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Atkinson, AL, Allen, RJ orcid.org/0000-0002-1887-3016, Baddeley, AD et al. (2 more authors) (2021) Can Valuable Information be Prioritized in Verbal Working Memory? Journal of Experimental Psychology: Learning, Memory, and Cognition, 47 (5). pp. 747-764. ISSN 0278-7393

https://doi.org/10.1037/xlm0000979

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Can Valuable Information be Prioritized in Verbal Working Memory?

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The authors would like to thank Isabel Eldergill-Storm, Sophie McGough and Anisha De Silva for assistance with data collection. This research was supported by an Economic and Social Research Council PhD Studentship to ALA. One of the authors of this paper (AHW) was supported by the supported by the National Institute for Health Research Yorkshire and Humber ARC (reference: NIHR20016). The views and opinions expressed are those of the author, and not necessarily those of the NHS, the NIHR or the Department of Health and Social Care. The authors declare no conflict of interest. The data and analysis scripts are available on the Open Science Framework (Atkinson et al., 2020).

Abstract

Though there is substantial evidence that individuals can prioritize more valuable information in visual working memory, little research has examined this in the verbal domain. Four experiments were conducted to investigate this and the conditions under which effects emerge. In each experiment, participants listened to digit sequences and then attempted to recall them in the correct order. At the start of each block, participants were either told that all items were of equal value, or that an item at a particular serial position was worth more points. Recall was enhanced for these higher value items (Experiment 1a), a finding that was replicated while rejecting an alternative account based on distinctiveness (Experiment 1b). Thus, valuable information can be prioritized in verbal working memory. Two further experiments investigated whether these boosts remained when participants completed a simple concurrent task disrupting verbal rehearsal (Experiment 2), or a complex concurrent task disrupting verbal rehearsal and executive resources (Experiment 3). Under simple concurrent task conditions, prioritization boosts were observed, but with increased costs to the less valuable items. Prioritization effects were also observed under complex concurrent task conditions, although this was accompanied by chance-level performance at most of the less valuable positions. A substantial recency advantage was also observed for the final item in each sequence, across all conditions. Taken together, this indicates that individuals can prioritize valuable information in verbal working memory even when rehearsal and executive resources are disrupted, though they do so by neglecting or abandoning other items in the sequence.

Keywords: prioritization, working memory, attention, verbal, concurrent task

Can Valuable Information be Prioritized in Verbal Working Memory?

Working memory (WM) refers to an individual's ability to store and process information for a brief period of time (Baddeley, 1986; 1992). It is considered essential for many everyday activities, including language comprehension (Daneman & Merikle, 1996), skill acquisition (Woltz, 1988), and learning (Gathercole & Pickering, 2000). As many of these tasks require individuals to maintain information that differs by value or goal-relevance (Gorgoraptis et al., 2011; Oberauer & Hein, 2012), WM should be flexible and offer the ability to prioritize particularly important information. Attention is thought to play a critical role in this, with information that is attended to in the external world substantially more likely to enter WM (Awh & Jonides, 2001; Chun & Johnson, 2011; Gazzaley & Nobre, 2012).

The contents of WM appear to be determined by a combination of automatic, perceptually driven and strategic, internally motivated attentional control processes (Allen et al., 2014; Chun et al., 2011); Hitch et al., 2019; Oberauer, 2019; Tamber-Rosenau et al., 2011). Environmental stimuli are more likely to be held at least briefly in an accessible state in WM when they are particularly salient and/or the most recently encountered item in a sequence. This occurs relatively automatically, as reflected by the recency advantage for the final 1-2 items in a sequence that is reliably observed when targets are presented serially (e.g. Allen et al., 2014). It is also possible to strategically direct attention towards target items that are deemed to be of increased value or goal relevance, and to continue to prioritize these items even when they are no longer present in the environment.

Evidence for such selectivity effects in visual WM has been demonstrated using a range of methods. For example, cueing paradigms involve the use of visual cues presented either before, during, or after target encoding to direct participants towards items that are particularly likely to be tested in the response phase (e.g., Griffin & Nobre, 2003; Schmidt et al., 2002; Souza & Oberauer, 2016). These typically show enhanced accuracy for cued items, along with reductions in memory for uncued items. Alternatively, participants are asked to strategically prioritize more ‘valuable’ information (Allen & Ueno, 2018; Atkinson et al., 2019; Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2014, 2016; Sandry & Ricker, 2020). For example, Hu et al. (2014) presented participants with series of coloured shapes and asked them to recall the colour of a probed item following a brief delay. Participants were either encouraged to prioritize the first or the final serial position via a points system that indicated that this item was more valuable. Prioritization boosts were observed, indicating that individuals can direct attention within visual WM. This came at a cost to other items, however, suggesting that prioritization does not increase WM capacity, but instead alters the allocation of attention. Indeed, prioritization effects in visual WM typically emerge in the form of value x serial position interactions, rather than any overall difference between priority conditions. Thus, differential item value changes how attention is strategically directed across the sequence, but doesn’t change working memory capacity or the attentional resources that are involved at a whole task level. These findings have since been replicated and extended in several other experiments, which have demonstrated that individuals can prioritize multiple items simultaneously in visual WM (Allen & Ueno, 2018; Hitch et al., 2018) and that boosts appear to be somewhat reliant on executive resources (Hu et al., 2016).

