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Competition for the Focus of Attention in Visual Working Memory:

Perceptual Recency vs Executive Control

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Abstract

Previous research on memory for a short sequence of visual stimuli indicates that access to the focus of attention can be achieved in either of two ways. The first is automatic and is indexed by the recency effect, the enhanced retention of the final item. The second is strategic and based on instructions to prioritize items differentially, a process that draws on executive capacity and boosts retention of information deemed important. In both cases, the increased level of retention can be selectively reduced by presenting a post- stimulus distractor (or 'suffix'). We manipulated these variables across three experiments. Experiment 1 generalized previous evidence that prioritizing a single item enhances its retention and increases its vulnerability to interference from a post-stimulus suffix. A second experiment showed that the enhancement from prioritizing one or two items comes at a cost to the recency effect. A third experiment showed that prioritizing two items renders memory for both vulnerable to interference from an irrelevant suffix. The results suggest that some, though not all, items in working memory compete to occupy a narrow focus of attention and that this competition is determined by a combination of perceptually-driven recency and internal executive control.

Keywords: Focus of attention; visual working memory; prioritization

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Perceptual Recency vs Executive Control

Working memory (WM) is the limited capacity system that combines mental operations and temporary information storage in the support of goal-directed cognition and behaviour.[1-5] It includes the focus of attention (FoA),[6-12] a readily accessible subregion of WM with a capacity of one item or chunk[7, 10, 13] or, in some accounts, three or four chunks.[6, 14, 15] We assume that external and internal attention[16] combine to determine the content of the FoA, where external attention refers to selection through perception and internal attention refers to selection from memory. Thus, on one hand there is a tendency for the most recently attended external perceptual input to occupy the FoA[7] whereas on the other hand executive processes such as "attentional refreshing" can be used to delay forgetting by periodically bringing important information back into the FoA.[17] Given its limited capacity, it follows that the FoA is subject to continuous competition. In the present investigation, we report on the competition between external and internal attention for access to the FoA in a visual WM task. We used perceptual distraction as a means of interfering with the ability to maintain the focus of external selective attention,[18] and instructions to prioritize a subset of the information in WM as a means of controlling internal attention.[19] We were particularly interested in whether these manipulations interact in a consistent way when the identity of the prioritized information is varied, as would be expected if they reflect competing influences on the FoA.

A recent review concluded that bringing information into the FoA enhances its stability and protects it from perceptual interference.[20] Here we extend evidence for a different view that emphasizes the instability of the FoA and its vulnerability to perceptual interference. It comes from testing immediate memory for a single item in a series of three or four colored shapes using either change detection (deciding

whether the color or shape of a test item changed between presentation and test) or cued recall (retrieving the color of one of the shapes or vice versa). In such tasks the most recent item is typically remembered best[21, 22] and this recency effect seems to reflect overwriting whereby later items interfere with items already in store.[23] Presenting a post-stimulus visual distractor (or "suffix") typically reduces recency while having no effect on earlier items,[24(Experiment 1)] consistent with the distractor tending to draw external attention and overwrite items in store. Importantly, this interpretation is supported by interference being greatest when the color or shape of a suffix are drawn from the same pool as study items[25, 26] and by features of such suffixes tending to intrude as errors in cued recall.[24]

We investigated the impact of internally-driven attention in our visual WM tasks by assigning differential rewards for correct recall according to serial position (SP). Given that any item could be tested on a trial this manipulation gave participants an incentive to prioritize highly rewarded items whilst not completely ignoring those with low reward. Two initial experiments were identical except that rewards prioritized the starts or ends of sequences.[24(Experiments 2,3)] The usual recency effect was present in both experiments and was disrupted by a suffix, especially one with features drawn from the same pool as study items, indicating a component of storage independent of prioritization. In contrast, prioritizing the beginnings of sequences induced a primacy effect and this effect was disrupted by a post-stimulus suffix distractor, especially one with relevant features. These effects on the first item were not present when the ends of sequences were prioritized. We suggest that prioritized early items and recent items have the same status in WM through having a higher probability of occupying the FoA. For the most recent items this is automatic, whereas executive processes are necessary to bring in high priority items. Consistent

with this two-component interpretation, a concurrent counting task requiring executive processes removes prioritization effects almost entirely but has no effect on recency or suffix effects.[27] Finally, in a further study,[24 (Experiment 4)] we found that the boost associated with prioritization was offset by poorer memory for the remaining items such that the total amount recalled remained constant. We interpret this as reflecting competition between internal and external attentional processes for access to the FoA.

The present study asked further questions about the flexibility and vulnerability of prioritization. Given that start and end SPs may have special status in WM,[28] it was important to see whether our previous results generalize to items at mid-sequence SPs and to explore capacity limitations further through the effects of prioritizing two items simultaneously.

