants were asked to type in the letters in the correct order. As in Experiment 1, a period could be inserted if the letter in that position could not be recalled.

A # could appear in any position in the list and this was chosen at random. A red # appeared in 25% of the lists and appeared in a randomly chosen color from the stimulus set in the remaining lists. Participants performed 5 blocks composed of 16 lists of 6 letters each. A practice run of four trials was given to participants before starting the main task.

As in Experiment 1, letters were accurately recalled if they were remembered in their correct position regardless of their order relative to other items in the list. Accuracy data for letters following a red # were discarded as participants may have missed the subsequent letter due to having to make a manual response. Moreover, trials in which participants responded to the letter were discarded ($n < 1\%$).

For seven participants, the randomization scheme resulted in an insufficient number of samples ($n < 8$) for letters at the end of the list in the task-relevant color

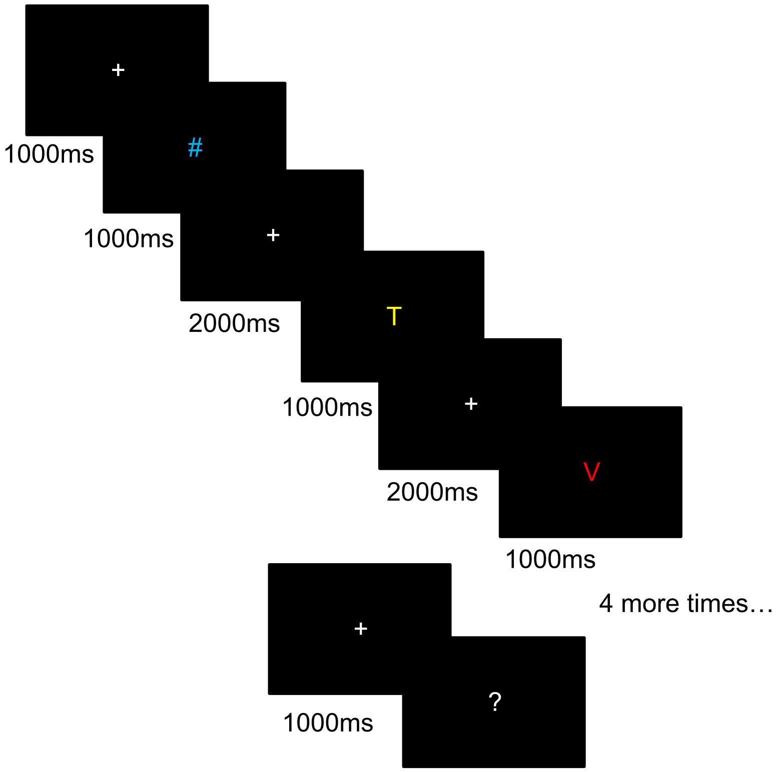

Fig. 3. Example of contingent capture paradigm in Experiment 2. Participants were instructed to respond to red number signs by pressing a key while simultaneously memorizing the sequence of the letters for later recall.

condition. After discarding the data from these seven participants the average number of trials in these conditions was 11 with a maximum of 18 trials. Moreover, the data from one participant was discarded because the participant failed to follow instructions. This left 35 participants with sufficient data for analysis.

Results

Accuracy on the target detection task was high. Participants detected the red # 98.5% of the time and made false alarms .5% of the time. A paired-sample *t*-test showed that hits ($t(34) = .89$, $p = .38$) and false alarms ($t(34) = .30$, $p = .76$) were equivalent for each list type. Hit RT also did not differ between similar and dissimilar-sounding lists ($t(34) = 1.14$, $p = .26$). Thus, target detection did not depend upon the similarity of the letter list in which it was embedded.

The PSE at each position in the list was assessed using a 2 (list type) × 6 (position) repeated-measures ANOVA (Fig. 4A). The results were identical to Experiment 1 with main effects of list ($F(1,34) = 24.64$, $p < .05$) and position ($F(5,170) = 24.9$, $p < .05$) as well as a significant interaction ($F(5,170) = 13.77$, $p < .05$). Paired-sample *t*-tests confirmed that the PSE at positions 5 and 6 was greater than at all other positions (*p*-values of all comparisons < .05).