These attentional selectivity effects in WM have been discussed in the context of a sub-region within WM, termed the focus of attention (FoA), that allows a limited amount of information to be held in a state of heightened accessibility (Hu et al., 2014; Oberauer, 2013). The FoA is central to several prominent theories of WM (Cowan, 1999; 2016; Oberauer, 2002; 2013) that discuss temporary storage as a form of activated long-term memory. It has also been considered in relation to a multiple component approach to WM (Baddeley, 2000, 2012; Baddeley et al., 2020). Within this framework, the concept of a focus of attention holding information in an accessible form has been associated with the episodic buffer (Hitch et al., 2019; Hu et al., 2014), a modality-general component responsible for integrating information across the WM components and long-term memory. Indeed, despite disagreement regarding the exact structure of WM, a common assumption is that such a FoA is modality-general (Cowan, 2005; Hitch et al., 2018; Hu et al., 2014; Oberauer, 2013), and can hold both visual and verbal information.

Despite this assumption, the vast majority of research exploring the interaction between attention and WM has focused on the visual domain. The close relationship between WM and attentional control described within visual WM might not necessarily extend in the same way across domains and modalities. In the context of dual tasking, for example, Wickens (1980, 1984, 2002) suggested the operation of distinct resources across structural dichotomies at the levels of sensory input modality (between auditory and visual) and processing codes (non-verbal vs. verbal). Auditory presentation may be more powerful in causing pre-emptive attentional capture (Wickens & Liu, 1988), and continued maintenance of verbal information is more readily supported by a speech output-based rehearsal mechanism, whereas performance in visual WM tasks may be more dependent on modality-general attentional control processes (e.g., Baddeley et al., 2020; Gray et al., 2017; Morey & Miron, 2016). Given such apparent differences between visual and auditory cognition, the generality of claims regarding WM and attention therefore need to be extended beyond a single domain, if we are to develop a more comprehensive understanding of cognitive processes. This will be useful in considering whether the FoA should be characterized as a modality-general component of WM, and whether environmentally driven perceptual control and amodal executive control resources operate in a similar way across different forms of input. Observations of strategic prioritization effects in an auditory-verbal context will also have implications for theoretical approaches to WM. For example, the multiple component WM framework describes separable storage capacities for visuo-spatial and phonological information. Whether similar or contrasting patterns of strategic prioritization effects emerge across tasks drawing on these different forms of storage may depend on whether or not common processing and attentional resources are involved in each case.

Turning to the verbal domain then, recent work within episodic long-term memory has shown that participants are able to selectively focus on visually presented words that are associated with higher reward values (e.g., Castel et al., 2002; Elliott & Brewer, 2019; Hennessee et al., 2017; Middlebrooks et al., 2017; Stefanidi et al., 2018). Analogous to claims in visual WM (Hu et al., 2016), this may represent the strategic control of attention and application of more effortful strategies during encoding (Castel, 2008). For example, imaging studies have indicated involvement of fronto-temporal regions, possibly supporting semantic processing, in the selectivity of high value words (Cohen et al., 2014, 2016). Enhanced pupil dilation, thought to indicate attention allocation and performance of cognitively demanding tasks (van der Wel & van Steenbergen, 2018), has also been observed during encoding of high value items for later recall (Ariel & Castel, 2014; Miller et al., 2019). The strategic control of attention within such tasks also appears to be related to individual differences in working memory capacity (Hayes et al., 2012; Robison & Unsworth, 2017), either through the ability to apply attentional control in the selective encoding of high value items, or the spontaneous use of optimal encoding strategies in these contexts. However, healthy older adults, who typically have reduced working memory capacity and executive control, tend to show similar memory selectivity effects to those seen in younger participants, alongside reduced memory performance overall (e.g., Castel et al., 2002; Siegel & Castel, 2018; Hayes et al., 2013). Furthermore, evidence using dual-task manipulations is mixed regarding the role of executive control. For example, Middlebrooks et al. (2017) found that high value enhanced recall regardless of whether or not participants engaged in an attentionally-demanding concurrent task. In contrast, Elliott and Brewer (2019) observed that value particularly impacted on ‘remember’ judgments within a recognition task (see also Hennessee et al, 2017), but that such effects were removed when performing executive-demanding concurrent tasks during encoding. Thus, value-directed encoding does impact on later episodic memory for visually presented words, though the role of executive attention in this process is unclear.

In the case of verbal WM, Rhodes et al. (2019) observed auditory-verbal prioritization in young and older adults at a whole-task level, with participants choosing to optimize performance either in an auditory-verbal working memory task or a concurrent visual-based mathematical verification task. However, to the best of our knowledge, only one set of studies has explored value-directed item selectivity effects for verbal material, and these used visual rather than auditory presentation (Sandry, Schwark, & MacDonald, 2014; Sandry et al., 2020). In these experiments, participants were visually presented with a series of three letters (Sandry et al., 2014) or words (Sandry et al., 2020) on screen. After a brief delay, participants had to recognise one item in a two-alternative forced choice test. In some trials, one letter appeared in red, which indicated that item was more valuable than the rest. During this task, participants performed articulatory suppression, a non-demanding concurrent task involving repetition of irrelevant verbal information (Baddeley, Lewis, & Vallar, 1984; Camos, Lagner, & Barrouillet, 2009; Richardson & Baddeley, 1975). This task disrupts an individual's ability to rehearse (Baddeley, 1986; Camos et al., 2009). Enhanced short-term and long-term memory performance was observed for high value items, suggesting that individuals can indeed direct attention to more valuable verbal information (Sandry et al., 2014; 2020). The presence of these effects under articulatory suppression also indicates that prioritization effects are not reliant on verbal rehearsal.