Experiment 1

This used the same design and procedure as Hu et al.,[24(Experiment 4)] but with instructions to prioritize either SP2 or SP3, with or without presentation of a post-sequence suffix distractor. If previous results generalize, prioritizing either item should boost its cued recall and the boost should be disrupted by a stimulus suffix. Regardless of prioritization there should be a recency effect that is also disrupted by a suffix. Following Hu et al.,[24] suffixes had features from the same pool as study items and participants engaged in concurrent articulation during sequence presentation to prevent verbal recoding.

Method

Participants. A sample size of 20 was chosen, consistent with previous experiments in the present series.[24, 27] Estimates of power for this sample size based on the data reported by Hu et al.[24(Experiment 4)] are as follows. With $\alpha = .05$, power to

detect an effect of prioritization at a SP was .98 (d_z = .88) and power to detect an

effect of a suffix at a prioritized SP was .95 (d_z = .76).[29] Twenty students (aged 18-26

years, mean age 22, 16 female, 4 male) from Northeast Normal University of China

were tested individually and were paid for participation. All participants reported

having normal color vision. The investigation was approved by the institutional ethics

committee.

Materials. The experiment was run on a Pentium PC with a 21-in. screen, using E-

prime (ver. 2.0). Stimuli were colored shapes (approximately 3° × 3°) presented

against a white background and viewed from approximately 50 cm. Each

trial involved the presentation of four study items randomly selected from a set of 64

items formed by crossing 8 colors (red, yellow, blue, green, sky blue, purple, gray,

and black) with 8 shapes (circle, diamond, cross, triangle, arrow, star, flag, and arch).

No shape or color could appear more than once among each set of study items.

Suffixes were selected from the same pool as study items, subject to the constraint

that for each trial neither the color nor shape of the suffix matched any of the study

items. The test cue was either a color-blob or a shape-outline corresponding to one of

the study items.

Design and procedure. Figure 1 illustrates the procedure. Each trial began with a 500

ms warning cross followed by a 500 ms blank screen. Next, a two-digit number

chosen randomly from the range 10 - 99 was shown for 1000ms. Participants were

required to repeat this number aloud until they were shown the test cue. Presentation

of the four study items began 250 ms after the offset of the 2-digit number. The study

items were shown one after another, at the corners of an invisible square

(approximately 6° × 6°, centered 3° above the center of the screen) in a random

spatio-temporal sequence. Each study item was shown for 250 ms and followed by a

250 ms blank interval. Next, either a suffix was shown for 250 ms at the center of the invisible square (suffix condition) or the screen remained blank for 250 ms (control condition). Both the suffix and the blank screen were accompanied by a 250 ms auditory beep to help participants discriminate the to-be-ignored suffix from the study items. Finally, 500 ms after the offset of the beep, the test cue was presented 3° below the center of the screen and remained visible until the participant made their recall response. A color cue required spoken recall of the shape of the study item with that color. Similarly, a shape cue required spoken recall of the color of the study item with that shape.

Figure 1 about here

A 2×2×4 repeated measures design manipulated the prioritized position (SP2 vs SP3), suffix (present vs control) and SP cued at recall (1-4). When SP2 was prioritized, participants were informed they would receive four points for correct recall when the item at SP2 was cued and one point when an item at any other SP was cued. The pattern of rewards was shifted correspondingly when SP3 was prioritized. Prioritization conditions were blocked. There were 16 practice trials followed by 4 sets of 20 test trials with short breaks between sets. Suffix condition and cued SP were randomly permuted within each set of 20 trials. Order of prioritization conditions was counterbalanced.

Results

A preliminary 2 (shape vs color) × 4 (cued SP) ANOVA on proportion correct indicated no significant differences between color and shape cues. Data are therefore collapsed over type of cue in the following analyses. Figure 2 (left panel) shows mean proportion correct when data for SP2 and SP3 are pooled. As expected, the most recent item and the prioritized item were recalled best, and a suffix impaired recall of

both types of item, with little effect on other items. The full serial position curves are

shown in Figure 2 (right panel).

Figure 2 about here

The data were subjected to a 2 (prioritized SP) $\times$2 (suffix condition) x 4 (cued

SP) ANOVA. There was no main effect of prioritized SP, $F(1,19)<1$, a significant

main effect of suffix, $F(1, 19) = 30.96$, MSE=.03, p<.001, $\eta_p^2=.62$, and a significant

main effect of cued SP, $F(3, 57) = 8.71$, MSE=.06, p<.001, $\eta_p^2=.31$. There was also a

significant three-way interaction, $F(3, 57) = 3.35$, MSE= .01, p<.05, $\eta_p^2= .15$, a

significant prioritized SP by cued SP interaction, $F(3, 57) = 9.81$, MSE= .06, p<.001,

$\eta_p^2=.34$, and a significant suffix condition by cued SP interaction, $F(3, 57) = 5.04$,

MSE= .02, p<.01, $\eta_p^2=.21$. The prioritized SP by suffix condition interaction was not

significant, $F(1,19) = 1.02$, MSE= .02, p=.33, $\eta_p^2=.05$.

