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Executive and Perceptual Attention play Different roles in Visual Working Memory: Evidence from Suffix and Strategy Effects

Yanmei Hu [a], Graham J. Hitch [b], Alan D. Baddeley [b], Ming Zhang [c] and Richard J. Allen [d]

[a] North East Normal University, Changchun, China

[b] University of York, UK

[c] Soochow University, Suzhou 215123,China

[d] University of Leeds, UK

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Author notes:

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Correspondence concerning this article should be addressed to Graham Hitch, Department of Psychology, University of York, York YO10 5DD, United Kingdom.

E-mail: graham.hitch@york.ac.uk

Abstract

Four experiments studied the interfering effects of a to-be-ignored 'stimulus suffix' on cued recall of feature bindings for a series of objects. When each object was given equal weight (Experiment 1) or rewards favored recent items (Experiments 2 and 4), a recency effect emerged that was selectively reduced by a suffix. The reduction was greater for a 'plausible' suffix with features drawn from the same set as the memory items, in which case a feature of the suffix was frequently recalled as an intrusion error. Changing pay-offs to reward recall of early items led to a primacy effect alongside recency (Experiments 3 and 4). Primacy, like recency, was reduced by a suffix and the reduction was greater for a suffix with plausible features, such features often being recalled as intrusion errors. Experiment 4 revealed a trade-off such that increased primacy came at the cost of a reduction in recency. These observations show that priority instructions and recency combine to determine a limited number of items that are the most accessible for immediate recall and yet at the same time the most vulnerable to interference. We interpret this outcome in terms of a labile, limited capacity 'privileged state' controlled by both central executive processes and perceptual attention. We suggest further that this privileged state can be usefully interpreted as the focus of attention in the episodic buffer.

Key words:

visual working memory, attention, episodic buffer, suffix, recency

Executive and Perceptual Attention play Different roles in Visual Working Memory:

Interference from an Irrelevant Stimulus Suffix depends on Task Strategy

The role of attention in visual working memory is controversial, and this is well illustrated by the problem of memory for feature bindings. Luck and Vogel (1997) showed that storage capacity is limited to a small number of multi-feature objects, with no corresponding limit on the number of individual features. Wheeler and Treisman (2002) followed this with evidence that attention is required for encoding and maintaining feature bindings but not individual features. These observations suggest a close relationship between storage capacity and attention. However, our own experiments led us to question this, as we found equal involvement of attention in memory for features and their bindings (Allen, Baddeley & Hitch, 2006, 2014; Baddeley, Allen & Hitch, 2011).

These contrasting conclusions about the role of attention in maintaining feature bindings in visual working memory are based on different kinds of evidence and, we suggest, different components of attention. Wheeler &Treisman (2002) used change-detection methodology and compared a whole-display test, re-presenting all the memorized items, with a single-probe test, presenting only a single item. They found that binding memory was selectively impaired with a whole-display test whereas feature memory was unaffected. This led them to conclude that a multiple-item test display required a reallocation of general attentional resources needed to maintain binding information in memory, whereas this was not the case for a single-probe test. In contrast, our own experiments studied attention using dual-task methodology, and showed that a demanding concurrent task did not disrupt memory for feature bindings any more than memory for individual features (Allen et al., 2006, 2014; Allen, Mate, Hitch, & Baddeley, 2012; Baddeley et al, 2011). In the present paper we develop the idea that resolution of this apparent contradiction and the key to further progress lies in a broad distinction between perceptual selective attention and executive attentional control (see e.g. Chun, Golomb & Turk-Browne, 2011; Lavie, 2010; Petersen & Posner, 2012). We present evidence that executive control and perceptual selection combine to determine the contents of working memory, and we use this to suggest that dual-task interference reflects competition for executive processes whereas effects of test display reflect perceptual attention.

Our previous dual-task studies stemmed from the hypothesis that encoding and maintaining *any* type of binding information in working memory is a function of a multi-modal 'episodic buffer' and involves executive control processes (Baddeley, 2000). As well as finding equal disruption to memory for visual features and their bindings (Allen et al., 2006, 2012), we found corresponding effects for cross-modal bindings of visual and auditory-verbal features (Allen et al., 2009; Karlsen et al., 2011). We also found similar results in parallel experiments on binding in memory for words and sentences (Baddeley, et al., 2009). These results led us to abandon the hypothesis that creating and maintaining any type of temporary binding in working memory is especially dependent on the central executive (Baddeley et al., 2011). However, a separate strand of evidence suggested that, in contrast, perceptual selective attention plays a key role in maintaining visual feature bindings by protecting them from interference from competing external stimuli. This became evident from the observation that showing an irrelevant 'stimulus suffix' shortly after an array of visual objects interferes with memory for the display (Ueno, Allen et al., 2011). In these experiments, participants were instructed to remember an array of colored shapes and ignore any further colored shape that appeared in a brief interval before the memory test. We found that such a stimulus suffix led to one of two patterns of retroactive interference, depending on its features. Thus, when color and shape features of the suffix were *implausible*, (i.e. had no overlap with the potential memory set), memory for individual features and feature conjunctions suffered similar amounts of retroactive interference. However, when features of the suffix were *plausible* (i.e. drawn from the same set as the memorized items - though without overlap on any given occasion), the amount of retroactive interference was much greater, especially with regard to memory for feature bindings.

INSERT FIGURE 1 HERE

We interpreted these visual suffix effects in terms of the conceptual model illustrated in Figure 1 (adapted from Baddeley et al., 2011). It contains four limited capacity elements: a perceptual attentional filter; a modality-specific short-term store (the visuo-spatial sketchpad); a multi-modal short-term store (the episodic buffer); and an internal attentional resource (the central executive). The model assumes that relevant stimuli pass the perceptual filter and are represented at feature and object levels in the visuo-spatial sketchpad, and that object representations feed into the episodic buffer. Object representations are assumed to be fragile and more prone to overwriting from further stimuli than feature representations, which benefit from being stored with greater redundancy at both the feature and object levels. An important aspect of the model concerns the different roles of the central executive and perceptual selective attention. Thus the central executive is responsible for control processes that include setting up and managing the external attentional filter online to admit relevant stimuli and exclude irrelevant stimuli, as well as operations such as re-activating or manipulating object representations. We assume the perceptual filter is feature-based (Ueno, Mate et al., 2011) and thus occasional failures to exclude a suffix from further processing will be more likely when the suffix has plausible features. When this happens, a representation of the suffix will tend to overwrite stored object information. A suffix with implausible features is less likely to pass the external filter, but keeping it out nevertheless draws on the limited resources of the central executive, resulting in a smaller but more general impairment in recall.

Our model was offered tentatively as a broad conceptual framework and the assumption of different roles for central executive and perceptual components of attention clearly requires further empirical support. One limitation of the studies discussed so far is that in common with most research on visual working memory, objects were presented in a simultaneous display. In the natural world, however, stimuli are distributed in time as well as space. Furthermore, analysis of the temporal dimension can provide useful information about underlying processes. This is illustrated by evidence that memory for sequentially presented visual stimuli shows a recency effect whereby memory for bindings drops away more steeply than memory for individual features, consistent with the assumption that object representations are fragile and more susceptible to retroactive interference from subsequent stimuli than features (Allen et al., 2006; see also Brown & Brockmole, 2010; Gorgoraptis et al., 2011; Logie, Brockmole, & Vandenbroucke, 2009). The present experiments explore what happens when a to-be-ignored visual suffix is presented immediately after a series of to-be-remembered stimuli.

Our model makes two straightforward predictions. The first is that, to the extent that a post-stimulus suffix passes the external attentional filter, it will interfere with memory and will do so more for recent items. This would be consistent with empirical evidence that the recency effect observed by Allen et al. (2006) and others reflects cumulative retroactive interference on earlier items from subsequent items, the final item being entirely free from such interference. When a post-stimulus suffix is presented it will generate additional retroactive interference and this will be greater the more recent the item, resulting in a reduced recency effect. A parallel result is well established in the auditory-verbal domain (Crowder and Morton, 1969), and we were encouraged by the fact that it has also been reported in immediate memory for a sequence of spatial locations (Parmentier, Tremblay & Jones, 2004). The second prediction is that the amount of interference will be greater for a suffix with plausible features. This follows from the assumption that a plausible suffix is more likely to pass the perceptual filter inadvertently. To anticipate, Experiment 1 confirmed these predictions, but data for some participants suggested that strategies could have large effects on performance. Experiments 2, 3 and 4 went on to investigate strategies by giving instructions that altered the pay-offs for remembering early versus late items, on the assumption that any differences would be due to changes in the allocation of central executive resources. Effects of a suffix were studied for different instructional sets to investigate the interplay of perceptual selective attention and executive control. We found that different strategies led to markedly different results, suggesting a significant elaboration of our conceptual model.

Experiment 1

Our initial experiment was an adaptation of the suffix procedure used by Ueno, Mate et al. (2011) in which participants memorised a set of four different colored shapes and shortly afterwards were probed unpredictably with the color or shape of one of the items for verbal recall of its remaining feature. The only difference was that Ueno, Mate et al. (2011) presented the memory items simultaneously at separate locations whereas here they were presented one-by-one in a randomly determined order using a 3 (plausible suffix, implausible suffix, control) × 4 (serial position) design. To recapitulate, we hypothesised there would be a recency effect in the control condition, a reduced recency effect with an implausible suffix, and an even more reduced recency effect with a plausible suffix. This would show that the findings of Ueno, Mate et al. (2011) extend to sequential displays, and would confirm our assumptions about the role of feature-based perceptual filtering in excluding a stimulus suffix from further processing.