However, as items were presented visually in this paradigm, it is difficult to draw any firm conclusions from this research regarding attentional flexibility and prioritization in auditory-verbal working memory. Visual presentation of verbal material leads to both visual and phonological codes (Logie et al., 2000; Saito et al., 2008). The latter form of representation requires phonological recoding for grapheme-phoneme conversion (Romero Lauro et al., 2020), with rehearsal then involved in conveying this newly recoded information into the phonological store (see Shallice & Papagno, 2019; Vallar, 2017; Vallar & Papagno, 2002, for reviews). Interfering with rehearsal through articulatory suppression may therefore prevent the effective verbal recoding of visual information (Baddeley et al., 1984; Baddeley & Hitch, 1994; Schendel & Palmer, 2007), and increase reliance on visual or semantic memory (Hanley & Bakopoulou, 2003; Salame & Baddeley, 1986). In contrast, with auditory-verbal presentation, each stimulus is assumed to automatically enter the phonological store. Thus, it remains to be seen whether the same patterns of strategic attentional control processes are in operation within this context.

The current experiments therefore represent the first exploration of strategic prioritization in auditory-verbal working memory, and the possible cognitive mechanisms that might be involved. Auditory presentation of items avoids, as much as possible, any reliance on visual coding, whilst also omitting the need for verbal recoding (Baddeley et al., 1984; Baddeley & Hitch, 1994; Schendel & Palmer, 2007). Experiment 1a examined whether participants can strategically prioritize items from one of the serial positions within the sequence. Experiment 1b then examined whether prioritization effects observed in the first experiment might be alternatively explained solely by a distinctiveness explanation. Following establishment of the effect in these first experiments, Experiments 2 and 3 then applied concurrent task logic to examine how the ability to recall more and less valuable items in an auditory-verbal WM task might change when either verbal processing (Experiment 2) or both verbal processing and executive control resources (Experiment 3) are disrupted during encoding and maintenance. We explored these questions using an immediate serial recall task, as this method is commonly used to assess verbal WM in the literature.

Digits were selected as the stimulus set, as digit span tasks feature in a range of cognitive batteries (Fliessbach et al., 2006; Conway et al., 2005; Torralva et al., 2009; Wechsler, 1997), and are also widely used in experimental research across the discipline (Conway et al., 2005). Use of digits may also reduce reliance on strategies such as association and story-formation, as these approaches might be more easily implemented when more meaningful stimuli such as words are used.

Experiment 1a

Experiment 1a explored whether individuals can direct attention to more valuable information in an auditory-verbal WM task. Participants listened to a series of digits and attempted to recall them in the correct serial order following a brief delay. Nine items were presented in each trial in order to reduce the likelihood of ceiling effects. This also allowed us to explore the effects of prioritization on tasks that are beyond capacity limits, which is when such an approach is likely to be most beneficial.

Participants completed four prioritization conditions. In three of these conditions, one of the serial positions was more valuable than the other items in the sequence (SP3, SP5 or SP7). There was also a Control condition in which all of the items were worth the same number of points. As Hitch et al. (2018) demonstrated that value-based prioritization boosts can be observed on any of four positions in a visual sequence, we had no a priori reason to predict substantial differences in effects between each differential condition; this range of positions was selected to sample across the sequence while avoiding early or late positions (which can be subject to ceiling effects and engagement of additional mechanisms in verbal memory).

Based on previous findings (Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2014; 2016; Middlebrooks et al., 2017; Sandry et al., 2014, 2020), it was predicted that prioritization boosts would emerge, with participants exhibiting higher accuracy for the more valuable item, relative to performance at the same serial position in the control condition where all items were of equal value. It was also predicted that costs would emerge to less valuable items. This would provide evidence that individuals can orient attention towards more valuable information in an auditory-verbal WM task, in a similar manner to the visual domain (Hitch et al., 2020). Such findings would also be consistent with suggestions that the FoA is modality-general and can hold either visual or verbal representations (Cowan, 2005; Hitch et al., 2018; Hu et al., 2014; Oberauer, 2013). Finally, in line with the view that the content of WM reflects the operation of automatic attentional control factors, we predicted the presence of a recency advantage for the final sequence item across all conditions, regardless of how participants were being asked to strategically direct their attention.

Method

Participants.

An initial estimated sample size calculation was carried out using G*Power 3 (Faul et al., 2009). The key comparison in this study was between the equal value control condition and the high value condition, at the prioritized position. Based on an effect size of $d = 1.33$ observed by Atkinson et al. (2018) for an equivalent comparison in the visual domain, power analysis indicated a required sample size of N=10 to achieve .95 power with alpha of .05. To enable comparison with our visual WM findings, a similar sample of (N>20) was adopted in this and subsequent experiments.

Twenty-four young adults took part (aged 18-25 years; $M = 21.14$, $SD = 2.04$; 3 males). In this experiment, and all subsequent experiments, participants were native English speakers with no known learning difficulties, normal or corrected-to-normal vision, and no colour blindness. Three participants were excluded for reaching length nine on the forward-digit recall (FDR) task. The analysis was therefore run on data from 21 participants (*M. age* = 21.10, *SD* = 1.99; 3 males).