To untangle the interactions, 2 (prioritized SP) x 2 (suffix condition) ANOVAs

were carried out on proportion correct at each cued SP in turn. There were no

significant effects at cued SP1 (prioritized SP, $F(1, 19) =1.85$, MSE=.03, p=.19,

$\eta_p^2=.09$; suffix, $F(1, 19) =2.44$, MSE=.01, p=.14, $\eta_p^2=.11$; interaction, $F(1, 19) =1.12$,

MSE=.01, p=.30, $\eta_p^2=.06$). At cued SP2, there was a significant effect of prioritized

SP, $F(1, 19) = 12.68$, MSE=.07, p<.01, $\eta_p^2=.40$, reflecting the boost when SP2 was

prioritized. There was also a marginally significant effect of suffix condition, $F(1, 19)$

$= 4.21$, MSE=.02, p=.05, $\eta_p^2=.18$ and a significant suffix condition by prioritized SP

interaction, $F(1, 19) = 5.01$, MSE=.02, p<.05, $\eta_p^2=.21$. Pairwise comparisons revealed

that presentation of a suffix impaired recall when SP2 was prioritized, $t(19) =3.07$,

p<.001, but had no significant effect when SP3 was prioritized, $t(19) = .00$. At cued

SP3, there were significant effects of prioritized SP, $F(1, 19) = 7.97$, MSE=.09, p< .05, η_p^2=.30, suffix condition, $F(1, 19) = 6.80$, MSE=.03, p<.05, η_p^2=.26, and their interaction, $F(1, 19) = 4.70$, MSE=.01, p<.05, η_p^2=.20. Pairwise comparisons confirmed that the boost from prioritizing SP3 was disrupted by a suffix, $t(19) = 3.03$, p<.01 whereas there was no effect of a suffix when SP2 was prioritized, $t(19) = 1.37$, p>.05. Finally, recall of the item at cued SP4 was impaired by a suffix and was poorer when SP2 rather than SP3 was prioritized, as reflected by significant effects of suffix, $F(1, 19) = 32.99$, MSE=.03, p<.001, η_p^2=.64, and prioritized SP, $F(1, 19) = 5.67$, MSE=.02, p< .05, v=.23. There was no interaction, $F(1, 19) = 0.27$, MSE=.02, p=.61, η_p^2=.01, indicating that the suffix effect did not differ between prioritization conditions.

Discussion

The results show that our previous findings on prioritizing SP1 or SP4[24(Experiment 4)] generalise to mid-sequence SPs, and so were not due to anything special about start or end items. In more detail, they confirm our hypotheses about the characteristics of the FoA, as follows.

The FoA as an accessible but unstable state vulnerable to perceptual interference. Prioritizing the item at SP2 or SP3 boosted its retention and at the same time rendered it sensitive to interference from a suffix distractor. In contrast the most recent item was well recalled and sensitive to interference from a suffix independently of prioritization. Thus, prioritized and recent items have a common status that combines raised accessibility with vulnerability to perceptual overwriting, properties we attribute to the FoA.

The FoA as a limited capacity state. There was no effect of different prioritization instructions on overall amount recalled when summed over all SPs. This

is consistent with previous evidence that prioritization alters the allocation of limited resources in WM.[24] However, by itself it does not rule out a general limit on the overall capacity of WM without the need to invoke a discrete FoA. If prioritized and recent items compete to occupy the FoA, the boost in retention due to prioritizing a mid-list item should come at the cost of the most recent item, and at no cost to items in WM but outside the FoA. While the experiment was not specifically designed to test this, two aspects of the results suggest such a trade-off. One is the significant reduction in recency when SP2 was prioritized as compared with SP3, possibly reflecting greater allocation of resources to prioritization due to a longer duration of attentional refreshing. The other is the low level of recency in both prioritization conditions. For example, when SP2 was prioritized, the most recent item was correct on only 55% of trials (see Figure 2, right panel, no suffix condition). This is low compared with a typical value of about 70% with no prioritization.[24(Experiment 1),30 (Experiment 3),27(Experiment 2)]

Experiment 2

Our next experiment provided a stronger test of whether the benefits of prioritization do indeed come at a cost specific to recency by including a baseline condition in which no items were differentially prioritized. A secondary aim was to investigate the effect of instructions to prioritize two items rather than one. Given a limit on the capacity of the FoA we would expect a benefit to memory for each item when two are prioritized together, but once again no increase in the overall amount recalled. To address this, we compared the effect of simultaneously prioritizing the items at SP1 and SP2 with prioritizing each item individually. In order to avoid overly long experimental sessions, we deferred investigating presentation of a suffix when two items were prioritized simultaneously until Experiment 3.

To summarize, if prioritized and recent items compete to occupy a limited capacity FoA, any boosts in retention due to prioritization should be offset by costs in recency. By the same token the benefits of prioritizing two items simultaneously should be shared between them.

Method

Participants. Twenty-four students (aged 18-27 years, mean age 22, 14 female, 10 male) from Northeast Normal University of China were tested individually and paid for participation. The small increase in sample size reflected a change in the constraints associated with counterbalancing. All participants reported having normal color vision.