Of primary interest was whether the PSE diminished for letters presented in the task-relevant color (Fig. 4B). A 2 (middle or end positions) × 2 (task-relevant or irrelevant color) × 2 (similar or dissimilar letter list) repeated-measures ANOVA on accuracy showed that, as in Experiment 1, the 3-way interaction was significant ($F(1,34) = 4.32$, $p < .05$). Again the interaction was examined with two separate 2 (color) × 2 (similarity) repeated-measure ANOVA on accuracy for the middle and end positions. The end positions showed a main effect of color ($F(1,34) = 5.49$, $p < .05$) and list ($F(1,34) = 20.11$, $p < .05$) as well as a significant interaction effect ($F(1,34) = 4.95$, $p < .05$). A paired-sample *t*-test showed that the PSE was smaller in the task-relevant color condition (7.4%) compared to letters presented in an irrelevant color (14.1%) ($t(34) = 2.22$, $p < .05$). Critically, phonologically similar letters that shared the same color as the target in the detection task were better recalled than those presented in a task-irrelevant color ($t(34) = 2.91$, $p < .05$), but no such difference was observed for phonologically dissimilar items ($t(34) = .11$, $p = .92$).

In contrast, the interaction of color and similarity was not significant for items in the middle positions ($F(1,34) = .51$, $p = .48$). Thus, the PSE for items in the middle position was unaffected by whether its color was relevant or irrelevant to the task.

One potential concern from this data set is that we compared one color to the average of the 6 remaining colors and it is possible that any one color could be different than all the rest because of regression to the mean. To assess

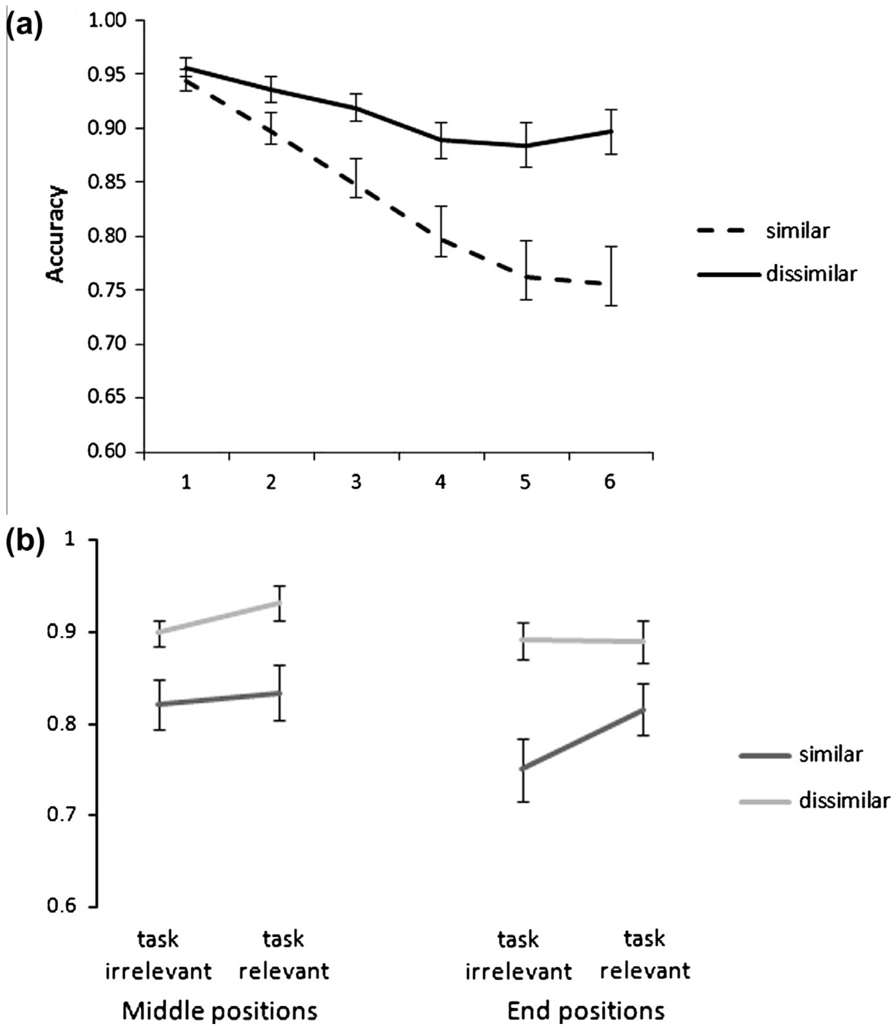

Fig. 4. Serial recall accuracy for (a) similar and dissimilar letters in each position and (b) at middle or end positions of the list for letters presented in task-relevant or irrelevant colors in Experiment 2. Error bars indicate the standard error of the mean.

this possibility, we compared each individual color (gray, blue, cyan, yellow, lime, or magenta) to the average of all the others. None of the interactions of list type and color were significant (all ps > .1).