Experiment 1, and all subsequent experiments in this study, was approved by the School of Psychology ethics committee at University of Leeds.

Design, materials and procedure.

A 4 x 9 within-subjects design was employed, which manipulated prioritization (Prioritize-SP3, Prioritize-SP5, Prioritize-SP7, Control) and serial position (SP; 1-9).

Forward digit recall.

Participants first completed a forward digit recall (FDR) task. This involved listening to a series of digits being read at a steady pace by the experimenter and then repeating them aloud. Each sequence contained series of digits from 0 to 9. Participants first completed two practice trials in which three digits were presented. They then completed the experimental trials, which progressed in difficulty from three to nine digits. Three trials were presented at each length. Participants continued this task until they responded incorrectly on two out of three trials at a given sequence length. This task was used to exclude participants who reached length nine, as it is likely they would have performed at ceiling in the main task.

Main verbal WM task.

Next, participants completed the verbal WM task. In each trial, nine digits were presented (ranging from 1 to 9) auditorily, with the constraint that no digit could appear more than once within the same sequence. Digits were read by a computer-generated female voice. Participants completed four blocks of 12 trials; one for each condition. The order of the condition blocks was fully counterbalanced. At the start of each block, participants completed two practice trials.

Each condition commenced with the provision of written instructions. Participants completed three differential value conditions, in which one of the SPs was more valuable.

This was either the third (Prioritize-SP3), the fifth (Prioritize-SP5) and the seventh (Prioritize-SP7) digit. They also completed a Control condition, in which all items were equally valuable. In the differential value conditions, participants were told that correct recall of the more valuable item (i.e. SP3, SP5 or SP7) would earn them four points, whilst correct recall of the other items would earn them one point. This was based on previous research in visual WM (Atkinson et al., 2018, 2019; Hu et al., 2014, 2016). In the Control condition, participants were told that each item was worth one point.

The experimental paradigm is displayed in Figure 1. To begin the trial, participants pressed the space bar. A fixation cross then appeared at the centre of the screen for 1000ms, which was followed by a delay of 1000ms. Nine digits were then played through headphones, separated by a pause of approximately 1000ms. In the Prioritise-SP3, Prioritise-SP5, and Prioritise-SP7 conditions, a yellow star was presented at the centre of the screen (measuring approximately 4.5cm x 7cm) for 500ms before the more valuable digit was played. This remained on screen until the digit had been presented and for approximately 500ms afterwards. In the Control condition, no visual cue was presented. After all the digits had been played, there was a post-stimulus retention interval of approximately 1500ms. This was followed by a white speech bubble with a black outline (measuring approximately 4cm x 5.5cm), displayed at the centre of the screen. This prompted participants to verbally recall the digits in the correct serial order, with these spoken responses recorded by the experimenter for later scoring. Participants were told they would only receive points for recalling an item if it was in the correct SP. If they couldn't remember a digit, participants were told to either guess or say 'blank'. There was no set time limit for the recall phase of each trial.

[Figure 1 about here]

Finally, at the end of this experiment (and all subsequent experiments), participants completed a questionnaire to assess whether participants believed that prioritization affected memory for the more valuable digit, as well as the other, less valuable items. Details of methodology and outcomes are provided in the supplementary materials.

Data Analysis

The dependent variable for the main verbal WM task was accuracy at each SP, determined by mean proportion correct. Of particular interest was whether prioritization enhanced memory of the more valuable item relative to the item at the same SP in the control condition. Therefore, following the initial omnibus analysis of all conditions and serial positions, targeted analysis was carried out comparing the control and priority conditions at each of the prioritized serial positions. Also, it was of interest whether recall of other, lower valuable items was affected by the direction of attention elsewhere in the sequence. To investigate this, a composite cost score was calculated for each differential value condition. This was calculated by averaging performance at the eight less valuable SPs (e.g., SPs 1-2 & 4-9 in the Prioritize-SP3 condition). This was then compared to a composite score for the Control condition, calculated by averaging accuracy at the same SPs. This method was employed, as opposed to assessing effects at each SP separately, to avoid the need for a large number of comparisons. Where multiple t-tests are reported, these were Bonferroni-Holm corrected.

Data were analysed using frequentist statistics, and Bayes Factor (BF) analysis. This combination of analytic techniques was applied to remedy possible shortcomings of frequentist statistics and provide additional information to aid interpretation (García & Puga, 2018; Halsey, 2019; Lakens et al., 2020; Quatto et al., 2020; Quintana & Williams, 2018). BF analysis was conducted using R (Morey et al., 2018; R Core Team, 2016). It assesses the strength of evidence for the alternative hypothesis by comparing it to the null hypothesis (Barchard, 2015; Mulder & Wagenmaker, 2016). It also provides a test of equivalence between conditions or groups (Mulder & Wagenmaker, 2016). The Bayesian ANOVAs were conducting using the default priors (Rouder et al., 2012), with the number of iterations set at 500,000. All possible models were assessed, which means that a model could contain an interaction even if the main effects were absent.

The most likely model given the data is reported, relative to a null model containing participant only. BFs for each main effect/interaction are also reported. If the main effect/interaction of interest is included in the most likely model, the BF was calculated by comparing the most likely model to the one excluding this factor. Conversely, if the main effect/interaction was not included in the most likely model, BF was calculated by comparing the most likely model plus the main effect/interaction of interest to the most likely model (Rouder et al., 2017). Both of these calculations give a BF_{10} value. A BF_{10} of below 1 provides evidence for the null hypothesis, whilst a BF_{10} above 1 supports the alternative hypothesis. Acknowledging that Bayes Factors should be interpreted as continuous rather than categorical outcomes, we refer to the classification scheme in which a BF_{10} of between .33 and 3 equates to weak or uninformative evidence (Jeffreys, 1961; Lee & Wagenmakers, 2014).