Design and procedure. Stimuli and presentation procedure were taken from Experiment 1 except that there was no suffix, the final study item being followed by a 500ms blank interval and the test cue.

As before, prioritization strategy was manipulated through the assignment of notional reward points to study items as a function of their SP. In one condition two items were prioritized simultaneously by giving four points for correct recall when SP1 or SP2 was cued and one point when SP3 or SP4 was cued. In two further conditions a single item was prioritized by giving four points for its correct cued recall and one point when any of the others was cued. In one of these the prioritized item was at SP1 and in the other it was at SP2. Finally, in a baseline condition, participants were given one point for the correct cued recall of any item, regardless of its SP.

The experiment had a 4 (prioritization conditions) by 4 (cued SP) within-participants design. The prioritization conditions were run in separate blocks, with the baseline run twice, once at the start of the experiment (Baseline 1) and again at the

end (Baseline 2). Comparison between the two baselines would provide a check for the potential complication of transfer effects between conditions. The three prioritization conditions were implemented in counterbalanced order in separate blocks after the first baseline. There were 5 blocks in total, each comprising 8 practice trials and 40 test trials with short breaks every 20 test trials.

Results

A 2 (Baseline 1 vs Baseline 2) by 4 (cued SP) ANOVA on correct responses found no significant effect of Baseline, $F(1, 23) = .90$, MSE=.03, p=.35, $\eta_p^2=.04$, and no interaction, $F(3, 69) = .42$, MSE=.02, p=.74, $\eta_p^2=.02$, indicating there were no transfer effects from the intervening strategy conditions. Data are therefore collapsed over Baselines 1 and 2 in the following analyses.

Figure 3 about here

The principal analysis took the form of a 4 (prioritization condition) $\times$ 4 (cued SP) repeated measures ANOVA on the data plotted in Figure 3 (right panel). This revealed no significant main effect of prioritization condition, $F(3, 69) = .60$, MSE=.02, p=.62, $\eta_p^2=.03$. Mean overall proportions correct were .48 (SE=.03) in the baseline, .49 (SE=.03) when prioritizing SP1, .48 (SE=.03) when prioritizing SP2 and .50 (SE=.03) when prioritizing SP1 and SP2. There was a significant effect of cued SP, $F(3, 69) = 37.47$, MSE=.05, p<.001, $\eta_p^2=.62$ and a significant prioritization by cued SP interaction, $F(9, 207) = 6.95$, MSE=.03, p<.001, $\eta_p^2=.23$.

The prioritization by cued SP interaction was explored through pairwise comparisons at each SP. At cued SP1 proportion correct was significantly higher when SP1 was prioritized either alone or together with SP2 compared with the baseline condition, $t(23) = 3.95$, p=.001 and 4.51, p<.001, respectively and compared with prioritizing SP2 alone, $t(23) = 4.32$ and 4.58, ps<.001, respectively. There were

no other significant differences at cued SP1 (baseline vs prioritize SP2, t(23)=1.55, p=.14; prioritize SP1 vs prioritize both SP1 and SP2, t(23)=1.09, p=.29). At cued SP2 proportion correct was significantly higher when SP2 was prioritized, either alone or in combination with SP1 when compared with the baseline, t(23) =2.81, p=.01 and 2.89, p<.01, respectively and when compared with prioritizing SP1 alone, t(23) =2.54 and 2.56, ps<.05, respectively. There were no other significant differences at cued SP2 (baseline vs prioritize SP1, t(23)=.00; prioritize SP2 vs prioritize SP1 and SP2, t(23)=1.13, p=.27). At cued SP3 there were no significant differences between any of the four reward conditions (baseline vs. prioritize SP1, t(23)=1.03, p=.31; t(23)<1 for the remaining comparisons). Finally, at cued SP4, recall was significantly more accurate in the baseline condition than when prioritizing SP1, SP2 or both SP1 and SP2, t(23) =-3.06, -2.41 and -2.39, p<.01 and ps<.05, respectively, which did not differ from one another, ts<1.

The above analyses show no significant differences between the effects of prioritizing a single item versus two items at cued SP1 or cued SP2. However, inspection of Figure 3 shows that in each case recall of a prioritized item was slightly lower when it was prioritized as one of a pair. To compare dual and single prioritization with more power, data were pooled over cued SP1 and cued SP2. Mean proportion correct for items prioritized individually was .52 (SE = .04) compared with .46 (SE = .04) for items prioritized simultaneously. This difference was, however, non-significant, t(23) =1.40, p=.09, 1-tailed.

Finally, we note that the sum of proportion correct over SPs sets an upper limit on the capacity of visual WM in our task. Averaging over the four prioritization conditions, mean correct recall was 1.94 items per sequence. This is an upper limit because it includes a certain amount of correct guessing from the set of 8 alternative

responses. One way of allowing for guessing is to use Cowan's method to estimate k, the number of items in store.[29] Using an adapted formula for cued recall,[31] gave an estimated capacity of k = 1.65 items. However, k should be interpreted with caution here as its calculation assumes a unitary store which is an oversimplification given the notion of a separate FoA.

