Retrospective and prospective prioritization in visual working memory

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Abstract

A growing body of research indicates that items assigned with a higher ‘value’ prior to presentation are better recalled in working memory tasks. This has been interpreted as reflecting the strategic prioritization of these items via selective attention during encoding, maintenance, and retrieval. The current study sought to establish whether value-based prioritization effects can be obtained in a sequential visual working memory task when value information is provided retrospectively during maintenance and items are no longer present in the environment. Enhanced recall of high value items along with costs to low value items (relative to equal value trials) was observed, although the high value benefit was only reliably found on the final sequence position. In comparison, a follow-up experiment in which values were provided prior to presentation found large prioritization benefits across sequence positions. This study illustrates that attention can be retrospective shifted between working memory representations based on value, but the effectiveness of this strategic process depends on item availability and accessibility, either in the environment or in working memory.

Keywords: working memory; prioritization; attention; value

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A defining feature of working memory (WM) is its limited capacity, with overloading potentially resulting in loss of information during encoding, retention, or retrieval. A key factor in determining WM success is the direction of attention, and indeed, a close relationship has been identified between these core components of cognition (e.g. Awh & Jonides, 2001; Cowan et al., 2021; Engle, 2002; Oberauer, 2019). Thus, information that is selectively and actively attended during encoding and maintenance is more likely to be available for retrieval. A growing body of work now indicates that items associated with higher ‘value’ can be strategically prioritized in WM. Recall is enhanced for high over low value items even though these values represent notional points and are unrelated to monetary reward or probability of being assessed. This has been observed in visual (Allen & Ueno, 2018; Hu et al., 2014) and verbal tasks (Atkinson et al., 2020), and in typically developing children (Atkinson et al., 2019) and healthy older adults (Allen et al., 2020). At a broad level, it has been claimed to represent the strategic prioritization of high value items within the focus of attention (FoA) within WM (Hitch et al., 2020). Thus, items can be maintained in a more accessible privileged state, though with the trade-off of costs to other items that are not being prioritized.

Whilst value-based prioritization has deepened our understanding of the relationship between WM and attention, other methods have also been used. Visual cueing enables attentional direction towards items either prior to (pre-cueing) or after (retro-cueing) target presentation (Griffin & Nobre, 2003; Souza & Oberauer, 2016). However, cueing effects are typically dependent on the cue being highly informative (or 100% predictive) regarding which item will be tested (Berryhill et al., 2012; Gunseli et al., 2015; Shimi et al., 2014), whereas value-directed prioritization effects appear to be independent of probe frequency (Atkinson et al., 2018). Moreover, value-based prioritization effects are vulnerable to subsequent interference from to-be-ignored environmental input (Allen & Ueno, 2018; Hu et al., 2014), while probe frequency (Atkinson et al., 2018) and visual cueing effects (Souza & Oberauer, 2016) are not. In fact, there is some evidence that retro-cues may operate by protecting from subsequent interference (Makovski et al., 2008; Matsukura

et al. 2007; Souza et al., 2016). Thus, not all forms of attentional direction in WM are equal (Atkinson et al., 2018). Research should therefore focus on identifying key similarities or differences across paradigms (Hitch et al., 2018), thus helping to define attentional direction in WM while also highlighting paradigm-dependent features and preventing overgeneralisation from any one approach.

When considering attentional direction in WM, it is important to consider the stage at which the information directing attention is presented. Visual retro-cues are presented after encoding so attentional direction must be applied to WM representations during maintenance or retrieval (see also guided-refreshing; Souza et al., 2015, 2018). In contrast, studies examining value-directed prioritization have presented value information prior to encoding, meaning that effects may emerge at encoding, maintenance or retrieval. The current study therefore explores whether value effects can be applied retrospectively, thus offering new insights into the mechanisms driving such effects, and into attentional direction in WM more generally. These effects (in Experiment 1) are then compared with those observed when values are also provided before encoding (Experiment 2). If prioritization effects partly emerge due to processes at encoding, the effect should be significantly reduced when value is only allocated after target presentation.

In line with the majority of work on value-directed prioritization, this was examined in a sequential memory task. As value effects have been observed at different sequence positions (Hitch et al., 2018; Hu et al., 2014), we would expect priority effects to be apparent at all positions when value is allocated prior to sequence commencement. This may also be apparent when value is allocated retrospectively. Indeed, Niklaus et al. (2019) observed a retro-cue benefit for visually presented words that remained constant across serial positions. Alternatively, if retrospective prioritization depends on item availability or accessibility, such effects should be larger for the most recent item in the sequence, as this is typically more easily recalled (Allen et al., 2006; 2014).