Probed recall has the advantage over recognition procedures of yielding error data that provide clues to the underlying processes. Following Ueno, Mate et al. (2011) we separated errors into within-sequence confusions and extra-sequence intrusions. Within-sequence confusions consist of recall of a feature from a different presented item from the one probed, and can thus be considered to reflect binding errors. Intrusions consist of recall of a feature that was not included among the memory items. Ueno, Mate et al. (2011) found that the extra interference caused by a plausible suffix was associated with increased intrusion errors, and that a high proportion of these involved recalling a feature of the suffix. In contrast, within-sequence confusions were insensitive to type of suffix. This pattern is consistent with our assumption that a plausible suffix is likely to pass through the perceptual attentional filter and consequently interfere with object representations. We anticipated similar patterns of errors in the present experiment, but that these would be restricted to the most recent items, i.e., those sensitive to suffix interference.

Method

Participants. Twenty students from the University of York were tested individually and were paid or given course credit. All participants reported having normal color vision.

Materials. The experiment was run on a Pentium PC with a 17-in. screen, using E-prime (ver. 2.0). Stimuli were colored shapes with a visual angle of approximately 0.75° presented against a white background and viewed from a distance of approximately 50 cm. Study items were selected from a set of 64 items formed by crossing 8 saturated colors (red, blue, yellow, green, sky blue, purple, gray, and black) with 8 shapes (circle, diamond, triangle, cross, arrow, star, flag, and arch). Suffixes were of two types: plausible or implausible. Plausible suffixes were selected from the same pool as the study items, subject to the constraint that for each trial neither the color nor shape of the suffix was included among the study items. Implausible suffixes were selected from a perceptually distinct set of 64 items formed by crossing 8 unfamiliar pale colors and 8 unnameable irregular shapes (corresponding to the boundaries of Japanese prefectures). The test cue was either a color-blob or a shape-outline corresponding to one of the study items. These stimuli were identical to those used in Ueno, Mate et al.'s (2011) second experiment.

Design and Procedure. Figure 2 illustrates the time course of events. Each trial began with a 500 ms warning cross at the center of the screen followed by a 250 ms blank screen. Next, four colored shapes were presented one after another at the corners of an invisible square. The center of this invisible square was 1.5° above the center of the screen and the center-to-center distance between items was approximately 2.25°. The four study items appeared in a random spatio-temporal sequence and were each shown for 250 ms separated by blank intervals of 250 ms. Immediately after the offset of the final study item there was either a 1000 ms blank interval (control condition), or a 250 ms blank interval followed by a 250 ms suffix, followed by a blank screen for 500 ms (suffix conditions). When there was a suffix, it was presented at the center of the invisible square. In all three conditions a 250 ms duration auditory beep was played 250 ms after the offset of the last study item (this was to help participants discriminate the to-be-ignored suffix from the study items). Finally, a test cue consisting of either a color-blob or a shape outline appeared 1.5° below the center of the screen. When a color cue was presented, participants were required to recall the name of the shape with that color in the study sequence. When a shape cue was presented they were required to recall the name of the color of that shape in the study sequence. Sets of study items were constructed by random selection from the pool of 64 items subject to the constraint that no shape or color appeared more than once in each trial. Blocks of 24 trials were constructed by randomly ordering the various permutations of suffix condition (3), type of cue (2) and serial position probed (4).

Participants were required to repeat the sequence "1-2-3-4" aloud at two digits per second from the onset of the warning cue until the test probe appeared. This articulatory suppression procedure was adopted to force participants to encode items into visual form rather than verbal form (Baddeley, 1986).

Participants were shown all the study items with their proper names as well as all the possible implausible suffixes before completing a block of 24 practice trials. The experiment proper consisted of 5 blocks of 24 trials with short rests between blocks.

INSERT FIGURE 2 HERE

Results

Each of the main dependent variables (proportion of correct responses, within-sequence confusions and intrusions) was analysed separately. Omissions were extremely rare

(<0.3%) and were not analyzed further. An initial set of ANOVAs found no differences between the shape- and color-cue conditions with respect to any of the experimental manipulations for any of the three aspects of performance (*p*s> .10). Data are therefore collapsed over cuing conditions in the following analyses. Where multiple comparisons are reported, *p* values have been Bonferroni-Holm corrected. These general remarks apply to all four experiments reported here. In the present experiment, the principal analyses took the form of a 3 (suffix condition) × 4 (serial position) repeated measures ANOVA on each dependent variable.

Accuracy. Figure 3 shows the proportions of correct responses in each condition. By inspection, the presence of a suffix reduced recency while having no effect on recall of information from the initial two serial positions, and this effect was greater when the suffix was plausible. ANOVA revealed significant effects of suffix condition, F (2, 38) = 7.71, MSE=0.20, p<.01, η^2=.29, serial position, F (3, 57) = 10.02, MSE=0.46, p<.01, η^2=.35, and their interaction, F (6, 114) = 3.38, MSE=0.05, p<.01, η^2=.15. Multiple comparisons at each serial position were used to explore these differences further. At serial position 4 the plausible and implausible suffix conditions were significantly less accurate than the control condition, t (19) =5.13 and 2.62, p<.001 and p<.05 respectively, and the plausible suffix condition was significantly less accurate than the implausible suffix condition, t (19) =2.33, p<.05. At serial position 3, the plausible suffix condition was significantly less accurate than both the control condition, t (19) =5.62, p<.001, and the implausible suffix condition, t (19) =2.60, p<.05, but the latter did not differ reliably, t (19) =1.09. At serial positions 1 and 2 there were no significant differences between any of the conditions, *ps*>.10.

INSERT FIGURE 3 HERE

Within-sequence confusions. These are errors of recalling a feature from a presented item other than the item probed. Table 1 shows the proportions of within-sequence confusions in each condition. ANOVA revealed a significant main effect of serial position, F (3, 57) =

7.34, *MSE*=0.73, $p<.01$, $\eta^2=.28$ and no other effects, *ps*>.10.Within-sequence confusion errors showed a recency effect coupled with a small primacy effect but were unaffected by either type of suffix.

INSERT TABLE 1 HERE

Intrusions. These are errors of recalling a feature that did not appear in the presented sequence. Overall, intrusions were less frequent than within-sequence confusions (M=15.9% vs. M=37.9%). They were most frequent with a plausible suffix and at mid-sequence positions (see Figure 4). ANOVA revealed significant effects of suffix condition, F (2, 38) = 10.67, *MSE*=0.16, $p< .01$, $\eta^2=.36$, and serial position, F (3, 57) = 3.42, *MSE*=0.04, $p<.05$, $\eta^2=.15$. However, the interaction was not significant, F (4, 76) = 1.40, *MSE*=0.02, $\eta^2=.07$. Multiple comparisons indicated that intrusions were significantly higher with a plausible suffix than in the control condition, t (19) =4.10, $p<.01$, and than with an implausible suffix, t(19) =2.81, $p<.05$. Intrusions were also higher with an implausible suffix than in the control condition, though this difference fell just short of significance, t (19) =2.04, p=0.06.

Finally, it was possible for an intrusion error to correspond to the color or shape of the suffix itself in the plausible suffix condition. The proportion of intrusions of this type was 45%, and was significantly above the 25% expected if all the non-presented features were equally probable, t (19) = 5.78, $p<.001$.

INSERT FIGURE 4 HERE

Discussion

The results demonstrate that the disruptive effect of a suffix on recall of simultaneously presented stimuli (Ueno, Allen et al., 2011; Ueno, Mate et al., 2011) generalizes to sequential presentation. Thus, there was an effect of suffix plausibility on overall recall accuracy, which was associated with intrusion errors that often consisted of a feature of the suffix itself. Such a detailed pattern of correspondences between results for simultaneous and successive displays points to the robustness of the suffix plausibility effect.

As already mentioned, one advantage of sequential presentation is that it allows analysis of the temporal dimension of performance. This is evident in the serial position curves for correct recall. These confirm the prediction of a recency effect that is selectively reduced by a suffix, with a bigger reduction when the suffix is plausible. The absence of any effects of a suffix on recall of earlier items is not due to any floor effect as performance at these serial positions was well above the chance level of .125.

According to the model in Figure 1, the recency effect follows from the assumption that binding memory is fragile and subject to retroactive interference from subsequent items. The disruptive effect of a suffix and its restriction to recent items follows from the assumption that occasional failures of perceptual selective attention allow an irrelevant stimulus to access the buffer and thereby cause extra retroactive interference. Finally, the plausibility effect and the occurrence of plausible suffix features as intrusion errors follow from the assumption that the perceptual filter is feature-based, and thus more likely to fail to exclude irrelevant items containing relevant features.

Two key assumptions in the above account are that filtering is feature-based and occurs at encoding. It might be argued that if both these assumptions are correct, a plausible suffix could not be distinguished from the memoranda during presentation, raising the alternative possibility that filtering occurs at retrieval rather than encoding. On this view both types of suffix enter working memory and generate interference, the amount of interference being greater for a plausible suffix because it is harder to filter out at retrieval. We attempted to rule out this possibility by presenting the suffix in a different location from the memory items and accompanying it with an auditory beep. Nevertheless, we note that we cannot dismiss entirely the possibility of some contribution to the plausibility effect at retrieval.