Discussion

We note firstly that overall retention was just as good in the baseline condition as in the prioritization conditions, providing further evidence that incentives mediate the allocation of limited resources. Our main objective was to test whether the allocation is specific to prioritized and recent items, in line with our view of the FoA. Comparisons against the baseline condition showed that the benefits of prioritization were restricted to prioritized items and that the cost fell on the final item, as predicted. However, the persistence of some recency even when earlier items are prioritized suggests that competition for resources is constrained. It appears that the bottom-up bias to represent recent (goal-relevant) perceptual inputs in the FoA is strong and can only be partially offset by top-down internal control processes.

The experiment included a supplementary test of the hypothesis that the FoA has limited capacity through the prediction that prioritizing two items simultaneously should result in shared benefits. The results confirmed this insofar as memory for each of two simultaneously prioritized items received a significant boost relative to baseline, without any improvement in the overall amount recalled.

Lastly, our results have implications for the capacity of the FoA. We note that the level of performance implied an overall storage capacity of less than two items in our visual WM task. Given that prioritization and recency effects account for only part of this total, our results are more consistent with the concept of a "narrow" FoA

of one item, [7, 10, 12, 13, 32] than the "broad" FoA of three or four items proposed by

Cowan and colleagues.[6, 14, 15]

Experiment 3

Our final experiment examined whether the boosts in recalling two

simultaneously prioritized items are both vulnerable to perceptual interference from a

suffix distractor, as predicted by our view of the FoA. Given ample evidence that a

suffix has no effect on recall at either SP1 or SP2 when that SP is not prioritized,[24]

[(Experiment1),27(Experiments 2,3)] we simply looked for the effect of a suffix at these SPs when

they were simultaneously prioritized.

Method

Participants. Twenty students (aged 19-27 years, mean age 22, 13 female, 7

male) from Northeast Normal University of China were tested individually and were

paid for participation. All participants reported having normal color vision.

Design and procedure. Stimuli and procedures in Experiment 3 were identical

to those in the suffix and no-suffix conditions of Experiment 1 except that there was

only a single prioritization condition in which the items at SP1 and SP2 were

emphasised. Participants were informed they would receive four points for correct

recall when either of the first two items in a sequence was cued and one point when

either of the last two items was cued. A 2 (suffix condition) ×4 (cued SP) repeated

measures design was implemented. Each participant completed 16 practice trials

followed by 8 blocks of 20 test trials in each of which suffix condition and SP probed

were randomly permuted.

Results

Figure 4 shows that presentation of a suffix reduced recall at all four SPs, with

a noticeably bigger effect on the most recent item. A 2 (suffix condition) × 4 (cued

SP) repeated measures ANOVA on proportion correct revealed significant effects of suffix condition, $F(1, 19) = 44.16$, MSE=.01, $p<.001$, $\eta_p^2=.70$, cued SP, $F(3, 57) = 8.43$, MSE=.03, $p<.001$, $\eta_p^2=.31$, and the suffix by cued SP interaction, $F(3, 57) = 4.25$, MSE=.01, $p<.01$, $\eta_p^2=.18$. Pairwise comparisons indicated that the interference due to a suffix was significant at all four cued SPs ($t(19) =2.36$, 2.27, 2.72, and 6.64, respectively, ps<.05s and p<.001). Further comparisons showed that the degree of suffix interference was greater at cued SP4 (M=.24) than at cued SP1 (M=.07), cued SP2 (M=.09), and cued SP3 (M=.11), $t(19) = 3.93$, 2.55, and 2.33, respectively, p=.001 and ps<.05. There were no differences between the amounts of suffix interference at cued SP1, cued SP2 and cued SP3 ($t(19)<1$ in each case).

<center>Figure 4 about here</center>

Discussion

The results confirm the prediction that simultaneously prioritizing SP1 and SP2 renders memory for both items susceptible to suffix interference, as when each SP is prioritized separately (for SP1 see[24(Experiment 4)]; for SP2 see Experiment 1 above). This stands in marked contrast to the absence of suffix effects at SP1 and SP2 when neither is prioritized.[24(Experiment 1),27(Experiments 2,3)] However, the suffix effects observed at SP3 and SP4 when prioritizing SP1 and SP2 correspond to the effects typically seen at these positions in the absence of prioritization instructions.[24(Experiment 1),27(Experiments 2,3)] Overall, therefore, the results are consistent with the operation of a FoA that tends to be occupied by recent perceptual input and is therefore susceptible to perceptual interference, but which can also be used to hold non-recent information that has been assigned high priority. The pattern of suffix effects suggests that every item in the sequence has some chance of occupying the FoA at the time of recall, and

confirms the strong bias towards recency even when earlier items are assigned the greatest importance, consistent with a largely automatic process.[25]

General Discussion

We set out to extend previous evidence on visual WM suggesting that prioritized information competes with recently presented information to occupy a limited capacity FoA.[24, 27] Three experiments confirmed that effects of prioritizing a single item at the start or end of a series,[24(Experiment 4)] generalize to other SPs and to prioritizing two items simultaneously. Thus, memory for prioritized items received a selective boost, recency was present regardless of prioritization, and both effects were reduced by a post-stimulus suffix distractor. Importantly, these effects persisted when two items were prioritized simultaneously, in that both items received a boost, and both boosts were reduced by a post-stimulus suffix. These findings provide further support for the conclusion that prioritized and recent items have shared properties of heightened accessibility and vulnerability to perceptual interference as compared with other items in WM. As before, we identify these properties with the FoA.