Experiment 1

This experiment examined whether recall accuracy varies with retrospective allocation of point values. This was implemented with trial types in which one ‘high value’ item was allocated 4 points and the remaining three ‘low value’ items in the sequence 1 point each, or all items in the display having equal value (1 point). A probe value effect would indicate that attention is being shifted between working memory representations in response to the item values. Any recall advantage for high value over equal value trials would indicate the benefit of prioritization, whereas a reduction for low value compared to equal value trials would represent the corresponding cost of attentional neglect.

Method

Participants

Thirty participants took part in this experiment (mean age = 19.93, SD = 2.43, 27 females, 3 males). All had normal or correct to normal vision and no colour blindness. The study received ethical approval from the School of Psychology, University of Leeds ethics committee.

A power analysis was conducted using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007). Atkinson et al. (2018, Experiment 1) observed a probe value effect size of $d = 1.33$, comparing high value vs. equal value items in an experiment in which value was assigned at the start of each block of trials. Based on the assumption that retrospective prioritisation would result in a relatively reduced benefit, the effect size obtained in Atkinson et al. was halved to calculate power in the present study. Thus, based on an effect size of $d = .665$ and $\alpha = .05$, a sample size of 30 was estimated to provide 94% power to detect the effect of interest.

Materials

The experiment was created in PsychoPy 2 (Pierce et al., 2019) and run on a 13 inch desktop PC. To-be-remembered coloured shape stimuli were drawn by combining from sets of six colours (blue, black, red, yellow, green, purple) and six shapes (circle, triangle, flag, cross, arch, arrow). Test probes consisted of black shape outlines.

Design and Procedure

A 3x4 repeated measures design was implemented in each experiment, with probe value (high value, equal value, low value) and probed serial position (SP 1:4) as the independent variables and cued recall accuracy as the dependent variable. There were 4 practice trials and 200 test trials, split into five blocks of 40 trials, with short rests between each block.

An illustration of the trial procedure within an example trial is provided in Figure 1A. Each trial began with an on-screen reminder to begin repeatedly articulating the phrase ‘coca-cola’ during the encoding and maintenance phases of the task, as a form of articulatory suppression. Following a fixation cross, four to-be-remembered colored shapes were sequentially presented. Each shape measured 1.5° visual angle, and no shape or color was repeated within a sequence. Each item was presented at a different corners of an invisible square with a width of 4° visual angle. At the test phase, a single black shape outline was presented at the screen centre, and participants were required to stop the articulatory suppression task and try to recall the color that was paired with this shape probe during presentation. The experimenter recorded the response using a keyboard with a key corresponding to each color.

Figure 1. Schematic illustration of trial procedure in Experiment 1 (A) and Experiment 2 (B)

Value was allocated to each item by presenting a display of four numbers (one high value of ‘4’ and three low values of ‘1’) on screen in the delay between the final sequence item and the test

probe, in the locations previously occupied by the to-be-remembered targets. Within the set of 200 trials for each participant, there was an equal probability for the high value to appear in any of the four spatial locations, or for all four locations to be associated with the low value (i.e. ‘1’ appeared in all four locations). Each serial position was probed 50 times across the total trial set. This resulted in approximately 40 high value probe trials, 40 low value probe trials, and 120 low value probe trials, for each participant. Both probe value and SP trial types were randomly intermixed. Task instructions were provided at the start of the experimental session, and an on-screen reminder of these instructions was presented after every 20 trials. Participants were informed that the value associated with a particular item would be earned if they were tested on this item and they responded correctly. In line with previous work in adults (e.g. Allen et al., 2020; Allen & Ueno, 2018; Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2014; 2016), feedback was not provided at any point (either concerning the number of trials answered correctly or the number of notional points collected).

Data analysis

All data is available on the Open Science Framework at

https://osf.io/2wa4z/?view_only=633641f7224f4e62aee29518293a87af *<private link will be reset to*

public upon publication>. The data were analysed using generalised linear mixed-effects models (GLMM). Analyses were run in R (Version 3.5.1; R Core Team, 2018) using the mixed function from the ‘afex’ package (Singmann et al., 2015). Following Barr et al. (2013), the maximal model was first fit (including a random intercept of subject, and random slopes for value, SP, and the value:SP interaction across subject). Where the model failed to converge, random slopes were removed based on their theoretical importance to the research questions (Barr et al., 2013). As the experiments primarily aimed to examine the effects of value, the random slope for SP across subject was first omitted. Where this model did not converge, the random slope for SP across subject was re-added, and the random slope for value:SP across subject was removed. All models converged with this latter random effects structure. The models were fit using the ‘bobyqa’ optimiser with

1,000,000 iterations. P-values were calculated using likelihood ratio tests. Bonferroni-Holm corrected post-hoc tests were conducted using the ‘emmeans’ package (Lenth et al., 2018). The ‘MuMIn’ package was used to calculate marginal R^2 (the variance explained by fixed effects) and conditional R^2 (the variance explained by the fixed and random effects; Bartoń, 2014).