A further concern arose from inspecting data from individual participants. While the majority behaved consistently with the group data, there were suggestions of a primacy effect and subjective reports of focusing on the first two items for a few participants, raising the question whether the model takes sufficient account of the role of task-specific strategies. For example, Phillips (1983) described an active process of visualization that is normally applied to the final pattern in a series but can also be voluntarily redeployed to privilege an earlier pattern, dramatically improving memory for that pattern. Relatedly, it has been argued that the final item in a sequence is in a privileged state known as the focus of attention, and that executive processes can be used to maintain other items in the focus at the same time (Oberauer & Hein, 2012). For our present purposes we considered the possibility that those few participants who showed a primacy effect were using control processes governed by the central executive to visualise earlier items in the sequence. If so, this would raise further questions, such as whether prioritising earlier items impairs memory for later items, as one might expect if both draw on the same limited capacity resources. We investigate the evidence for such a trade-off in our final experiment, but first we report experiments to see whether the pattern of results illustrated in Figure 3 can indeed be modified by the way executive attentional control is deployed. To achieve this we re-ran Experiment 1 with explicit instructions rewarding retention of more recent (Experiment 2) or earlier items (Experiment 3).

Experiment 2

Our next experiment was a replication of Experiment 1 with instructions designed to discourage a primacy strategy by giving priority to recent items. It used a novel manipulation that rewarded correct recall of each item with a different number of points that incremented in steps of 1 from the first to the last. We entertained the same hypotheses as before, anticipating that results might be more clear-cut when we could be more confident that all participants approached the memory task with a recency strategy.

Method

Participants. Another twenty students from the University of York were tested individually and were paid or given course credit for participation.

Design and Procedure. These were identical in all respects to Experiment 1 save that participants were instructed that different numbers of reward points were assigned to different study items: 1 point for correctly recalling the first item, 2 points for the second, 3 points for the third, and 4 points for the last. Participants were informed that points were offered as purely notional rewards.

Results

Accuracy. Figure 5 shows the proportions of correct responses in each condition. Retention of the final item was again interfered with by the presence of a suffix and the amount of such interference was greater with a plausible suffix. ANOVA revealed significant effects of suffix condition, F (2, 38) = 11.82, MSE=0.28, p<.001, η^2=.38, serial position, F (3, 57) = 21.52, MSE=1.36, p<.001, η^2=.53, and their interaction, F (6, 114) = 2.61, MSE=0.05, p<.05, η^2=.12. Multiple comparisons at each serial position revealed no significant differences between any of the conditions at positions 1 and 2, *ps*>.10. At serial position 3, accuracy in both plausible and implausible suffix conditions was significantly lower than the control condition, t (19) =3.51 and 2.43, p<.01 and p=.05 respectively. However, accuracy in the plausible suffix condition was not significantly below the implausible suffix condition, t (19) =1.35. At serial position 4, accuracy in the plausible suffix condition was significantly lower than the control and implausible suffix conditions, t (19) =5.10, p<.001, and t (19) =2.10, p<.05, respectively. The implausible suffix condition was also significantly less accurate than the control condition, t (19) =2.48, p<.05.

INSERT FIGURE 5 HERE

Within-sequence confusions. Table 1 contains a summary of mean numbers of within-sequence confusions. ANOVA revealed a significant main effect of serial position, F (3, 57) = 22.01, MSE=0.83, p<.001, η^2=.54, with as before a recency effect accompanied by a smaller primacy effect. Neither the main effect of suffix condition nor the interaction was significant.

Intrusions. Figure 6 shows the proportions of intrusions in each condition. By inspection, differences among conditions were restricted to the final serial position where their frequency was increased with a plausible suffix. ANOVA revealed significant main effects of suffix condition, F (2, 38) = 10.59, MSE=0.13, p< .001, η^2=.36 and serial position, F (3, 57) = 4.07, MSE=0.07, p<.05, η^2=.18, and their interaction, F (6, 114) = 2.44, MSE=0.04, p<.05, η^2=.11. Multiple comparisons at serial position 4 indicated that intrusions were significantly higher with a plausible suffix than with no suffix, t (19) =4.80, p<.001, or an implausible suffix, t (19) =3.14, p=.01. There were also significantly more intrusions with an implausible suffix than with no suffix, t (19) =2.46, p<.05. Multiple comparisons at each of the earlier serial positions did not reveal any significant pairwise differences, *ps*>.10.

Recall of a suffix feature occurred in 53% of the total intrusions in the plausible suffix condition (i.e. significantly above the 25% expected if each non-presented feature was equally probable, t (19) = 4.60, p<.001).

INSERT FIGURE 6 HERE

Discussion

The results replicate the main features of the initial experiment, and as anticipated present a somewhat clearer picture. Once again presentation of a suffix impaired recall of more recent items while having no effect on recall of early items, and this effect was greater when the suffix was plausible. The pattern of intrusion errors had the same form as in Experiment 1 but this time there were significant differences among all three conditions at the final position. As before, intrusions tended to include a feature from a plausible suffix. In summary, instructing a recency strategy had little effect beyond making the pattern of results slightly clearer, presumably by reducing uncontrolled variation in strategies.

The next question is what happens when rewards are switched to prioritise earlier rather than more recent items. Firstly, we expected to continue to observe a recency effect that is sensitive to suffix interference despite the change in task priorities. This would be consistent with the suggestion that the final item in a sequence has a privileged status (Oberauer & Hein, 2012; McElree & Dosher, 1989). Secondly, the change in priorities should encourage a strategy of actively visualizing earlier items (Phillips, 1983), boosting their recall and generating a primacy effect in the serial position curve. Furthermore, if maintaining items in the focus of attention results in more stable memory representations (Cowan, 1999), items showing a primacy effect should be protected from interference from a post-sequence suffix. However, an alternative possibility is that the focus of attention is highly labile, more like William James' notion of the stream of conscious awareness (James, 1890). On such an alternative account, the privileged state combines high availability with high vulnerability to interference, and if prioritizing early items involves the same privileged state as recent items, then early items should be susceptible to interference from a suffix in the same way as recent items.

Experiment 3

Method

The method was exactly the same as in Experiments 1 and 2 except that the allocations of rewards were reversed to favor recall of information from the start of the sequence. Thus, participants were told that correct recall of the first item would get 4 points, the second 3 points, the third 2 points and the last item 1 point. Another twenty students from the University of York were tested individually and were paid or given course credit for participation.

Results

Accuracy. Figure 7 shows proportions of correct responses. By inspection, the control condition showed a strong 1-item primacy effect combined with more extensive recency. Presentation of a stimulus suffix reduced primacy as well as recency, in each case the amount of interference being greater with a plausible suffix. ANOVA revealed significant effects of suffix condition, F (2, 38) = 22.45, MSE=0.55, p<.001, η^2=.54, serial position, F (3, 57) =

8.89, *MSE*=0.48, $p<.001$, $\eta^2=.32$, and their interaction, F (6, 114) = 2.82, *MSE*=0.05, $p<.05$, $\eta^2=.13$. Multiple comparisons at serial position 1 showed that the plausible and implausible suffix conditions were significantly less accurate than the control condition, t (19) = 4.80, $p<.001$ and t (19) = 2.53, $p<.05$, respectively, and accuracy was significantly lower with a plausible than an implausible suffix, t (19) = 2.48, $p<.05$. The same pattern was found at serial position 4, where the plausible and implausible suffix conditions were again significantly less accurate than the control, t (19) = 6.37, $p< .001$ and t (19) = 2.53, $p<.05$, respectively, and the plausible suffix condition was again significantly less accurate than the implausible suffix condition, t (19) = 2.65, $p<.05$. At serial position 3, accuracy was lower in the plausible suffix condition than in the control condition, t (19) =4.66, $p<.001$. No other significant difference was found at this position and there were no differences at serial position 2, *ps*>.10.

INSERT FIGURE 7 HERE

Within-sequence confusions. Table 1 summarizes mean numbers of within-sequence confusions. ANOVA revealed a significant main effect of serial position, F (3, 57) = 5.62, *MSE*=0.14, $p<.01$, $\eta^2=.23$, reflecting a combination of recency and primacy. Neither the main effect of suffix condition nor the interaction was significant, *ps*>.10.

Intrusions. Figure 8 shows proportions of intrusions. The pattern of effects broadly reflects that in correct responses, with effects of a suffix at serial positions 1 and 4 and to a lesser extent serial position 3. ANOVA revealed significant effects of suffix condition, F (2, 38) = 25.98, *MSE*=0.27, $p< .001$, $\eta^2=.58$, serial position, F (3, 57) = 3.09, *MSE*=0.08, $p<.05$, $\eta^2=.14$, and their interaction, F (6, 114) = 2.35, *MSE*=0.04, $p<.05$, $\eta^2=.11$. Multiple comparisons were carried out at each serial position. At position 1 intrusions were significantly higher with a plausible suffix than control, t (19) =4.41, $p<.001$, and fell just short of being significantly higher with a plausible than an implausible suffix, t (19) =2.36, $p=.06$, and with an implausible suffix than control, t (19) =2.05, $p=.05$. Corresponding analysis at position 4 indicated that intrusions were significantly more frequent with a plausible or implausible suffix than control, t (19) =5.12 and 2.10, $p < .001$ and $p < .05$, respectively, and were significantly higher with a plausible than an implausible suffix, t (19)=3.09, $p < .05$. At position 3, intrusions were significantly higher with a plausible suffix than control, t (19) =2.38, $p < .05$ but the other pairwise differences were not significant, *ps*>.10. There were no significant differences between conditions at position 3, *ps*>.10.

In the plausible suffix condition some 45% of intrusions corresponded to a feature of the suffix itself which was significantly above the chance level of 25%, t (19) = 5.75, $p < .001$.