The boost due to prioritization came at a cost that fell principally on memory for the most recent item, reflecting the limited capacity of the FoA. This was strongly suggested by Experiment 1 and confirmed using an improved design in Experiment 2. Experiment 2 showed further that two items could be prioritized simultaneously at a cost to memory for the final item, with no improvement in the total amount of information recalled. Taking the results altogether, therefore, we have shown that our previous results generalize to a wider range of prioritization conditions. In so doing we have obtained stronger evidence for a specific competition between prioritized and recent items for limited capacity, a competition that does not include the other items in WM.

An important question is whether the results can be explained more parsimoniously by a unitary account of visual WM that does not assume a discrete FoA. Influential unitary accounts assume either an undifferentiated capacity to store items in a fixed number of slots,[33] or a pool of resources that can be allocated continuously to determine the precision of representations,[34] or a combination.[35] At first sight unitary accounts of visual WM would find it difficult to explain why a suffix should disrupt memory for prioritized and recent items and yet have no effect on unprioritized or non-recent items. Such accounts could do this, however, by assuming that only items whose strength or quality of representation exceeds a certain threshold are sensitive to suffix interference. Unitary accounts could also be elaborated to explain why executive resources are required for prioritization but not recency or suffix effects[27(Experiments 1, 2)] and the importance of whether or not a suffix has task-relevant features.[24] Such elaborations would be post hoc, but their possibility underlines the need for further evidence to demarcate the FoA as a separate component within WM.

We turn next to consider further the picture of the FoA painted by the present results. It is important to note that SP curves reflect data aggregated over trials, and that we have interpreted experimental effects in terms of the probabilities of items occupying the FoA at the time of test. The view that has emerged is one in which the FoA contains a single item in a readily accessible but highly labile state, the item in question being determined by a combination of perceptual recency and top-down internal control. These external and internal processes compete for access to the FoA, generating a constant flux as fresh perceptual inputs are encountered and older items refreshed. We assume that executive processes of attentional refreshing involve

reactivating an item to bring it back into the focus of attention, where it remains briefly until displaced by either a fresh perceptual input or another cycle of refreshing. Assuming items circulate in and out of the FoA, with more in-focus time for prioritized items, prioritized items will be more likely to be in the focus at the time of test or will have been in the focus more recently. This account of attentional refreshing is very close to the view that has come from studies of performance in complex span tasks[32] and is analogous to effects of the recency of verbally rehearsing items in free recall.[36] However, it is worth noting that whereas Camos & Barrouillet[32] assume refreshing is used to reactivate items that have undergone time-based decay, the present account emphasizes the use of refreshing to offset overwriting, which seems more appropriate in the case of visual working memory. A somewhat different way of interpreting the present results could be in terms of the greater time spent by prioritized items in the FoA. Previous research suggests that items tend to be better consolidated in working memory if they dwell longer in the FoA when first presented.[37-39] However, an interpretation in terms of consolidation seems unlikely given that we consistently observed that prioritization renders items more vulnerable to interference rather than less.

As noted earlier, our data are more consistent with a narrow FoA limited to a single item or chunk[7, 10-13, 32] than with a broad FoA comprising three or four chunks.[3, 14, 15] Interestingly, however, subsequent work by Cowan and colleagues has shown that the overall capacity of about three colored shapes in visual WM comprises complete binding information for only about one item and incomplete binding information for the others.[40] Other recent evidence shows good fits for models in which about three objects are retained in WM but with incomplete featural

information for some of them.[41, 42] Thus, evidence on the quality of representations

indicates a degree of convergence on the idea of a narrow rather than a broad FoA.

We assume the FoA is multi-modal, as part of the episodic buffer[43, 24] or as in

Cowan's embedded processes model.[3] Multi-modality would seem essential for the

FoA to play a central role in goal-directed processing and behavior, as suggested by

Oberauer and Bialkova.[44] Such broader considerations serve as a useful reminder that

the tendency for the FoA to be dominated by recent inputs may reflect its mode of

operation in a task such as ours in which the goal is to remember a series of rapidly

presented stimuli. Other tasks involving WM, such as reasoning or mental arithmetic,

would appear to be quite different in demonstrating an ability to concentrate by

shutting out irrelevant external distraction. Thus, we expect task-set and context to be

important, potentially crucial factors in determining the way the FoA is used. This in

turn serves as a warning against drawing general conclusions from any single

paradigm and argues instead for a converging operations approach. Such an approach

would aim to identify invariant characteristics of the FoA and differentiate them from

incidental features that vary from task to task. Based on our own data we suggest that

the former include entry dependent on competition between external and internal

attention, one-item capacity, heightened accessibility and fragility, and a refreshing

process reliant on executive resources. Other potential hallmark characteristics

include heightened speed of access,[7] multi-modality,[3] and occupation by a fully bound

item or chunk.[40, 42]