Results

Mean proportion correct (and standard error (SE)) is presented in Figure 2A as a function of probe value, and in Figure 3A separating by serial position. The number of correct responses were analysed using a Value (high, equal, low) x SP (1-4) logit mixed-effects model. The model included a random intercept of subject, and random slopes for value and SP across subject (*marginal R^2 = 0.07, conditional R^2 = 0.13*). There was a main effect of value [$\chi^2(2) = 18.73, p < .001$], whereby performance was significantly better in the high value condition (Mean (M) = .50, $SE = .01$) than the equal ($M = .45, SE = .01; p = .021$) or low value ($M = .36, SE = .01; p < .001$) conditions. Accuracy was also higher in the equal value condition than the low value condition ($p < .001$). A significant effect of SP also emerged [$\chi^2(3) = 53.64, p < .001$], with performance at SP4 ($M = .57, SE = .01$) superior to SP1 ($M = .37, SE = .01; p < .001$), SP2 ($M = .30, SE = .01; p < .001$), and SP3 ($M = .38, SE = .01; p < .001$). In addition, accuracy at SP2 was significantly lower than at SP1 ($p = .008$) and SP3 ($p < .001$). Finally, there was a significant interaction between value and SP [$\chi^2(6) = 12.73, p = .047$].

To explore the value-SP interaction, value pairs (high-low, high-equal, equal-low) were compared at each SP. At SP1, performance in the low value condition ($M = .32, SE = .02$) was worse than performance in the equal ($M = .42, SE = .03; p = .024$) and high value conditions ($M = .43, SE = .03; p = .024$). The equal and high value conditions did not significantly differ ($p = .704$). At SP2, there were no significant differences between any of the conditions ($M_{High} = .37, SE = .03; M_{Equal} = .31, SE = .03; M_{Low} = .28, SE = .01$), including between the high and low value conditions ($p = .078$). At SP3, performance in the low value condition ($M = .34, SE = .02$) was worse than in the equal ($M = .42, SE = .03; p = .021$) and high value ($M = .49, SE = .03; p < .001$) conditions. The

difference between the high and equal value conditions was not statistically significant ($p = .086$).

Finally, at SP4, there were significant differences between high ($M = .73$, $SE = .03$) and low value ($M = .49$, $SE = .02$; $p < .001$), high and equal value ($M = .63$, $SE = .03$; $p = .028$), and equal and low value conditions ($p < .001$).

Figure 2. Mean proportion correct in Experiment 1 (A) and Experiment 2 (B), as a function of probe value. Error bars denote SE.

Figure 3. Mean proportion correct in Experiment 1 (A) and Experiment 2 (B), as a function of value and SP. Error bars denote SE.

Discussion

A probe value effect was observed, indicating that attention was shifted between WM representations, with evidence for both benefits (high > equal) and costs (equal > low) of retrospective prioritization. These effects also changed across serial positions. For non-final positions, they were more reliably driven by a cost for less valuable items. At SP4, there were both costs for less valuable items and boosts for high value items. The effectiveness of strategic retrospective direction of attention is dependent on the item being available and accessible. Recency effects were apparent across all value conditions, perhaps reflecting a greater likelihood of storage within the FoA (Hitch et al., 2020) or increased strength of memory representation (Donkin & Nosofsky, 2012; Niklaus et al., 2019) at the point at which values are allocated. In either case, this final item would be more accessible within WM and therefore easier to prioritize. For earlier items, applying higher value and prioritization may not be effective when they are outside the FoA or otherwise have reduced accessibility.

Overall, Experiment 1 indicates that value allocated to items that are no longer present in the environment can be used to guide strategic prioritization, though this is more effective for the final item in a sequence. Having established this, it was then important to compare these priority effects with a situation in which value is also allocated prior to encoding. Directly comparing the patterns that are observed in each case enables a separation of priority effects that arise either during the encoding phase or during maintenance/retrieval.