INSERT FIGURE 8 HERE

Discussion

When pay-offs were switched to favor retention of earlier rather than recent items, the results were partly similar and partly dissimilar. For recent items, effects were broadly as before, namely a recency effect, a reduction in recency with a suffix reflected in intrusion errors on the final item, and larger effects for a plausible suffix. The novel additional finding was the emergence of a simultaneous primacy effect with similar properties. Thus enhanced recall of the first item was reduced by a suffix, this effect was reflected in increased intrusion errors and there was a greater effect of a plausible suffix. We note that some of the contrasts in intrusion errors in recall of the first item were of marginal significance, suggesting the need for further evidence before drawing firm conclusions.

The primacy effect confirms the prediction that prioritizing early items would encourage a strategy of actively visualizing them, enhancing their recall. Its restriction to the first serial position suggests that participants were only able to apply this strategy to a single item at a time (Phillips, 1983). More surprising was the sensitivity of the initial item to interference from a post-stimulus suffix. This argues against the idea that maintaining an item in the focus of attention stabilizes its memory representation and protects it from interference, as in Cowan's (1999) account. The similar pattern of suffix effects for primacy and recency items instead suggests an account in terms of a common privileged status such that items are more readily accessible for recall but at the same time more vulnerable to retroactive interference from an irrelevant stimulus suffix, especially when the suffix has plausible features. It seems that this privileged status can arise from an item being the most recent stimulus to receive perceptual attention, regardless of strategy, or through strategies such as active visualization which involve executive control. The privileged state can still be identified with the focus of attention, provided this is regarded as a highly labile state rather than one in which maintaining information stabilizes its contents (Cowan, 1999).

Given the unexpected sensitivity of the primacy effect to suffix interference, the above interpretation was *post hoc*. Our final experiment was an attempt to replicate using a more powerful design. Thus the comparison between primacy and recency strategies was made within participants, the implausible suffix condition was dropped, and instead of graded allocations of points across serial positions, instructions specified four points for recall of the first item and one point for each of the other items (primacy strategy), or the converse (recency strategy). A further aim was to explore whether strategies induce a trade-off between primacy and recency. There was a tendency for the emergence of primacy in Experiment 3 to be accompanied by a modest reduction in recency as compared with Experiment 2, but a cross-experiment analysis proved uninformative. Such a trade-off would be expected if the number of items that can have privileged status is constrained by a capacity limitation. However, we note that Cowan (2011) concluded there was no evidence for a trade-off of this sort, and therefore no evidence that the special status of the last item reflects the focus of attention. Experiment 4 provided an opportunity to examine this question within a single study.

Experiment 4

As described above, our final experiment consisted of a within-participants comparison of recall with instructions that emphasise either the first or last item as a function of whether the sequence was followed by a plausible suffix. We kept to the same procedure as before. To summarise our expectations, these were that recency instructions would lead to a recency effect without primacy in correct recall whereas primacy instructions would result in both primacy and recency. Furthermore, recency and primacy effects would be vulnerable to disruption by a suffix and the suffix feature would often appear as an intrusion error. Confirmation of these predictions would support the suggestion that items can enjoy equivalent privileged status as a function of either recency or executive control, and that items in this privileged state are vulnerable to disruption from an irrelevant stimulus. Finally, we reasoned that if the number of items that can be in the privileged state at any time reflects a limited capacity, there should be trade-off such that when primacy is increased there is an accompanying reduction in recency.

Method

A further twenty students from the University of York were tested individually and were paid or given course credit for participation. All participants reported as having normal color vision.

All details were the same as in the earlier experiments save for the change in instructions, their manipulation within-subjects in counterbalanced order, and the omission of the implausible suffix condition. In the Primacy condition, participants were told they would receive 4 points for recall of the first item and one point for each of the other three items. In the Recency condition they were told they would be given 4 points for recall of the last item and one point for each of the other three items.

Results

The main data analyses were a series of 2 (Strategy: Primacy, Recency) × 2 (suffix condition: plausible, control) × 4 (serial position: 1-4) repeated measures ANOVAs on correct responses, within-sequence confusions and intrusions. These were supplemented by 2

(Strategy: Primacy, Recency) × 2 (suffix condition: plausible, control) ANOVAs at each serial position where appropriate.

Accuracy. The 2 x 2 x 4 ANOVA on correct responses revealed a significant effect of serial position, F (1, 19) = 26.72, MSE=1.82, p<.001, η^2=.58, coupled with no main effect of strategy, F<1, and a significant strategy by serial position interaction, F (3,57) = 12.19, MSE = 12.19, p<.001, η^2=.39. The interaction reflects a cross-over whereby the Recency strategy was associated with stronger recency and the Primacy strategy with more primacy (see Figure 9). Recency was present in both strategy conditions whereas primacy was only clearly present under Primacy instructions. Pairwise comparisons between strategy conditions at each serial position indicated that primacy instructions were associated with significantly better recall at position 1, t (19) = 2.42, p< .05, whereas recency instructions were associated with significantly higher recall at position 3, t (19) = 4.90, p< .001 and position 4, t (19) = 7.99, p< .001. There was no effect of strategy at serial position 2.

INSERT FIGURE 9 HERE

The above pattern was modified by the presence or absence of a suffix. Figure 10 shows serial position curves for all four combinations of strategy and suffix conditions. These show that presentation of a suffix reduced only recency under recency instructions whereas it reduced primacy as well as recency under primacy instructions. These observations were reflected in the ANOVA by significant effects of the three-way interaction, F (3, 57) = 4.36, MSE= 0.07, p<.01, η^2= .19, the suffix condition by serial position interaction, F (3, 57) = 13.17, MSE=0.14, p<.001, η^2=.41, and the main effect of suffix condition, F (1, 19) = 60.50, MSE=0.80, p<.001, η^2=.76.

INSERT FIGURE 10 HERE

To explore further, separate 2 (Strategy) x 2 (Suffix condition) ANOVAs were carried out for each serial position. At position 1, there were significant effects of suffix condition, F

(1, 19) = 5.84, *MSE*=0.08, $p<.05$, $\eta^2=.24$, strategy, F (1, 19) = 14.56, *MSE*=0.63, $p=.001$, $\eta^2=.43$, and their interaction, F (1, 19) = 5.39, *MSE*=0.09, $p<.05$, $\eta^2=.22$. Pairwise comparisons revealed that with primacy instructions the suffix condition was less accurate than the control condition, t (19)=4.46, $p<.001$, but with recency instructions there was no significant effect of a suffix, $t<1$.There were no significant effects at serial position 2, *Fs*<1. At serial position 3, there were again significant effects of suffix condition, F (1, 19) = 24.01, *MSE*=0.22, $p<.001$, $\eta^2=.56$, strategy, F (1, 19) = 5.09, *MSE*=0.18, $p< .05$, $\eta^2=.21$, and their interaction, F (1, 19) = 10.56, *MSE*=0.11, $p<.01$, $\eta^2=.36$. However pairwise comparisons revealed that the pattern of interaction was the opposite of that at serial position 1. Thus, in the case of Primacy instructions recall was unaffected by a suffix, t (19) =1.03, $p>.05$, whereas with Recency instructions a suffix significantly impaired recall, t (19) =5.34, $p<.001$. Finally, at serial position 4 there were significant effects of suffix condition, F (1, 19) = 63.76, *MSE*=0.93, $p<.001$, $\eta^2=.77$, and strategy, F (1, 19) = 9.28, *MSE*=0.51, $p< .01$, $\eta^2=.33$, but not the interaction, $F<1$. Here, presentation of a suffix impaired recall of the last item in a sequence regardless of instructions.

Within-sequence confusions. Table 2 shows mean numbers of confusion errors in the various conditions. Overall, there were fewest confusion errors at the final position. The 2 × 2 × 4 ANOVA revealed a significant main effect of serial position, F (1, 19) = 23.58, *MSE*=0.87, $p<.001$, $\eta^2=.55$, and its interaction with strategy, F (3, 57) = 7.26, *MSE*=0.20, $p<.001$, $\eta^2=.28$. No other effects were significant. Pairwise comparisons indicated that the interaction reflected fewer within-sequence confusions in the Primacy condition at serial position 1, t (19) = 2.58, $p< .05$, and a difference in the opposite direction at serial position 4, t (19) = 3.23, $p< .01$.There were no significant differences associated with strategy condition at positions 2 and 3. It is interesting to note that the form of this interaction runs broadly parallel with the trade-off between recency and primacy in correct responses.

INSERT TABLE 2 HERE

Intrusions. The distribution of intrusions over serial positions was broadly the inverse of the accuracy serial position curves. Thus, a suffix tended to increase intrusions at positions 1 and 4 in the Primacy condition and positions 3 and 4 in the Recency condition. ANOVA showed significant effects of suffix condition, F (1, 19) = 42.80, MSE=0.46, p<.001, η^2=.69, serial position, F (1, 19) = 9.11, MSE=0.22, p<.001, η^2=.32, and the interaction between suffix condition and serial position, F (3, 57) = 4.20, MSE=0.07, p<.01, η^2=.18. However, the three-way interaction involving strategy was only marginally significant, F (3, 57) = 2.72, MSE=0.050, p=.06, η^2=.13. There were no other significant effects, ps>.10.

The proportion of intrusions that corresponded to a feature of the suffix was 45% in the Primacy condition and 42% in the Recency condition. Both proportions were significantly greater than that expected if all 4 non-presented features were equally likely, t (19) = 5.12 and 5.97 respectively, p<.001 in each case.