As mentioned in the introduction, previous work on the FoA has led to the

conclusion that attending to representations in WM strengthens and stabilizes them,

protecting them from perceptual interference.[20] However, this conclusion was drawn

from studies of retro-cueing, a procedure in which a cue shown during the retention

interval of a WM task guides attention to one of the items in WM.[45] It does this by correctly indicating the item to be tested subsequently in an above chance proportion of trials. Although our own conclusions agree with those from retro-cueing to the extent that prioritizing an item strengthens its representation in WM, they differ in that the boost is not at all stable, being distinguished by its vulnerability to perceptual interference. We note a potentially important difference between the two paradigms concerning the way prioritization is manipulated. A retrocue typically indicates the frequencies with which different items are tested whereas prioritization instructions in the present experiments indicated the reward value of different items, each of which was equally likely to be tested. Although it is beyond the scope of this paper to address differences between paradigms, it is interesting to note that altering the frequency with which an item is probed in our task boosts that item's retention but appears to do so in a fundamentally different way from prioritization, the boost being unaffected by an executive load.[46] This contrast between effects of importance due to reward value and importance due to frequency further illustrates the need for a converging operations approach along the lines discussed earlier, aimed at separating out defining properties of the FoA from those that reflect task-specific strategies.

In conclusion, effects of prioritizing items during encoding and of subsequent perceptual distraction form a coherent and systematic pattern consistent with a limited capacity narrow FoA of approximately one item (or chunk) in WM. Our results suggest that the FoA operates at the interface between externally driven perceptual selection and internally driven executive control. We suggest that in our sequential visual WM task, relevant perceptual inputs have a strong tendency to access the narrow FoA automatically and overwrite its current content but that this can be partially offset by refreshing earlier information according to its prioritization. We

suggest also that in serial visual WM tasks, and perhaps more generally, these processes compete to place a single representation in the FoA at any instant. On the present evidence, information in the FoA is readily accessible and yet highly labile. These characteristics of flux and fluidity stand in contrast to the picture that has emerged from studies of retro-cueing. This apparent contradiction together with wider considerations suggest that task set and context are important in determining the way the FoA is used, cautioning against relying too heavily on any one paradigm. If, as Oberauer and Bialkova suggest, the FoA serves a crucial central role in goal-directed processing and behavior,[44] its investigation merits a broad, multi-faceted, converging operations approach.