Experiment 2

This experiment aimed to establish the magnitude of value-driven prioritisation effects in WM when value is allocated based on spatial location prior to sequence presentation. Previous studies examining pre-prioritization have allocated value in a predictable way (Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016), potentially allowing development of a task set that may enable

larger prioritization boosts than if the more valuable serial position changed on a trial-by-trial basis. As Experiment 1 in the current series necessarily applied values to items in a way that changed unpredictably on every trial, Experiment 2 took the same approach, but allocating values prior to sequence presentation.

Method

Participants

Thirty participants took part in this experiment (mean age = 21.43, SD = 1.85, 25 females, 5 males). All had normal or correct to normal vision and no colour blindness. The study received ethical approval from the School of Psychology ethics committee.

Materials, Design, & Procedure

The method was closely based on Experiment 1, with the same material set, design, and trial procedure. The key difference was that, within each trial, the display indicating value distributions on each trial was displayed prior to each sequence, as well as after its completion (see Figure 1B). Thus, the values allocated to each item location were presented for 1000ms on two occasions; once after fixation and before the first item on screen, and again after sequence completion and prior to the test phase (as in Experiment 1). The second presentation of value allocations was retained in this experiment to control for any interference effects caused by introduction of a visual display during working memory maintenance, and to enable direct comparison of probe value effects when values are provided before and after (Experiment 2), or only after (Experiment 1) sequence presentation.

Results

Mean proportion correct (and SE) is presented in Figure 2B, as a function of value, and in Figure 3B, as a function of value and SP. A Value (high, equal, low; within-subject) x SP (1-4; between-subject) logit mixed-effects model was run. The model included a random intercept of subject, and random slopes of value and SP across subject (*marginal* $R^2 = 0.13$, *conditional* $R^2 = 0.21$). A main effect of value was observed [$\chi^2(2) = 37.07$, $p < .001$]. Post-hoc comparisons revealed better performance in the high value condition ($M = .74$, $SE = .01$) relative to the equal ($M = .48$, $SE = .01$;

$p < .001$) and low value ($M = .39$, $SE = .01$; $p < .001$) conditions. In addition, accuracy was significantly higher in the equal value relative to the low value condition ($p < .001$). A main effect of SP was also observed [$\chi^2(3) = 24.15$, $p < .001$], with performance at SP4 ($M = .58$, $SE = .01$) superior to SP1 ($M = .43$, $SE = .01$; $p < .001$), SP2 ($M = .41$, $SE = .01$; $p < .001$), and SP3 ($M = .49$, $SE = .01$; $p < .001$). Accuracy at SP3 was also higher than SP2 ($p = .012$). No significant interaction was observed between value and SP [$\chi^2(6) = 9.76$, $p = .135$], so value effects were not examined at each serial position.

Discussion

Clear probe value effects were apparent, with a substantial recall advantage for high over equal and low value items and a smaller (yet highly statistically significant) difference between the latter two probe types. Thus, participants can make effective use of value information in WM when these value distributions shift unpredictably between items across trials. These effects were consistent across the sequence, extending previous observations at different positions (Hitch et al., 2018; Hu et al., 2014).

Across experiment comparisons

Data from the two experiments were analysed together to confirm whether the effects of probe value vary depending on when values are allocated. A Value (high, equal, low; within-subject) x SP (1-4; within-subject) x Experiment (retro-prioritisation, pre-prioritisation; between-subject) logit mixed-effects model was run. The model included a random intercept of subject, and random slopes of value and SP across subject (*marginal* $R^2 = 0.11$, *conditional* $R^2 = 0.18$). Here, we focus on the main and interactive effects of Experiment; the full set of outcomes are reported in the supplementary materials section. A main effect of experiment was observed [$\chi^2(1) = 22.84$, $p < .001$], with superior performance in the pre-prioritization experiment ($M = .48$, $SE = .01$) than the retro-prioritization experiment ($M = .40$, $SE = .01$). A significant interaction emerged between value and experiment [$\chi^2(2) = 19.33$, $p < .001$], though there was no significant 3-way interaction between value, SP, and experiment [$\chi^2(6) = 7.06$, $p = .316$].

To understand the interaction between value and experiment, we assessed whether there was a significant difference between the retro-prioritization and pre-prioritization experiments for each level of value. For high value items, performance was significantly better in the pre-prioritization experiment than in the retro-prioritization experiment ($p < .001$). No significant difference between experiments emerged in the equal ($p = .194$) or low ($p = .217$) value conditions.