INSERT FIGURE 11 HERE

Discussion

The results confirm Experiments 2 and 3 in showing that primacy and recency strategies have markedly different effects on the recall of items from different positions in a sequence. Use of a within-participants design and instructions emphasising the first or last item versus the remainder had the desired outcome of giving clearer results. Thus, a recency effect was observed for both primacy and recency instructions. In each case the recency effect was disrupted by a to-be-ignored stimulus suffix and the disruption was reflected in an increase in intrusion errors. These effects embraced items from the last two positions for the recency strategy, but only the final item for the primacy strategy. As regards the primacy effect, this was only observed with primacy instructions and was restricted to a single item. However, akin to recency and as in Experiment 3, enhanced memory for the first item was disrupted by a stimulus suffix and the disruption was reflected in increased intrusion errors. In terms of the idea of a privileged state, we can thus be more confident in distinguishing two different ways by which information can gain access – one a consequence of recency and another that is strategy-dependent and can apply to items prioritised through instructions. The key defining characteristic of this privileged state is that items have a relatively high probability of recall but are at the same time particularly vulnerable to interference from subsequent stimuli, even when instructions stress the importance of not paying attention to such stimuli, as in the case of a suffix.

The second main aspect of the results is evidence for a trade-off such that enhanced primacy due to instructions is accompanied by reduced recency. This is important as it argues against Cowan's (2011) conclusion that the special status of the last item does not reflect the focus of attention. It suggests instead that common resources limit the number of items that can have privileged status at any time. We note, however, that the trade-off leaves a large component of recency intact, suggesting that the trade-off is limited to the executive resources required for active visualization. Finally, it is interesting to note also that enhanced primacy and enhanced recency were each accompanied by a decrease in within-sequence confusions, as would be expected if the boost to memory associated with executive control processes involved strengthening feature bindings.

General Discussion

Previous research had shown that a to-be-ignored stimulus suffix presented shortly after a simultaneous display of objects interferes with memory for the objects, and that the pattern of effects depends critically on the features of the suffix (Ueno, Allen et al., 2011; Ueno, Mate et al., 2011). For an 'implausible' suffix (with features from a different pool from the objects), the amount of interference is the same for individual features and feature bindings. However for a 'plausible' suffix (with features drawn from the same pool as the objects) interference is greater, and memory for feature bindings is disrupted significantly more than memory for individual features. Other evidence had shown that when objects are presented sequentially, recency effects are observed, with feature bindings more vulnerable to retroactive interference from later items than individual features (Allen et al., 2006). Putting these two sets of findings together we predicted that a to-be-ignored suffix would have its greatest effect on memory for the most recent items in a sequence, and that a suffix with plausible features would do this to a greater extent.

Experiments 1 and 2 confirmed these predictions and showed further that suffix interference was reflected in increased intrusion errors that often consisted of a feature of a plausible suffix. We took these results as consistent with the conceptual model in Figure 1 according to which an irrelevant, to-be-ignored suffix sometimes passes a feature-based perceptual filter and overwrites object representations, being more likely to pass and interfere when its features are compatible with the set of potential memory items.

Experiments 2, 3 and 4 examined suffix effects in the context of instructions encouraging primacy or recency-based memorisation strategies. In theoretical terms, strategies are interesting because they require the central executive component within our model. Therefore the interplay between executive attentional control and perceptual selective attention should be reflected in the way that strategy and suffix effects interact. Although the detailed results of Experiments 2, 3 and 4 were complex, they formed a simple general pattern comprising separate clusters of similar effects. One cluster was broadly independent of strategy and consisted of enhanced recall of the most recently presented items; the other cluster was highly dependent on strategy and consisted of enhanced recall of either early or recent items, depending on whether instructions emphasised primacy or recency. Within each cluster, the enhancement in recall was vulnerable to suffix interference, the reduction in recall was greater when the suffix was plausible, and intrusion errors often comprised a feature of a plausible suffix. Outside these clusters, recall was unaffected by either presentation of a suffix or instructed strategy. Finally, Experiment 4 demonstrated a trade-off whereby prioritising the first item not only increased primacy but also reduced recency relative to prioritising the final item. Thus, our main empirical observation is that a limited number of items have higher accessibility for recall but are also vulnerable to retroactive interference, and the identities of these items depend on both instructed task priorities and recency of presentation.

In the course of obtaining these results we developed the hypothesis that a limited subset of items can occupy a highly accessible privileged state, either as a function of being the most recently presented, or optionally for any item, depending on strategy. We assume that access to the privileged state is the default state for new information entering working memory as a consequence of selection by the perceptual filter. We assume further that items in the privileged state are fragile and vulnerable to overwriting, as for example when there is a failure of perceptual selective attention and a stimulus suffix gains access to the privileged state despite instructions to ignore it. Inappropriate selection of a suffix due to faulty filtering would be more likely for plausible suffixes that match the feature-based criteria for perceptual selection. Thus, the general picture is that the boost to memory performance for items within the privileged state comes at the cost of being particularly susceptible to interference from subsequent items that pass the perceptual filter. We assume that such overwriting can be counteracted, to a certain extent, by the deployment of executive control processes. Thus, the executive assigns priorities to items according to the overall task strategy and uses processes such as active visualisation (Phillips, 1983) to attempt to maintain items in the privileged state. Our principal evidence that these executive processes involve a limited resource is the observation that prioritising recall of either the first or last item results in a trade-off between the amounts of primacy and recency in recall (Experiment 4, see Figure 9). These fairly simple assumptions help us begin to explain the rich set of results reported here, including (1) the recency effect and its ubiquity, (2) the primacy effect and its dependence on strategy, (3) the parallel effects of plausible and implausible suffixes on recency and primacy, (4) the suffix plausibility effect, (5) the tendency for a feature of a plausible suffix to be recalled as an intrusion error, and (6) the trade-off between strategy-induced primacy and recency. There are of course caveats and concerns, and we consider these after first discussing alternative interpretations.

First, we note that alternative accounts of suffix interference in terms of either the overwriting of sensory information (Crowder and Morton, 1969) or perceptual grouping of the suffix with the memory items (Kahneman & Henik, 1977; Frick & De Rose, 1986) do not seem applicable to the present results. The sensory overwriting account was developed to explain modality-specific suffix effects in the auditory-verbal domain, where echoic memory makes a substantial contribution to recency. However, with visual stimuli, iconic storage is unlikely to make a substantial contribution to recall given the luminance and time intervals used here (Greene, 2007). Furthermore it seems unlikely that instructions could result in the first item being represented in iconic memory, and it is difficult to explain the effect of suffix plausibility in terms of sensory processes. Perceptual grouping fares slightly better as it can explain the effect of suffix plausibility on recency but it too struggles to explain the emergence of a primacy effect showing the same pattern of vulnerability to suffix interference. Thus perceptual grouping would not be expected to operate over a series of intervening items, nor would it be affected by task priorities. We note that Parmentier et al. (2004) also rejected grouping and overwriting interpretations of the effect of a visuo-spatial suffix on memory for a sequence of spatial locations, preferring instead an interpretation in terms of perceptual attention.

Our suggestion of a privileged state in which items are readily accessible yet prone to overwriting raises several further questions. While our views have much in common with those proposed by Cowan (1988; 1999) they differ on a number of important points. According to Cowan, the focus of attention corresponds to a subset of more completely activated long-term memory representations and maintaining items in the focus stabilizes these representations. On this account, therefore, the primacy effect induced by prioritizing early items in a sequence should not be disrupted by a post-stimulus suffix, contrary to the present results. Another inconsistency is that according to Cowan (2011) the special status of the final item in a series does not reflect the focus of attention. The present results suggest instead that the privileged state can embrace both early and recent items. They suggest also that it involves a limited amount of accessible temporary information that is in constant flux due to interference from external stimuli and the effects of executive processes. Our preferred interpretation is that these dynamic properties of the focus of attention are well captured by identifying it with the contents of the limited capacity multimodal episodic buffer (Baddeley, 2000; see also Figure 1) but we note that they are not necessarily inconsistent with viewing the focus as a subset of highly activated representations in long-term memory (Cowan, 1999; Oberauer & Hein, 2012).

Our results agree with many suggestions that the focus of attention is not restricted to a single item (Beck, Hollingworth, & Luck, 2012; Cowan, 2000; Gilchrist & Cowan, 2011; Oberauer & Bialkova, 2011; Oberauer & Hein, 2012). In one sense our present interpretation might be regarded as closest to the position developed by Oberauer and Hein (2012) according to which the most recently presented item is in the focus and control processes can be used to broaden it to include other items. However, Oberauer and Hein (2012) argued that this was only possible when conditions ensure that multiple items are very different from one another, a condition not met in the present experiments. Detailed examination of our serial position data suggest that around two items can be in the privileged state on any trial, a figure that seems low compared with estimates of three or four items from a wide range of evidence (Cowan, 2000). However, our estimate is based solely on the recall data and ignores any requirement for the focus of attention in other aspects of the task, which include responding to the recall cue. Taking this omission into account the present data are not necessarily inconsistent with previous capacity estimates. Lastly, we note that in all the present experiments items in serial position 2 were never affected by either instructions or a suffix, implying they were not recalled from the privileged state, an observation consistent with evidence of a separate neural basis for short-term storage outside the focus of attention (Lewis-Peacock, Drysdale, Oberauer & Postle, 2012).

An implication of our theoretical interpretation is that when a series of items is memorised the contents of the focus of attention are continually changing. This is due to successive items benefiting briefly from automatic storage in the focus but being subject to displacement by subsequent items. Continued maintenance of items in the focus of attention in the face of subsequent stimuli requires the deployment of executive processes to offset these losses. Thus, we would expect that if executive resources are deployed elsewhere, memory for earlier items will be adversely affected whereas the final item will retain its automatic representation in the focus of attention. In a recent series of experiments we explored this prediction by studying the effect of an irrelevant demanding task requiring executive processes during the presentation of a sequence of objects for later recall (Allen, Baddeley, & Hitch, 2014). The results confirmed our prediction that dual-task interference would be greatest for early items in the sequence with little or no disruption for the most recent item.