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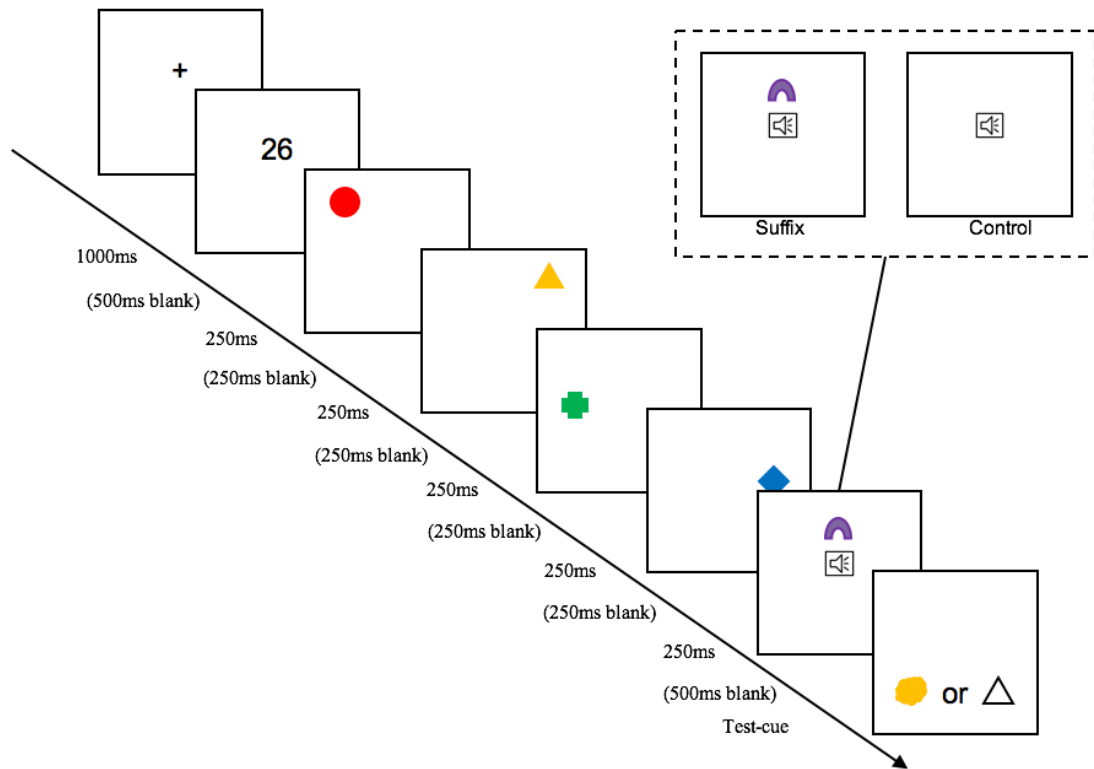
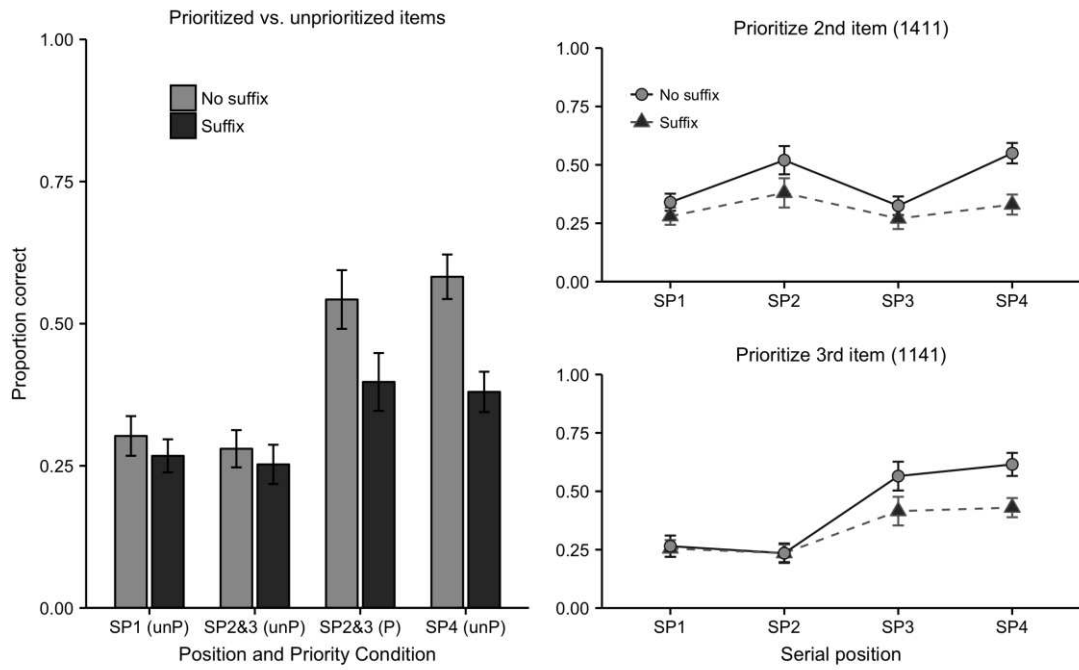46.   Atkinson, A.L., E. Berry, A.H. Waternan, et al. submitted.
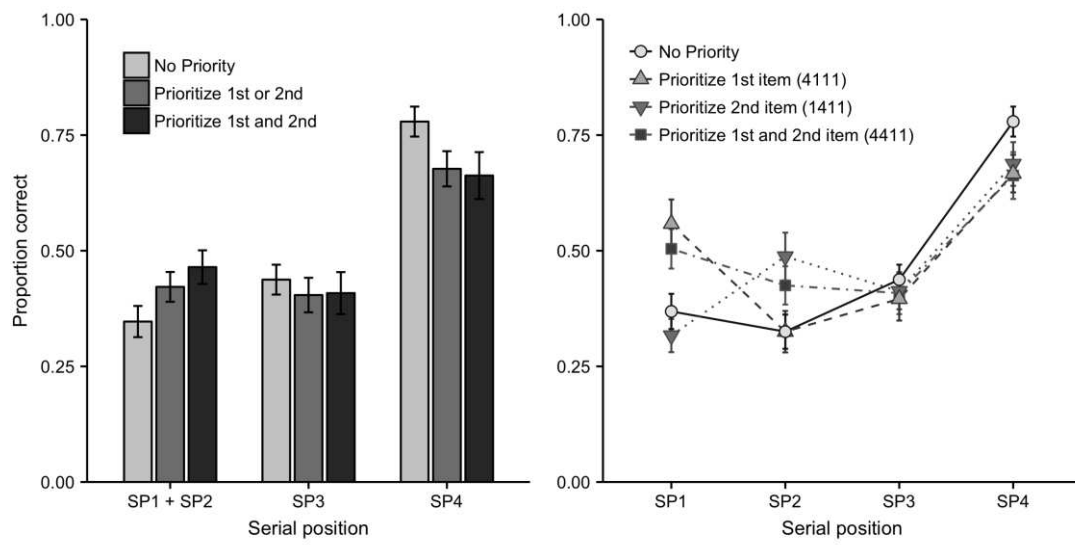
Figure 1

Figure 2

Figure 3

Figure 4