Discussion

Experiment 2 replicated the principal finding from Experiment 1, that stimulus-based attention modulates the PSE by improving WM for similar items in the final positions of the list. The PSE was reduced for letters that matched the color of the concurrent target detection task but not for letters presented in a different color. This benefit was due to the advantage of the task-relevant color for similar items rather than a reduction in accuracy for dissimilar letters. Critically, in Experiment 2, the task-relevant color occurred as frequently as other colors in the list so should not have acted as a distinctive cue to retrieval. Together, these experiments provide strong evidence that stimulus-driven attention can facilitate encoding.

The next experiment provided a stronger test of whether similar letters benefitted more from stimulus-driven attention than dissimilar items by making the latter condition more difficult. In Experiments 1 and 2, the number of vowels in the dissimilar list was higher than the similar list, and this might have facilitated recall in this condition if participants formed the letter strings into words. Note that this does not negate our previous finding that stimulus-driven attention improves performance for similar letters as these conditions were matched in the number consonants and vowels in the list. However, the lack of improvement in the dissimilar letters and the reduction of the PSE might be due to ceiling performance in this condition. To test this, we removed all vowels from both the similar and dissimilar lists.

Second, we included a condition with eight-item lists so that accuracy would further drop for dissimilar letters in the middle positions. These manipulations will provide a more sensitive test of whether the loss of stimulus-driven attention is one factor producing the PSE.

Experiment 3

The purpose of this experiment was to conduct a strong test of whether stimulus-driven attention could reduce the PSE, at least for items at the end of the list. In Experiments 1 and 2, performance in the dissimilar conditions was close to ceiling and did not allow us to determine whether a larger advantage of attention would be observed for similar letters than dissimilar. The question addressed in this experiment is whether the attentional manipulation has different effects on the phonologically-similar and dissimilar items.

One hypothesis is that enhancing stimulus-driven attention is important in situations in which items are unlikely to be voluntarily attended. Dissimilar items may capture attention regardless of serial position because of their relatively higher novelty and, thus, further increasing their saliency by presenting them in a task-relevant color has no effect. Intriguingly, according to this account, one source of the PSE may be a loss of stimulus-driven attention to similar-sounding items at encoding.

An alternative hypothesis is that recall at the end of the list is simply a function of time rather than of inter-item similarity; that is, the effort of sustaining voluntary attention is more likely to fail for items presented later in the list regardless of their similarity. This hypothesis predicts that recall of both similar and dissimilar items should benefit from enhancing stimulus-driven attention. Thus, we increased the difficulty of encoding by adding additional items in order to see whether the reduction of the PSE was due to a larger effect of attention on similar items or due to the fact that recall had little room to improve in the dissimilar condition.

Materials and methods

Participants

Forty-five undergraduates (average age: 19.3 years, 32 F) from Michigan State University participated in this experiment for course credit. All participants provided informed consent.

Stimuli

Eight letters formed the set of dissimilar (F, H, J, L, M, Q, R, S) and similar (B, C, D, G, P, T, V, Z) items.

Procedure

The procedure was similar to Experiment 2 with the following changes: (1) vowels were removed from the letter lists, (2) the task-relevant color was counterbalanced across participants and could be either yellow, lime, or red, (3) the inter-item interval was set to 2 s rather than 3, (4) task-relevant letters could only occur in positions 3–6 and (5) lists of 6 or 8 letters were used. We compared performance for the same positions in each list; namely, positions 3 and 4 were contrasted with recall of letters at positions 5 and 6 so that we could more directly compare performance between each load.

Participants completed 4 blocks of fifteen trials in each of the high- and low-load lists in a counterbalanced order (AABBBBAA or BBAAAABB). A practice run of four trials was given to participants before starting the main task.

For four participants, the randomization scheme resulted in an insufficient number of samples ($n < 8$) for letters at the end or middle of the list in the task-relevant color condition. After discarding the data from these four participants the average number of trials in these conditions was 14 with a maximum of 22 trials. Moreover, the data from six participants were discarded because they failed to follow instructions; that is, five participants never responded to the target number sign and one participant responded only to the number sign without recalling any letters. Finally, two participants were at floor, recalling less than 25% of items in the low-load, dissimilar condition, and their data were excluded. This left 33 participants whose data were analyzed.