Our investigation began by noting contradictory views about the role of attention with respect to the storage of individual features and feature bindings in visual working memory. Comparisons between different types of test display in change detection tasks suggest that attention is required for encoding and maintaining feature bindings but not features (Wheeler & Treisman, 2002) whereas dual-task studies suggest attention is no more required for bindings than for features (Allen et al., 2006, 2012; Baddeley et al., 2011). We considered the possibility that this apparent paradox might be resolved by distinguishing between executive control and perceptual filtering components of attention (Chun, et al., 2011; Lavie, 2010; Petersen & Posner, 2012). According to this account, dual-task interference is primarily due to the disruption of executive control processes whereas effects of selecting external stimuli for processing involve perceptual attention.

Although the present experiments did not address the interpretation of Wheeler and Treisman's (2002) results directly, it is incumbent upon us to consider how our theoretical approach might explain them. We begin by noting that in the change detection task the perceptual filter is set to process the test stimulus for comparison with information in memory. This is in contrast to the recall task we have described here in which the filter is set to exclude a post-stimulus suffix. The critical point is that processing a whole-display test item in a change detection task involves passing more information through the perceptual filter than a single probe test item. This difference is most evident when the test item is 'new'. Thus, for a new whole-display test item, two novel objects receive perceptual attention (i.e. the pair whose features are exchanged), whereas for a new single probe test item only a single novel object is attended. We suggest that paying perceptual attention to and processing these novel objects interferes with stored bindings in visual working memory, with whole-display recognition causing greater interference than single probe recognition because it involves processing more novel objects. However, we accept that this account is speculative and we offer it primarily as a hypothesis for future work.

It remains to consider broader limitations and implications. One obvious concern is that while we have found that priorities and suffixes influence visual working memory in different ways, further evidence is required to support our claim that interactions between executive control and perceptual selective attention are responsible for these effects. Another potential concern is that individual differences in the efficacies of perceptual selective attention and executive control are correlated (Engle, 2002), which could be regarded as evidence against the distinction we are assuming. However, we note that this correlation can be just as easily interpreted as reflecting a common focus of attention (Oberauer & Hein, 2012), consistent with our present position. A further issue is whether it is useful to identify perceptual selective attention with bottom-up processes and executive attention with top-down processes, as proposed by Chun et al. (2011). We regard this as too simplistic. In particular, there is a large literature showing that attending to auditory and visual stimuli involves a combination of bottom-up and top-down processes, consistent with the assumption in our model that executive processes are required to set up and manage the perceptual filter (as illustrated by the curved arrow in Figure 1). We would also agree with Awh, Belopolsky and Theeuwes' (2012) argument for a further component of attention they term a 'priority map' that reflects past history and rewards. In this approach, controlling the perceptual filter and implementing memorisation strategies would each involve the priority map. Finally, we would emphasise that we are not arguing that attention can be neatly subdivided into discrete components. The view we hold is closer to the general taxonomy developed by Chun et al (2011) in which different aspects of attention can be classified along an internal-external dimension, with the focus of attention in working memory located somewhere in between its extremes. Thus, rather than a precise model, we are proposing a broad framework that we hope will prove useful for integrating existing evidence about the roles of perceptual selective attention and executive attention in visual working memory as well as generating further questions.

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Table 1

Proportions of Within-sequence Confusions and Standard Errors in Experiments 1-3

	Suffix condition	Serial position				Grand mean
		P1	P2	P3	P4	
Experiment 1	Plausible	0.41 ± 0.04	0.41 ± 0.0	0.40 ± 0.04	0.32 ± 0.03	0.38 ± 0.02
	Implausible	0.40 ± 0.04	0.47 ± 0.04	0.35 ± 0.04	0.32 ± 0.04	0.38 ± 0.02
	Control	0.41 ± 0.04	0.46 ± 0.04	0.38 ± 0.04	0.25 ± 0.04	0.37 ± 0.03
Experiment 2	Plausible	0.46 ± 0.04	0.52 ± 0.05	0.41 ± 0.04	0.23 ± 0.04	0.41 ± 0.03
	Implausible	0.45 ± 0.05	0.51 ± 0.04	0.38 ± 0.04	0.28 ± 0.05	0.40 ± 0.02
	Control	0.44 ± 0.03	0.49 ± 0.05	0.31 ± 0.04	0.20 ± 0.03	0.36 ± 0.02
Experiment 3	Plausible	0.38 ± 0.04	0.39 ± 0.03	0.38 ± 0.03	0.29 ± 0.04	0.36 ± 0.02
	Implausible	0.40 ± 0.04	0.42 ± 0.03	0.33 ± 0.04	0.27 ± 0.04	0.35 ± 0.02
	Control	0.36 ± 0.03	0.36 ± 0.03	0.30 ± 0.03	0.23 ± 0.04	0.31 ± 0.02

Table 2

Proportions of Within-sequence Confusions and Standard Errors in Experiment 4

	Suffix condition	Strategy	Serial position				Grand mean
			P1	P2	P3	P4	
Experiment 4	Plausible	Primacy	0.32 ± 0.04	0.41 ± 0.03	0.39 ± 0.03	0.26 ± 0.04	0.35 ± 0.01
		Recency	0.44 ± 0.04	0.43 ± 0.03	0.35 ± 0.04	0.17 ± 0.03	0.34 ± 0.02
	Control	Primacy	0.30 ± 0.05	0.38 ± 0.04	0.40 ± 0.03	0.20 ± 0.03	0.32 ± 0.02
		Recency	0.43 ± 0.04	0.46 ± 0.04	0.31 ± 0.04	0.10 ± 0.02	0.32 ± 0.02

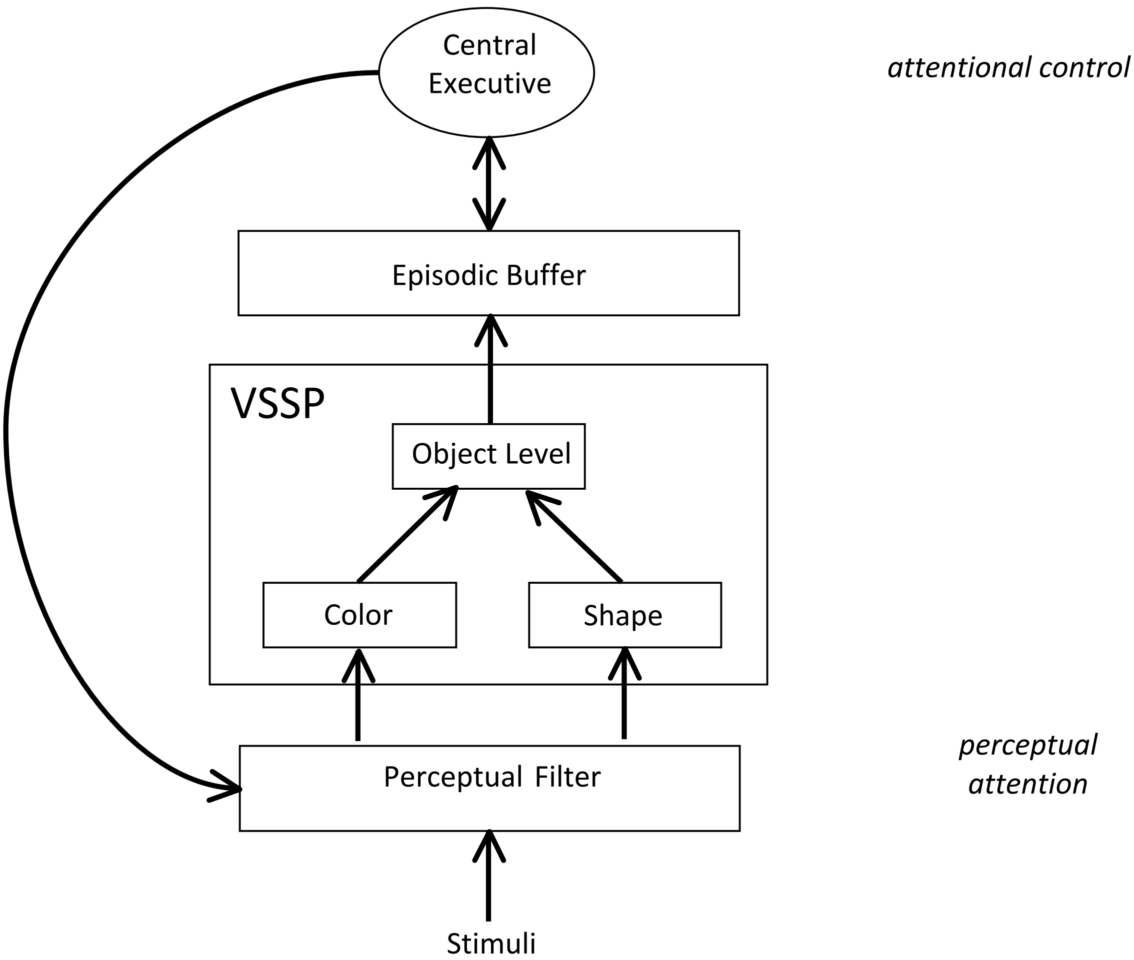

Figure 1. A proposed model of visual working memory and attention (adapted from Baddeley et al., 2011). VSSP = Visuo-spatial sketchpad.