Results

Accuracy across SPs.

Mean proportion correct (and SE) as a function of prioritization and SP is displayed in Figure 2A.

[Figure 2 about here]

A 4 (prioritization) x 9 (SP) within-subjects ANOVA revealed no significant effect of prioritization (*F*(3, 60) = 1.11, *MSE* = .06, *p* = .354, η_p^2 = .05, BF_{10} = 0.09). There was, however, a significant effect of SP (*Greenhouse-Geisser (GG) corrected F*(2.64, 52.87) = 50.20, *MSE* = .15, $p < .001$, η_p^2 = .72, $BF_{10} > 10{,}000$). Of most interest, there was also a significant interaction between prioritization and SP (*GG corrected F*(8.52, 170.45) = 6.98, *MSE* = .06, $p < .001$, η_p^2 = .26, $BF_{10} > 10{,}000$). The BF analysis indicated that the most likely model included effects of SP, as well as an interaction between prioritization and SP ($BF_{10} >$ 10,000 relative to a model containing participant only).

To explore the interaction further, paired sample t-tests, comparing accuracy at the more valuable SP with accuracy at the same SP in the Control condition, were run to establish whether a value-related boost was observed in each case. At SP3, recall of the item at SP3 was higher in Prioritize-SP3 than the Control condition (*t*(20) = 2.97, *p* = .020, *d* = 0.56, BF_{10} = 2.90). Similarly, performance at SP5 was better in the Prioritize-SP5 relative to the Control condition (*t*(20) = 4.39, $p < .001$, *d* = 0.96; BF_{10} = 109.02). Recall of the item at SP7 was also higher in Prioritize-SP7 relative to the Control condition (*t*(20) = 4.94, $p < .001$, *d* = 1.09; BF_{10} = 339.59). Performance in the differential value conditions (i.e. Prioritise-SP3, Prioritise-SP5 and Prioritise-SP7) relative to the Control condition is displayed in Figure 2B. Analysis comparing the size of the prioritization boosts at the different SPs targeted (SP3, SP5 and SP7) is presented in the supplementary materials.

Effects to less valuable items.

Composite scores were calculated for each differential value condition by averaging performance at the eight less valuable SPs. These scores were compared to composite scores for the Control condition, which again were calculated by averaging performance at the same SPs (i.e. omitting the critical SP in each case). A series of paired-samples t-tests was conducted to compare composite scores in the differential value and Control conditions, with p-values corrected for multiple comparisons using Bonferroni-Holm. There was no difference between composite scores in the Control condition ($M = .60$, $SE = .03$) and Prioritize-SP3 ($M = .59$, $SE = .03$; $t(20) = -0.36$, $p = .963$, $d = -.08$, $BF_{10} = .24$), or between Control ($M = .62$, $SE = .03$) and Prioritize-SP5 ($M = .60$, $SE = .03$; $t(20) = -.72$, $p = .963$, $d = -.16$, $BF_{10} = .29$). There was a significant difference between composite scores in the Control ($M = .65$, $SE = .03$) and Prioritize-SP7 ($M = .58$, $SE = .04$) conditions ($t(20) = -2.72$, $p = .040$, $d = -.59$, $BF_{10} = 4.00$), whereby participants exhibited higher accuracy in the former condition.

Discussion

This experiment was the first to examine whether value-directed strategic prioritization can be applied within an auditory-verbal WM task. Prioritization boosts were indeed observed, whereby accuracy at the targeted position was higher when that item was associated with more points, relative to a condition in which all items were equally valuable. These boosts were observed in all conditions. Thus, individuals can direct attention to more valuable information in auditory-verbal WM. This extends previous findings that have used visually presented verbal information in WM (Sandry et al. 2014, 2020) and long-term memory (Middlebrooks et al., 2017) tasks. It also extends findings from the visual domain (Atkinson et al., 2018; Hu et al., 2014; 2016; Hitch et al., 2018) demonstrating that prioritization effects are not modality specific. There were significant costs to the less valuable items in the Prioritise-SP7 condition, but not in the Prioritise-SP3 and Prioritise-SP5 conditions, indicating that prioritization might not always come with cost to less valuable items in auditory-verbal WM. There was also no main effect of prioritization on overall recall performance. This would indicate that, as in the visual domain (e.g., Hu et al., 2014), participants can strategically direct a limited capacity focus of attention to different parts of a to-be-remembered item set, without incurring any increased costs overall.

In addition to the peaks in recall performance at prioritized serial positions, a clear recency advantage for the final item in the sequence was also observed in all conditions. This was the case even when participants were attempting to prioritize an earlier item in the sequence. Examination of SP9 recall in each priority condition indicates it only declined, relative to the control condition, in the Prioritize-SP7 condition ($t(20) = 3.03$, $p < .05$, $d = .66$, $BF_{10} = 7.17$), and even then it remained superior to recall at some of the preceding positions in that condition. Thus, in line with work in the visual domain (Hitch et al., 2019), auditory-verbal WM recall reflects a combination of strategic and automatic attentional control processes. There is a well-established literature on primacy and recency patterns in immediate serial recall (e.g., Burgess & Hitch, 1999; Page & Norris, 1998). This work tends to approach this task with the assumption that participants are allocating equivalent value to every item within the sequence. While an extended consideration of the precise mechanisms underlying serial position effects is beyond the scope of the present work, the findings from Experiment 1a clearly illustrate how otherwise more weakly recalled mid-sequence items can be improved through strategic prioritization, while leaving both primacy and recency effects intact.