Results

Participants detected the target # 86.8% of the time and made false alarms 1% of the time. A 2 (load) × 2 (similarity) repeated-measures ANOVA showed that hit rate was affected by load ($F(1,32) = 5.16$, $p < .05$). Hit rate was higher in the low-load (89%) than high-load (84%) conditions, but did not differ by list type ($F(1,32) = 0$, $p = 1$). There was no significant interaction ($F(1,32) = .8$, $p = .38$). Hit RT was 23 ms slower in the high-load condition ($F(1,32) = 10.97$, $p < .05$), but did not vary by list similarity ($F(1,32) = .23$, $p = .64$). The interaction between list type and load was not significant ($F(1,32) = 1.26$, $p = .27$). As in the previous experiment, target detection did not depend upon the similarity of the letter list in which it was embedded. However, a high load significantly reduced performance on the concurrent detection task.

The PSE at each position in the list was assessed for each load using separate 2 (list type) × 2 (load) repeated-measures ANOVA (Fig. 5A). The results for the low-load condition were identical to Experiment 1 with main effects of list ($F(1,32) = 46.7$, $p < .05$) and position ($F(5,160) = 23.7$, $p < .05$) as well as a significant interaction effect ($F(5,160) = 12.79$, $p < .05$). Paired-sample *t*-tests confirmed that the PSE at positions 5 and 6 was greater than the first three positions (*p*-values of all comparisons < .05), but not position 4. In contrast, the interaction between position and similarity was not significant at the high load ($F(7,224) = 1.33$, $p = .24$), although main effects of position ($F(7,224) = 48.33$, $p < .05$) and similarity ($F(1,32) = 31.94$, $p < .05$) were observed. Thus, the higher PSE effect for the final positions was not observed once we eliminated ceiling effects. This suggests that the benefit of stimulus-driven attention observed in our three experiments was due to the fatigue of voluntary attention over time rather than to the habituation of similar-sounding items.

Consistent with this interpretation, we no longer found a 3-way interaction indicating that attention selectively improved memory for similar letters at the end of the list (position × color × similarity: $F(1,32) = .06$, $p = .81$). (Fig. 5B). Instead, we found that presenting letters in the task-relevant color enhanced recall of letters at the end of the list regardless of similarity (position × color: $F(1,34) = 4.19$, $p < .05$). A paired-sample *t*-test on accuracy