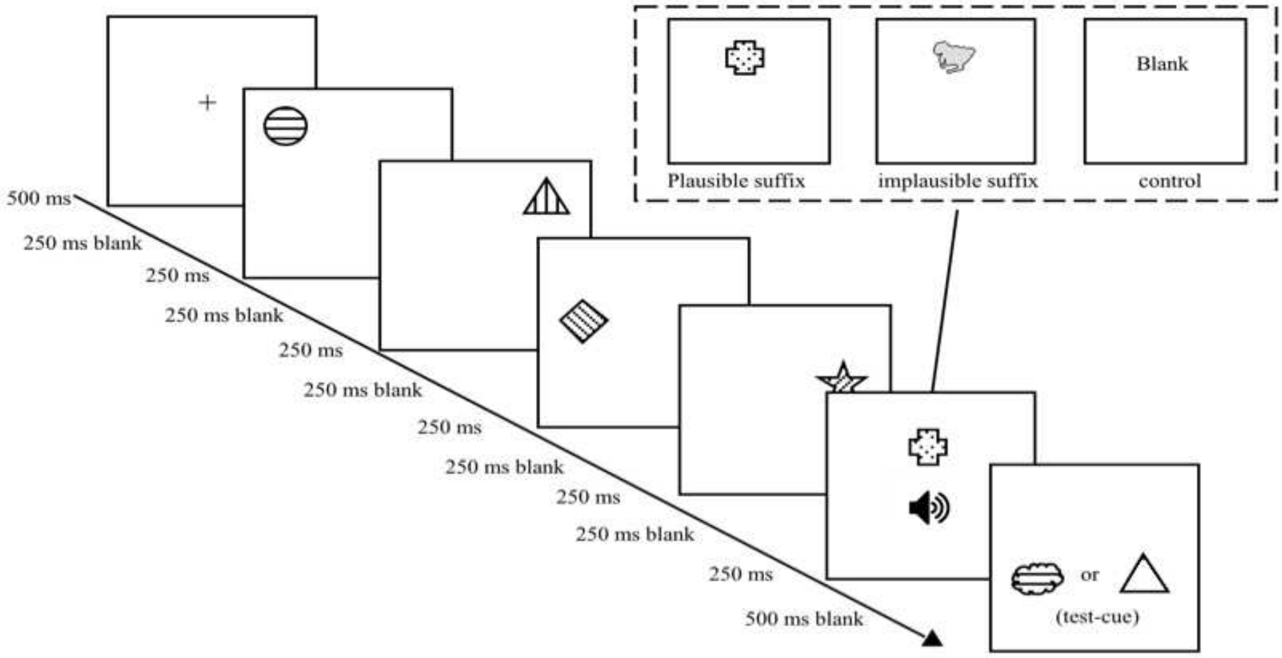

Figure 2. Time-course of each trial in Experiment 1. Colors are denoted by shading. A series of 4 memory items was presented followed by either a blank field or one of two types of suffix, and then a recall cue that was either a color patch (shown left) or a colorless shape (shown right). Participants were instructed to ignore any suffix item and recall the shape/color of the memory item that had the color/shape of the cue.

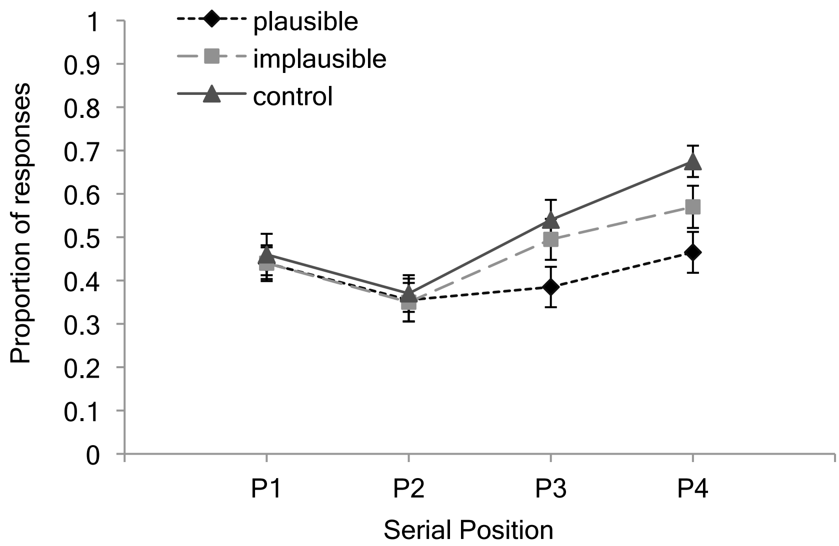

Figure 3. Proportions of correct responses and standard errors in Experiment 1 as a function of serial position

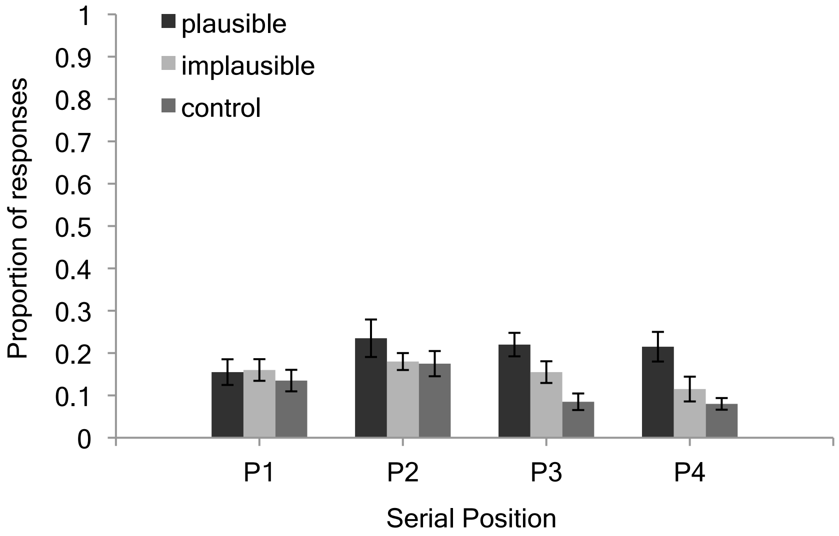

Figure 4. Proportions of intrusions and standard errors in Experiment 1

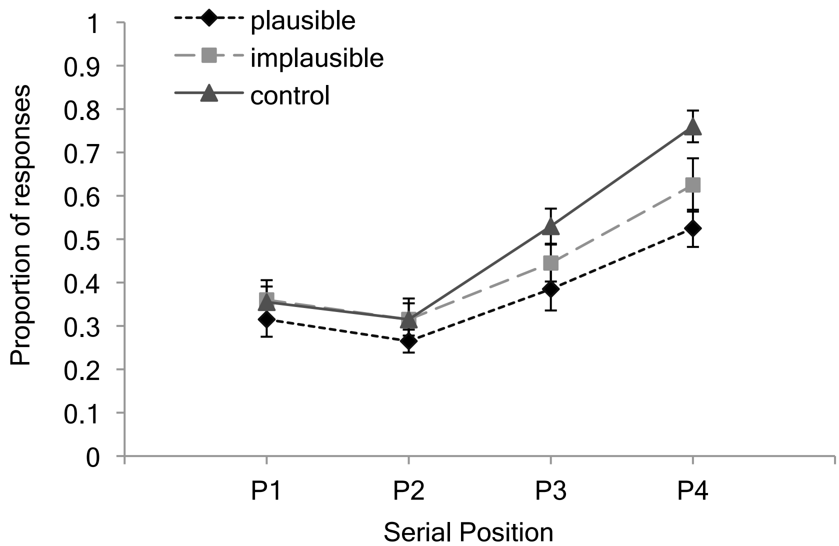

Figure 5. Proportions of correct responses and standard errors in Experiment 2 as a function of serial position

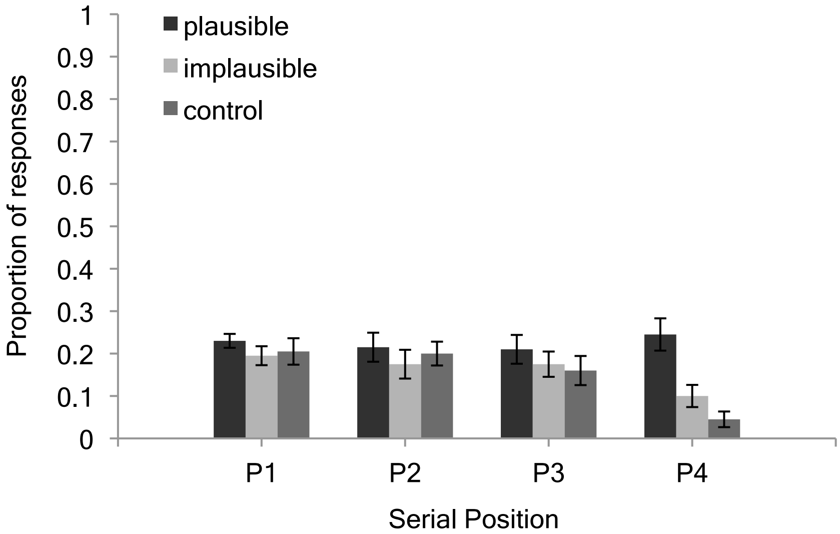

Figure 6. Proportions of intrusions and standard errors in Experiment 2

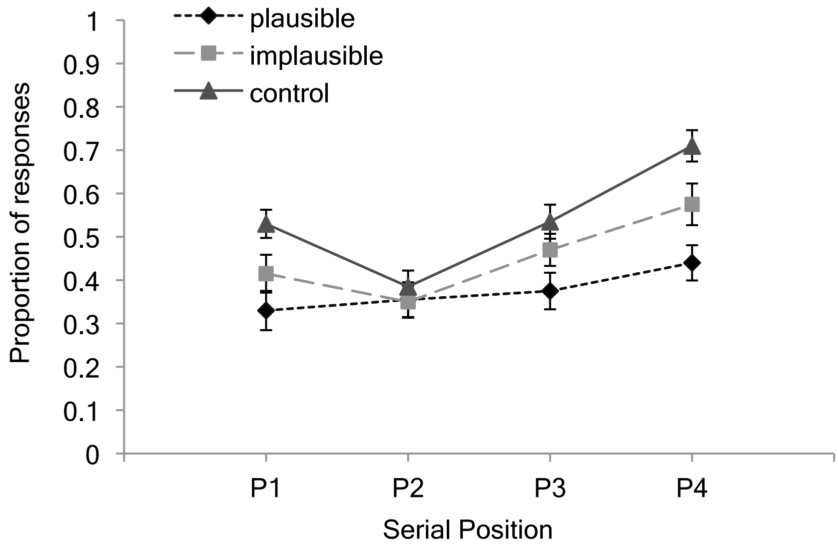

Figure 7. Proportions of correct responses and standard errors in Experiment 3 as a function of serial position