Before continuing to explore the possible mechanisms underlying these effects, it is important to establish whether the recall benefits for high value items observed in Experiment 1a genuinely reflect strategic attentional prioritization, rather than other artefacts associated with how the manipulation was implemented. In the current experimental series, the high value item within a sequence was signalled through the presentation of a visual cue (a yellow star) alongside auditory presentation of the relevant digit. This was implemented to avoid placing additional processing demands on the participant associated with identifying, from within a relatively long sequence of stimuli, which serial position they were being directed to prioritize. However, it might give rise to the possibility that any improvements in recall for these high value items do not reflect strategic prioritization, and are instead solely attributable to an increased distinctiveness or the Von Restorff isolation effect (Hunt, 1995; Schmidt, 1991; Von Restorff, 1933; Wallace, 1965) elicited by the pairing of the high value auditory stimulus with a concurrent visual cue[1]. Such an explanation was recently rejected by Sandry et al. (2020) in their exploration of visually presented verbal stimuli; a recall advantage was found for high value words that were cued via presentation in a different font color, but no such effect was observed for stimuli presented in a distinct color when value was equated (see also Sandry & Ricker, 2020). Nevertheless, it is important to establish that evidence for value-driven prioritization in auditory-verbal working memory can be distinguished from any effect of distinctiveness. This was examined in Experiment 1b.

Experiment 1b

The methodology in this experiment was closely based on Experiment 1a, with a few adjustments. In order to demonstrate that recall improvements for high value items reflect strategic prioritization and not distinctiveness, the visual cue used in the broader experimental series to indicate these items was not used in this experiment. Within the relevant conditions, participants were instructed to prioritize a certain item that was assigned high value but were not provided with any assistance in identifying this item from within the sequence. In this case, any resulting recall improvements for this item cannot be attributed to distinctiveness as encoding context is identical across high and low value items, and all priority conditions. Experiment 1b focused only on conditions that allocated value to SPs 3 or 5 (alongside an equal value control condition), as we assumed that monitoring and identifying for prioritization the 7th item in a 9-item sequence would be too demanding without visual cue support.

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[1] We would like to thank our anonymous reviewers for this suggestion.

Method

Participants.

Twenty-two young adults took part (aged 18-23 years; *M* = 20, *SD* = 1.48; 3 males). One participant was excluded for reaching length nine on the forward-digit recall (FDR) task. The analysis was therefore run on data from 21 participants (*M. age* = 19.95, *SD* = 1.50; 3 males). None of the participants had completed Experiment 1a.

Design, materials and procedure. A 3 x 9 within-subjects design was employed, which manipulated prioritization (Prioritize-SP3, Prioritize-SP5, Control) and serial position (SP; 1-9).

Results

Accuracy across SPs. Mean proportion correct (and SE) as a function of prioritization and SP is displayed in Figure 3A.

[Figure 3 about here]

A 3 (prioritization) x 9 (SP) within-subjects ANOVA revealed no significant effect of prioritization (*F*(2, 40) = 1.43, *MSE* = .06, $p = .251$, $\eta_p^2 = .07$, $BF_{10} =$ .06), indicating that the instruction to prioritise did not itself make demands on the available attentional capacity. There was, however, a significant effect of SP (*Greenhouse-Geisser (GG) corrected F*(3.94, 78.80) = 47.70, *MSE* = .10, $p < .001$, $\eta_p^2 = .71$, $BF_{10} > 10,000$), and a significant interaction between prioritization and SP (*GG corrected F*(6.52, 130.45) = 3.20, *MSE* = .06, $p = .005$, $\eta_p^2 = .14$, $BF_{10} = 3.16$). The BF analysis indicated that the most likely model included effects of SP, as well as an interaction between prioritization and SP ($BF_{10} > 10,000$ relative to a model containing participant only).

To explore the interaction further, paired sample t-tests, comparing accuracy at the more valuable SP with accuracy at the same SP in the Control condition, were run to establish whether a value-related boost was observed in each case. At SP3, recall of the item at SP3 was higher in Prioritize-SP3 than the Control condition ($t(20) = 2.53$, $p = .020$, $d = .55$, $BF_{10} = 2.87$). Similarly, performance at SP5 was better in the Prioritize-SP5 relative to the Control condition ($t(20) = 3.04$, $p = .006$, $d = .66$; $BF_{10} = 7.31$). Performance in the differential value conditions (i.e. Prioritise-SP3 and Prioritise-SP5) relative to the Control condition is displayed in Figure 3B. Analysis comparing the size of the prioritization boosts is presented in the supplementary materials.

Effects to less valuable items. Composite scores were again calculated for each differential value condition by averaging performance at the eight less valuable SPs and compared against composite scores for the Control condition at the same SPs. There was no difference between composite scores in the Control condition ($M = 0.56$, $SE = .03$) and Prioritize-SP3 ($M = 0.51$, $SE = .03$; $t(20) = -1.85$, $p = .08$, $d = -.40$, $BF_{10} = .96$), or between Control ($M = 0.57$, $SE = .03$) and Prioritize-SP5 ($M = 0.57$, $SE = .03$; $t(20) = -0.26$, $p = .79$, $d = -.06$, $BF_{10} = .24$).