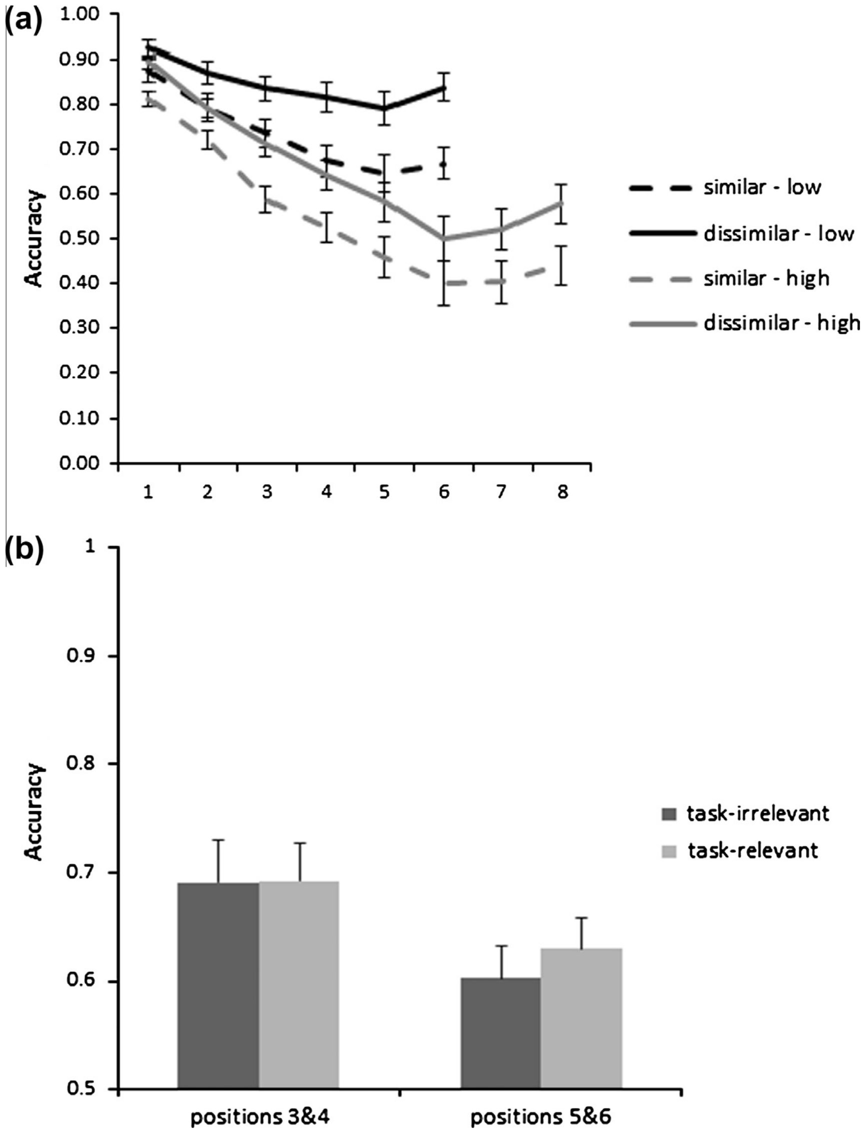

Fig. 5. Serial recall accuracy for (a) similar and dissimilar letters in each position and (b) at middle or end positions of the list for letters presented in task-relevant or irrelevant colors in Experiment 3 (collapsed across similarity and load). Error bars indicate the standard error of the mean.

(collapsed across load and similarity) showed that performance improved for items presented in the task-relevant color at positions 5 and 6 ($t(32) = 2.35$, $p < .05$), but not at positions 3 and 4 ($t(32) = .15$, $p = .88$).

Apart from a significant interaction of position and load ($F(1,34) = 21.7$, $p < .05$), no other interactions were significant.

Stimulus-driven factors allow attention to be re-oriented to task-relevant information. The duration of this effect remains unclear; for example, does stimulus-driven attention have an effect only for the item that captures attention or does it re-engage attention to the sequence of items? In Experiments 1 and 2, we did not have enough data to assess this question given that the only one remaining item in the list (position 6) that could show a benefit of stimulus-driven attention to the previous item. We examined potential benefits of stimulus-driven attention for items 6 and 7 in Experiment 3 to observe whether attention was re-engaged to the sequence or whether the benefit was selective to the particular item drawing stimulus-driven attention. Accuracy for items immediately following a task-relevant colored stimulus at positions 6 and 7 (55%) was very similar to accuracy following an item that was not presented in a task relevant color (54.3%). This difference was not significant ($t(32) = .69$, $p = .49$) suggesting that the benefit was selective to the particular item in the task-relevant color.

Discussion

Experiment 3 replicates the findings of the previous two studies demonstrating that a boost of stimulus-driven attention to items presented later in the list improves recall. Again, this was observed as a function of time and may be reflective of a lapse in sustaining voluntary attention to incoming information. Stimulus-driven attention strengthened the trace of items in WM. This benefit appeared to be selective to individual items rather than drawing attention back to the list of successive items.

In contrast to Experiments 1 and 2, we did not find a selective enhancement for the recall of similar-sounding letters. This suggests that the improvement of the PSE we observed in the previous experiments was due to the ceiling performance in the dissimilar letter condition. By making the task more difficult, we observed the benefits of stimulus-driven attention on both types of lists. Thus, it is unlikely that a loss of stimulus-driven attention is a fundamental explanation for the PSE, although, more research is warranted.

General discussion

Stimulus-driven attention improved recall for items at the end of the list in two different experimental paradigms. Presenting items at an unexpected location or in a task-relevant color boosted stimulus-driven attention to this information at encoding at times when voluntary attentional resources may be diminished. Thus, stimulus-driven attention to relevant stimuli can facilitate encoding in circumstances in which voluntary attention is expected to have lapsed.

The results of these experiments support models of WM that posit a facilitative role of stimulus-driven attention to task-relevant information during encoding (Cowan, 1999; Farrell & Lewandowsky, 2002). It further delineates these models by specifying the context in which stimulus-driven attention facilitates performance; namely, it supports WM encoding primarily in situations where voluntary attention is likely to be diminished. These results are consistent with the idea of a single focus of attention that can be moved through either stimulus-driven or voluntary means; that is, we did not find that stimulus-driven attention enhanced memory for items in the middle of the list over and above the benefits they incurred from being attended voluntarily. Although these results are consistent with the idea that voluntary and stimulus-driven factors compete for the focus of attention, both types of attention can benefit WM encoding by bring task-relevant information into the focus of attention.

These results are consistent with studies examining the benefits of visual salience for later working memory recall (Fine & Minnery, 2009; Santangelo & Macaluso, 2012). Unlike the current experiments, these previous studies placed high demands on visual selection by presenting multiple items, simultaneously. Although recall in those studies was better for items that were highly salient (and, presumably, also captured stimulus-driven attention), it was unclear whether this benefit was due to the enhancement of the memory trace or prioritization during encoding. In these experiments, items were presented serially so that memoranda were not competing for visual selection. Thus, stimulus-driven attention enhanced memory accuracy even without high selection demands induced by stimulus competition at encoding. These results suggest that the strength of the memory representation is enhanced at encoding by stimulus-driven attention and does not merely serve as a starting point for encoding.