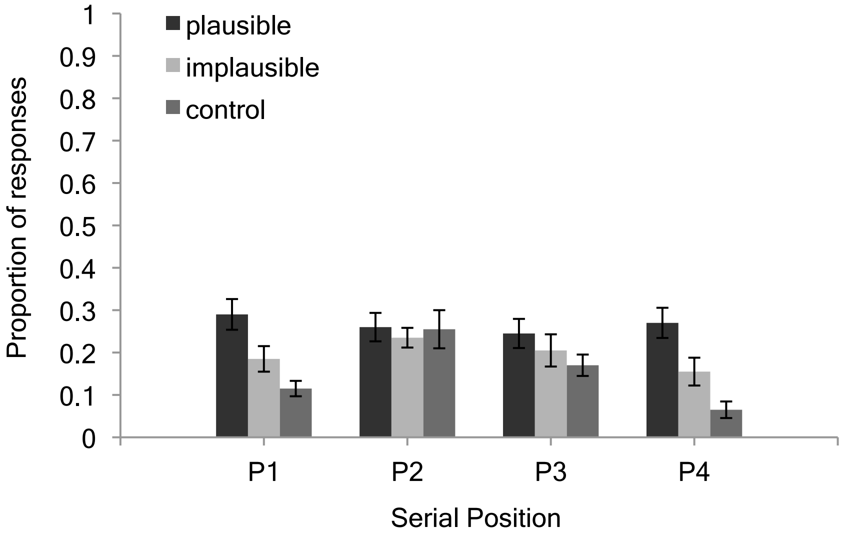

Figure 8. Proportions of intrusions and standard errors in Experiment 3

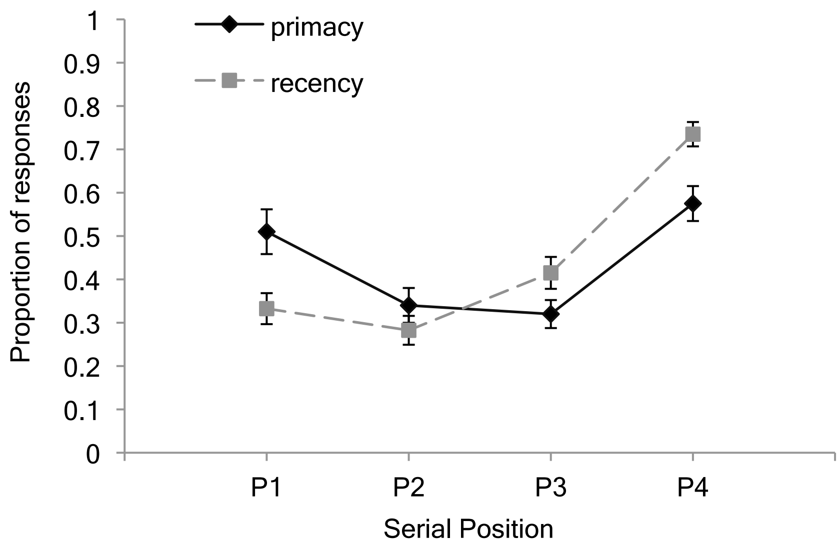

Figure 9. Average percentage correct responses and standard errors in the Recency and Primacy conditions in Experiment 4 as a function of serial position.

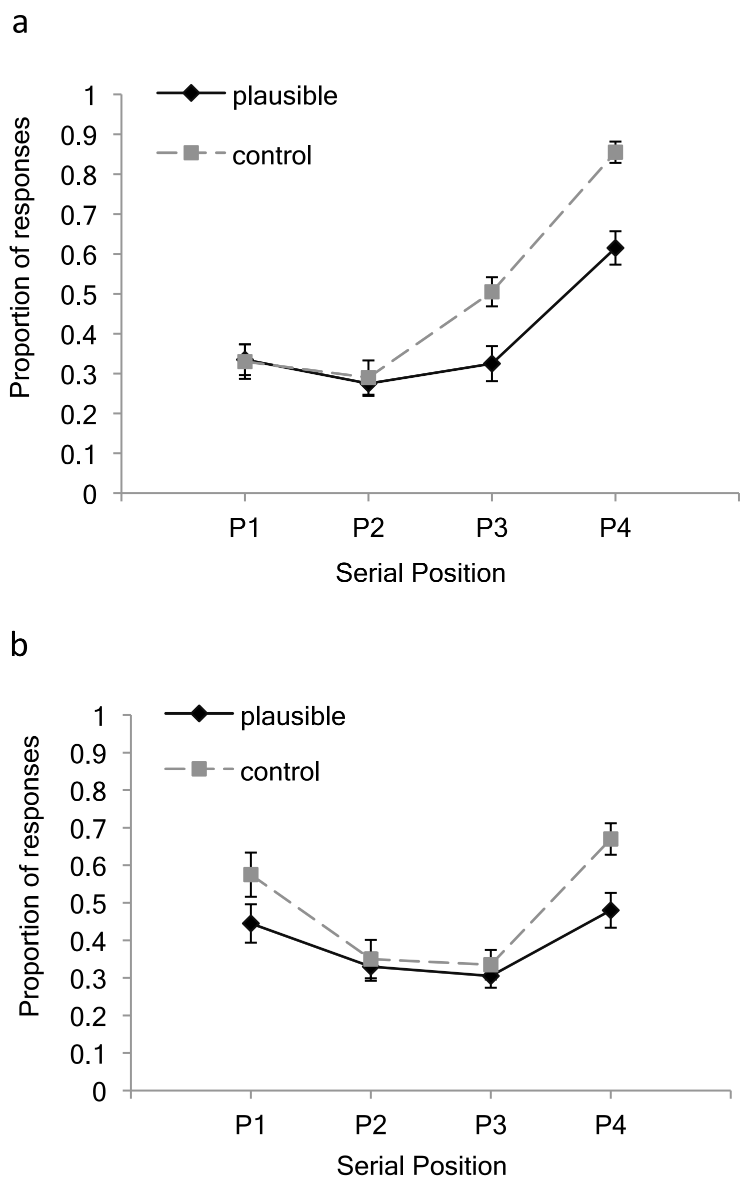

Figure 10. Proportions of correct responses and standard errors in Experiment 4 as a function of serial position: a) Recency condition; b) Primacy condition.

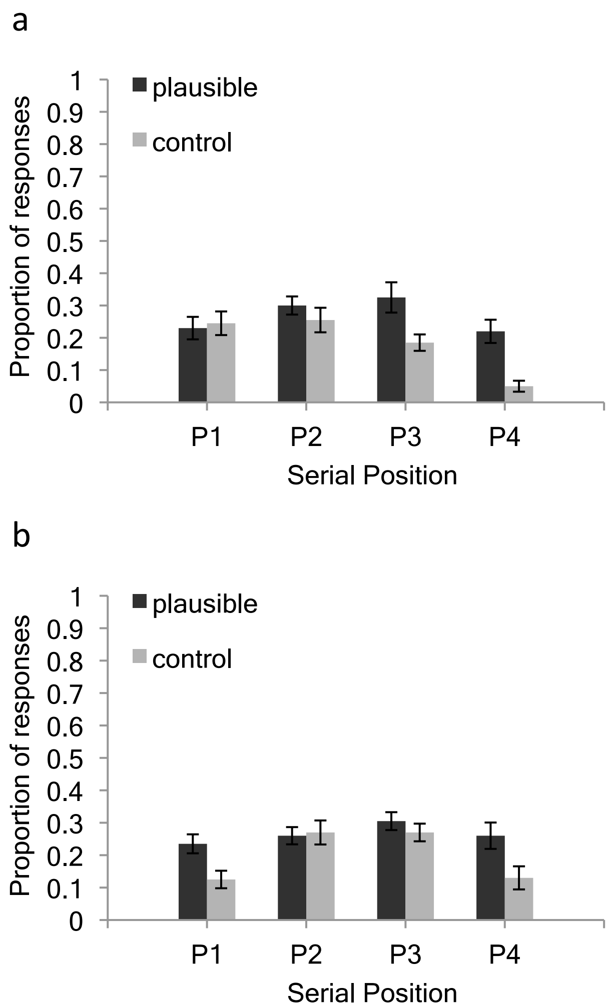

Figure 11. Proportions of intrusions and standard errors in Experiment 4: a) Recency condition; b) Primacy condition.