Discussion

Experiment 1b demonstrated that, even when no visual cue was provided to help guide participants in the appropriate serial position to prioritize, enhanced recall for high value items from within an auditory-verbal sequence was still observed. These benefits were very similar in magnitude to those seen in Experiment 1, and once again emerged in the context of no overall main effect of prioritization. This clearly illustrates that strategic value-driven prioritization effects can be observed in auditory-verbal working memory that are not attributable to variable distinctiveness during encoding (see also Sandry & Ricker, 2020; Sandry et al., 2020). The remaining experiments in the current study use dual-task manipulations to explore how prioritization might be achieved. These reverted to the methodology implemented in Experiment 1a, based on the assumption of a small processing cost associated with identifying an item for prioritization from within a relatively long sequence.

Experiment 2

What might be the maintenance mechanisms involved in supporting the ability to prioritize certain items other overs? In the visual domain, such effects are typically observed even though participants are asked to concurrently articulate irrelevant verbal information during presentation and maintenance (e.g., Atkinson et al., 2018; Hu et al., 2014; 2016; Hitch et al., 2018), and are therefore unlikely to critically involve verbal rehearsal. Similarly, Sandry et al. (2014) observed that prioritization effects for visually presented verbal material remained intact under a similar form of articulatory suppression. However, it is unclear whether the same applies when to-be-remembered information is aurally encountered, with no corresponding visual component to the task. Visual WM is potentially more closely related to executive control (Baddeley et al., 2020; Gray et al., 2017; Morey & Miron, 2016). Indeed, Hu et al (2016) found priority effects in visual WM are reliant on executive resources. In contrast, participants may be more likely to rely on verbal rehearsal in auditory-verbal memory tasks, as no recoding is needed. Thus, prioritization effects might be more reliant on rehearsal when material is encountered aurally.

Experiment 2 therefore examined the effects of prioritization to more and less valuable items if participants' ability to verbally rehearse is disrupted by articulatory suppression (Baddeley, 1986; Camos et al., 2009). A simple verbal concurrent task was therefore applied during the digit presentation phase and the maintanence phase, with participants required to articulate a short verbal sequence until the retrieval phase. If boosts are reduced or abolished under such conditions, this would indicate that prioritization is critically dependent on verbal rehearsal when information is presented aurally. In contrast, evidence that individuals are able to direct their attention under suppression would be consistent with previous findings using visual modes of presentation (Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2014; 2016; Sandry et al., 2014), suggesting that effects are not solely reliant on rehearsal. Participants completed the same verbal WM task as was employed in Experiment 1a. Whilst doing so, participants completed no concurrent task or a simple concurrent task (articulatory suppression). As concurrent task was added as an additional variable, the number of prioritization conditions was reduced to two (Prioritize-SP5 and Control) in order to prevent the experiment from becoming too lengthy, which might introduce fatigue effects. SP5 was selected, as this represents the mid-point in the sequence and generated reliable prioritization boosts in Experiments 1a and 1b.

Method

Participants.

Twenty-four young adults took part (aged 18-24 years; *M* = 21.03, *SD* = 1.48; 5 males). Two participants were excluded for reaching length nine on the FDR task, one participant was removed for not following the instructions correctly and one participant for equipment failure. The analysis was therefore run on data from 20 participants (*M. age* = 21.00, *SD* = 1.49; 5 males). None of the participants had completed Experiment 1a or Experiment 1b.

Design, materials and procedure.

A 2 x 2 x 9 within-subjects design was employed, which manipulated prioritization (Prioritize-SP5 vs. Control), concurrent task (no concurrent task vs. simple concurrent task) and SP (1-9). The materials and procedure were identical to Experiment 1a, except that in the simple concurrent task conditions, participants were presented with a randomly selected day of the week and a month of the year (e.g., Monday, July) at the centre of the screen for 1000ms before the fixation cross (Calia, Darling, Havelka, & Allen, 2018). Participants were told to repeat this aloud (e.g., *Monday, July, Monday, July*) until the test probe was displayed.

Results

Accuracy across SPs.

Mean proportion correct (and SE) as a function of prioritization, SP, and concurrent task are displayed in Figure 4A. Performance in each Prioritize-SP5 condition relative to the equivalent control condition is displayed in Figure 3B, as a function of SP and concurrent task.

[Figure 4 about here]

A 2 (prioritization) x 2 (concurrent task) x 9 (SP) within-subjects ANOVA revealed no significant effect of prioritization ($F(1, 19) = .32$, $MSE = .07$, $p = .577$, $\eta_p^2 = .02$, $BF_{10} = .10$. There was, however, a significant effect of SP (GG corrected $F(2.59, 49.27) = 38.02$, $MSE = .20$, $p < .001$, $\eta_p^2 = .67$, $BF_{10} > 10{,}000$), characterised by primacy and recency effects, as well as superior performance at SP5. There was also a significant effect of concurrent task ($F(1, 19) = 50.12$, $MSE = .12$, $p < .001$, $\eta_p^2 = .73$, $BF_{10} > 10{,}000$), with participants exhibiting higher accuracy in the no concurrent task condition. The interaction between prioritization and concurrent task approached significance ($F(1, 19) = 3.97$, $MSE = .05$, $p = .061$, $\eta_p^2 = .17$, $BF_{10} = 1.32$). There was a significant interaction between prioritization and SP (GG corrected $F(3.10, 58.95) = 12.01$, $MSE = .09$, $p < .001$, $\eta_p^2 = .39$, $BF_{10} > 10{,}000$). There was also a significant interaction between concurrent task and SP (GG $F(3.85, 73.23) = 3.92$, $MSE =$