These findings stand in contrast to the null effects of stimulus-driven attention in the accuracy of visual perception (Prinzmetal et al., 2005). Difficult face or letter identification was faster with involuntary cues but not more accurate. Here we find a small but reliable effect on accuracy suggesting that the perceptual representation itself was enhanced by stimulus-driven attention. We should note, however, that the WM task used here does not require subtle perceptual discrimination as all of the stimuli are easily discriminable letters which the subjects are highly practiced at recognizing; the WM task is difficult not because the items are difficult to identify but because many items must be encoded and maintained. Thus, one possibility is that the enhancement is post-perceptual, consistent with the findings that stimulus-driven attention can shorten RT. Another possibility is that stimulus-driven attention serves as a mechanism to move attention to the item, but enhancement of the memory trace will only occur if attention is then sustained voluntarily for some amount of time. In the visual perception studies showing no benefit of stimulus-driven attention to accuracy, stimulus presentation was always less than 250 ms (Prinzmetal et al., 2005, 2010). According to this idea, stimulus-driven attention is beneficial only if sustained attention to the item can be subsequently maintained voluntarily.

We have suggested that stimulus-driven and voluntary attention may act cooperatively; for example, an item capturing stimulus-driven attention may then undergo further processing if attention is sustained to that item through voluntary means. Neuroimaging studies of these attention networks, however, have primarily demonstrated competitive interactions between the stimulus-driven attention network in the temporal parietal junction (TPJ) and the voluntary attention network in the dorsal fronto-parietal cortex (Majerus et al., 2012; Shulman, Astafiev, McAvoy, d'Avossa, & Corbetta, 2007; Todd, Fougnie, & Marois, 2005; Wen, Yao, Liu, & Ding, 2012). For example, greater activation of the voluntary attention network has been associated with better performance in perception (Wen et al., 2012) and WM tasks (Majerus et al., 2012; Todd et al., 2005) whereas performance is adversely affected with greater activation of the stimulus-driven attention network (Majerus et al., 2012; Shulman, Astafiev, McAvoy, d'Avossa, & Corbetta, 2007; Todd et al., 2005; Wen et al., 2012). Moreover, this trade-off between the two attention systems becomes more apparent with higher WM load (Majerus et al., 2012; Gillebert et al., 2012).

The critical difference between studies showing competitive interactions between voluntary and stimulus-driven attention and the present experiments is the presence of distracting stimuli. Indeed, if stimulus-driven attention is engaged by salient features of task-irrelevant information, performance will suffer to the extent that voluntary attention can prevent the re-orienting of attention to salient distractors. This suppression of the stimulus-driven attention network by the voluntary attention network is even more critical when distraction is present and load is high. The results reported in the present experiments suggest a more complex relationship between these two attention networks; namely, it is not always better if the voluntary network wins the competition to determine the focus of attention. In some situations, stimulus-driven attention may be critical to encoding task-relevant items when the voluntary attention system has failed to bring those items into the focus of attention.

Our finding of enhanced encoding with stimulus-driven attention to items that are to be maintained in WM is consistent with a separate line of research focusing on the role of the TPJ in WM (Ravizza, Hazeltine, Ruiz, & Zhu, 2011). Studies of patients with low verbal short-term memory spans point to a region in the inferior parietal lobe close to the Sylvian fissure as being the location of maximal overlap of lesions producing this deficit (Koenigs et al., 2011; Shallice & Vallar, 1990). This result has been interpreted as indicating that the left TPJ acts as a phonological storage buffer. However, much evidence has supported a role for the TPJ in stimulus-driven attention. This study provides support that stimulus-driven attention can be important for WM encoding and suggests that patients with lesions to the TPJ may have low verbal spans because of less stimulus-driven attention during encoding.[1]

A critical aspect of the current experiments is that attention effects were assessed with verbal rather than visuospatial WM. Most work assessing the interaction of attention and WM has focused on the latter so that it is unclear whether there are domain-specific effects (see Awh et al., 2006). In future studies, however, it will be important to confirm that the facilitative effects of stimulus-driven attention are also observed for visuospatial information.