General Discussion

These experiments represent the first attempt to examine whether value-driven prioritization can be retrospectively applied in WM and to directly compare this with pre-prioritization, in which attention can be directed during encoding, maintenance or retrieval. Experiment 1 demonstrated that items retrospectively assigned a high value were better recalled than low value items, with both benefits and costs relative to equal value trials. Across the sequence, costs were apparent at earlier and final positions, while benefits were only reliably observed for the most recent item. For Experiment 2, provision of values prior to sequence onset led to large prioritization effects across the sequence. Directly comparing the two experiments indicated that the high value items were more accurately recalled in the pre-prioritization experiment (relative to retro-prioritization), whereas equal and low value item recall did not differ.

Thus, value-directed prioritization can be applied retroactively, but not as effectively as when it is possible during encoding. There are two broad and not mutually exclusive possibilities for this. Firstly, prioritization effects previously observed (see Hitch et al., 2020) may partly reflect processes during the encoding phase. Secondly, items may be less accessible or available for retrospective prioritization. It is not the case, however, that attempting to apply retrospective priority is intrinsically more cognitively demanding or contributes to a more difficult task set, as performance on the equal and low value trials was equivalent in the two experiments.

What might underlie this type of prioritization? Given that Hu et al. (2016) observed diminished prioritization effects with a more demanding concurrent task, the process likely relies on executive resources. For pre-prioritization, although we assume each item is attended during

sequential presentation, spatial attention does not mandate WM storage (Allen, 2019; Oberauer, 2019); high value items may be more actively processed as they are encountered, leading to a stronger representation. They may also be prioritized over subsequently presented stimuli and possibly held in the FoA through attentional refreshing and/or visualisation (Camos et al., 2018; Hitch et al., 2020; Raye et al., 2002), operating either in a cyclical but biased manner, or through continuous ‘online’ refreshing (Johnson, 1992; Johnson et al., 2002; Sandry & Ricker, 2020).

Following sequence completion, we assume that the high value item is retrieved into (Experiment 1) or continues to be held (Experiment 2) in the FoA. For retrospective prioritization, item accessibility is important. The most recently encountered item is more likely to be within the FoA (Hitch et al., 2020), whereas other items would need to be retrieved into this accessible state, which is likely to be a challenging and error-prone process, with the item potentially no longer available. Alternatively, the recency advantage may reflect a strength effect on a power gradient (Niklaus et al., 2019). In either case, this final item would be easier to prioritize relative to items encountered earlier on in the sequence. Continued maintenance might then be supported via refreshing. As participants can be instructed to refresh particular items during maintenance (Souza et al., 2015; 2018), future work should examine the commonalities between this manipulation and value-directed prioritization to examine whether the latter effects emerge at least partly through refreshing during retention. During this maintenance interval, low value item representations are neglected, resulting in poorer accuracy at test. Given that any item might be tested, and all items were remembered at above-chance levels, low value items are not irreversibly removed from WM, though they could be removed in a temporary, reversible way (Lewis-Peacock et al., 2018).

The observation of both prospective and retrospective value-driven prioritization is broadly analogous to effects of pre- and retro-cueing (see Souza & Oberauer, 2016). Larger benefits for pre- versus retro-prioritized items map onto similar findings with cueing (Janczyk & Reuss, 2016; Shimi et al., 2014; Souza, 2016), though outcomes are mixed (Asthle et al., 2012; Griffin & Nobre, 2003; Li & Saiki, 2015; Shimi & Scerif, 2017). Children do seem to show larger pre- than retro-cueing

effects across all studies (Astle et al. 2012; Shimi et al., 2014), and it may be informative to similarly examine retroactive prioritization in developmental groups (Berry et al., 2018; Atkinson et al., 2019). Both these methods of attentional direction involve allocation of executive control resources (Janczyk & Berryhill, 2012; Hu et al., 2016). However, cueing effects are typically dependent on being predictive of the test phase, unlike value-directed prioritization (Atkinson et al., 2018). Indeed, Oberauer (2019, p.3) characterised this latter type of prioritization as a ‘more lenient form of selective attention, encoding the prioritized item without completely neglecting the not-prioritized ones.’, which might explain why these manipulations respond differently to environmental interference. Thus, following the suggestion of Myers et al. (2017) that retro-cued items are selected and reconfigured for the anticipated test phase, prioritized high value items in the current study may be selected and held in an accessible state without being ‘reconfigured’ for further action. Future work should aim to develop convergent lines of evidence concerning when and how attention can be directed prospectively and retrospectively in WM.

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