We proposed that one source of the PSE may be habituation during encoding rather than interference during maintenance or retrieval. We used the PSE was to demonstrate that stimulus-driven attention can benefit encoding in situations in which there is a low probability that items are in the focus of attention. In the first two experiments, similar items primarily benefited from boosting stimulus-driven attention because the dissimilar lists were so much easier to recall. In the third experiment, stimulus-driven attention did not improve the PSE when ceiling effects were eliminated. This supports non-attention based explanations of the PSE as a product of overlapping representations that results in interference during maintenance (Baddeley, 1992) or at retrieval (Nairne, 1990). Recall for items at the end of the list improved regardless of inter-item similarity and encoding of all items at the end of the list is facilitated.

While our results did not support an attention account of the PSE, it would be important to test this with trial-unique stimuli. The dissimilar letters are less likely to be habituated because they are not similar to each other, however, the repetitiveness of the letters across trials may have reduced the overall saliency of the dissimilar letters. Perhaps with a larger list of similar and dissimilar-sounding non-words a larger benefit of stimulus-driven attention would be observed for similar-sounding items.

In conclusion, our results demonstrate that stimulus-driven attention can be beneficial for encoding information into WM. When stimulus-driven attention is captured by stimuli that should be remembered, then it can strengthen the encoding of that information. We argue that this benefit is primarily observed when the ability to sustain voluntary attention to incoming information is diminished. Thus, stimulus-driven and voluntary attention work together to ensure that attention is directed toward relevant information.

[1] The region of the TPJ assessed in the Ravizza et al. (2011) study was more anterior and superior that the region termed the SPT that has been found in studies of auditory–motor integration (Hickok, Buchsbaum, Humphries, & Muftuler, 2003). The conclusion of that paper was that these are functionally separable regions.

Acknowledgments

The authors would like to thank Christopher Blackledge, Elliott Browne, Jordan Ooms, Daniel Rosenblum, and Kelli Starrenberg for testing participants in these experiments. Thanks to Zach Hambrick for reading a version of this manuscript and to Bill Prinzmetal for helpful discussions. This study was funded by the National Science Foundation Early Development CAREER award (#1149078) to S.R.

References

Anticevic, A., Repovs, G., Shulman, G. L., & Barch, D. M. (2009). When less is more: TPJ and default network deactivation during encoding predicts working memory performance. *Neuroimage, 49*, 2638–2648.
Awh, E., Vogel, E. K., & Oh, S. H. (2006). Interactions between attention and working memory. *Neuroscience, 139*, 201–208.
Baddeley, A. (1992). Working memory. *Science, 255*, 556–559.
Brown, G. D., Preece, T., & Hulme, C. (2000). Oscillator-based memory for serial order. *Psychological Review, 107*, 127–181.
Corbetta, M., Kincade, J. M., Ollinger, J. M., McAvoy, M. P., & Shulman, G. L. (2000). Voluntary orienting is dissociated from target detection in human posterior parietal cortex. *Nature Neuroscience, 3*, 292–297.
Corbetta, M., Kincade, J. M., & Shulman, G. L. (2002). Neural systems for visual orienting and their relationships to spatial working memory. *Journal of Cognitive Neuroscience, 14*, 508–523.
Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychological Bulletin, 104*, 163–191.
Cowan, N. (1999). An embedded-processes model of working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 63–101). New York: Cambridge University Press.
Farrell, S., & Lewandowsky, S. (2002). An endogenous distributed model of ordering in serial recall. *Psychonomic Bulletin & Review, 9*, 59–79.
Fine, M. S., & Minnery, B. S. (2009). Visual salience affects performance in a working memory task. *Journal of Neuroscience, 29*, 8016–8021.
Folk, C. L., Leber, A. B., & Egeth, H. E. (2002). Made you blink! Contingent attentional capture produces a spatial blink. *Perception & Psychophysics, 64*, 741–753.
Gazzaley, A., & Nobre, A. C. (2012). Top-down modulation: Bridging selective attention and working memory. *Trends in Cognitive Sciences, 16*, 129–135.
Gillebert, C. R., Dyrholm, M., Vangkilde, S., Kyllingsbaek, S., Peeters, R., & Vandenberghe, R. (2012). Attentional priorities and access to short-term memory: Parietal interactions. *Neuroimage, 62*, 1551–1562.
Hickok, G., Buchsbaum, B., Humphries, C., & Muftuler, T. (2003). Auditory–motor interaction revealed by fMRI: Speech, music and working memory in area Spt. *Journal of Cognitive Neuroscience, 15*, 1–10.
Koenigs, M., Acheson, D. J., Barbey, A. K., Solomon, J., Postle, B. R., & Grafman, J. (2011). Areas of left perisylvian cortex mediate auditory-verbal short-term memory. *Neuropsychologia, 49*, 3612–3619.
Lewandowsky, S., & Farrell, S. (2008). Phonological similarity in serial recall: Constraints on theories of memory. *Journal of Memory and Language, 58*, 429–448.

Majerus, S., Attout, L., D'Argembeau, A., Degueldre, C., Fias, W., Maquet, P., et al. (2012). Attention supports verbal short-term memory via competition between dorsal and ventral attention networks. *Cerebral Cortex, 22*, 1086–1097.

Nairne, J. S. (1990). A feature model of immediate memory. *Memory & Cognition, 18*, 251–269.

Olesen, P. J., Macoveanu, J., Tegner, J., & Klingberg, T. (2007). Brain activity related to working memory and distraction in children and adults. *Cerebral Cortex, 17*, 1047–1054.

Olivers, C. N., Meijer, F., & Theeuwes, J. (2006). Feature-based memory-driven attentional capture: Visual working memory content affects visual attention. *Journal of Experimental Psychology: Human Perception and Performance, 32*, 1243–1265.

Page, M. P., & Norris, D. (1998). The primacy model: A new model of immediate serial recall. *Psychological Review, 105*, 761–781.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*, 3–25.

Prinzmetal, W., Ha, R., & Khani, A. (2010). The mechanisms of involuntary attention. *Journal of Experimental Psychology: Human Perception and Performance, 36*, 255–267.

Prinzmetal, W., & Landau, A. (2008). Dissecting spatial visual attention. In V. Coltheart (Ed.), *Tutorials in visual cognition* (pp. 43–66). New York: Psychology Press.

Prinzmetal, W., McCool, C., & Park, S. (2005). Attention: Reaction time and accuracy reveal different mechanisms. *Journal of Experimental Psychology: General, 134*, 73–92.

Ravizza, S. M., Hazeltine, E., Ruiz, S., & Zhu, D. C. (2011). Left TPJ activity in verbal working memory: Implications for storage- and sensory-specific models of short term memory. *Neuroimage, 55*, 1836–1846.

Santangelo, V., & Macaluso, E. (2012). Visual salience improves spatial working memory via enhanced parieto-temporal functional connectivity. *Journal of Neuroscience, 33*, 4110–4117.

Schmidt, B. K., Vogel, E. K., Woodman, G. F., & Luck, S. J. (2002). Voluntazy and automatic attentional control of visual working memory. *Perception & Psychophysics, 64*, 754–763.

Serences, J. T., & Yantis, S. (2007). Spatially selective representations of voluntary and stimulus-driven attentional priority in human occipital, parietal, and frontal cortex. *Cerebral Cortex, 17*, 284–293.

Shallice, T., & Vallar, G. (1990). The impairment of auditory-verbal short-term storage. In G. Vallar & T. Shallice (Eds.), *Neuropsychological impairments of short-term memory* (pp. 11–53). New York: Cambridge University Press.

Shulman, G. L., Astafiev, S. V., McAvoy, M. P., d'Avossa, G., & Corbetta, M. (2007). Right TPJ deactivation during visual search: functional significance and support for a filter hypothesis. *Cerebral Cortex, 17*, 2625–2633.

Soto, D., Hodsoll, J., Rotshtein, P., & Humphreys, G. W. (2008). Automatic guidance of attention from working memory. *Trends in Cognitive Sciences, 12*, 342–348.

Todd, J. J., Fougnie, D., & Marois, R. (2005). Visual short-term memory load suppresses temporo-parietal junction activity and induces inattentional blindness. *Psychological Science, 16*, 965–972.

Usher, M., & McClelland, J. L. (2001). The time course of perceptual choice: The leaky, competing accumulator model. *Psychological Review, 108*, 550–592.

Von Restorff, H. (1933). Uber die Virkung von Bereichsbildungen im Spurenfeld. *Psychologie Forschung, 18*, 299–342.

Wallace, W. P. (1965). Review of the historical, empirical, and theoretical status of the Von Restorff phenomenon. *Psychological Bulletin, 63*, 410–424.

Wen, X., Yao, L., Liu, Y., & Ding, M. (2012). Causal interactions in attention networks predict behavioral performance. *Journal of Neuroscience, 32*, 1284–1292.

West, R. (1999). Visual distraction, working memory, and aging. *Memory & Cognition, 27*, 1064–1072.

Woodman, G. F., & Luck, S. J. (2007). Do the contents of visual working memory automatically influence attentional selection during visual search? *Journal of Experimental Psychology: Human Perception and Performance, 33*, 363–377.