.05, $p = .007$, $\eta_p^2 = .17$, $BF_{10} = 1.48$). A three-way interaction between prioritization, concurrent task, and SP also emerged (GG corrected $F(3.51, 66.61) = 4.66$, $MSE = .05$, $p = .003$, $\eta_p^2 = .20$, $BF_{10} = 1.88$). The Bayes factor for this three-way interaction was only weak, although the η_p^2 was medium in size. The BF analysis indicated that the most likely model included main effects of concurrent task and SP, as well as two-way interactions between prioritization and SP, concurrent task and SP, and prioritization and concurrent task, and a three-way interaction between prioritization, concurrent task and SP ($BF_{10} > 10{,}000$ relative to a model containing participant only).

Analysis of SP5.

A 2 (prioritization) x 2 (concurrent task) within-subjects ANOVA revealed a significant main effect of prioritization ($F(1, 19) = 46.97$, $MSE = .05$, $p < .001$, $\eta_p^2 = .71$, $BF_{10} > 10{,}000$), whereby participants exhibited greater accuracy at SP5 in the Prioritize-SP5 condition than the Control condition. There was also a significant main effect of concurrent task ($F(1, 19) = 18.88$, $MSE = .03$, $p < .001$, $\eta_p^2 = .50$, $BF_{10} = 251.37$), with participants exhibiting greater accuracy in the no concurrent task condition. A significant interaction between prioritization and concurrent task also emerged ($F(1, 19) = 6.65$, $MSE = 0.02$, $p = .018$, $\eta_p^2 = .26$, $BF_{10} = 1.22$). The Bayes factor for this interaction was not informative, although the η_p^2 was large in size. BF analysis revealed that the most likely model included main effects of prioritization and concurrent task, as well as an interaction between prioritization and concurrent task ($BF_{10} > 10{,}000$ relative to a model containing participant only).

Further analysis indicated that accuracy was significantly higher in the Prioritize-SP5 relative to the Control conditions when participants completed no concurrent task ($t(19) = 4.28$, $p < .001$, $d = .96$, $BF_{10} = 80.30$), and the simple concurrent task ($t(19) = 8.07$, $p < .001$, $d = 1.81$, $BF_{10} > 10{,}000$), though the effect size was larger in the latter condition. Thus, the prioritization effect was not diminished, and was actually somewhat larger, under articulatory suppression.

Analysis of less valuable items.

As in Experiments 1a and 1b, composite scores were calculated for each condition by averaging performance across all SPs except SP5. A 2 (prioritization) x 2 (concurrent task) within-subjects ANOVA revealed no significant main effect of prioritization ($F(1, 19) = 2.70$, $MSE < .01$, $p = .117$, $\eta_p^2 = .13$, $BF_{10} = .57$). There was a significant main effect of concurrent task ($F(1, 19) = 49.04$, $MSE = .01$, $p < .001$, $\eta_p^2 = .72$, $BF_{10} > 10{,}000$) with participants exhibiting reduced accuracy for less valuable items in the simple concurrent task condition ($M = .36$, $SE = .03$) than the no concurrent task condition ($M = .55$, $SE = .04$). There was a significant interaction between prioritization and concurrent task ($F(1, 19) = 7.45$, $MSE < .01$, $p = .013$, $\eta_p^2 = .28$, $BF_{10} = 1.83$). The Bayes factor for this interaction was not informative, although the η_p^2 was large in size. Follow-up paired samples t-tests revealed no significant costs in the no concurrent task condition ($t(19) = .60$, $p = .558$, $d = .13$, $BF_{10} = .27$), but significant costs in the simple concurrent task condition ($t(19) = -3.01$, $p = .015$, $d = -.67$, $BF_{10} = 6.70$). The BF analysis indicated that the most likely model includes a main effect of concurrent task and an interaction between prioritization and concurrent task ($BF_{10} > 10{,}000$ relative to a model containing participant only)..

Discussion

Accuracy at SP5 was significantly higher when this position was associated with more points (Prioritize-SP5), relative to a condition in which all items were equally valuable (Control). This finding replicates the earlier experiments and further demonstrates that individuals can direct their attention to more valuable information in auditory-verbal WM. These prioritization boosts were not reduced by concurrent verbal articulation (and were in fact somewhat larger in size under suppression), demonstrating that individuals are able to prioritize more valuable verbal information when rehearsal is disrupted.

Replicating outcomes from the same condition in Experiments 1a and 1b (Prioritize-SP5), there were no significant costs of prioritization in the no concurrent task condition. This therefore provides further evidence that directing attention to a particular item does not always significantly affect others within the sequence. Prioritization costs did emerge in the simple concurrent task condition, suggesting that, when attention is directed to a particular item, rehearsal is used to retain less valuable information. Rehearsal processes are thought to be relatively cost-free (Camos & Barrouillet, 2014; Camos et al., 2011), and may thus serve as a way to retain less important information when items differ in value. Finally, as in Experiments 1a and 1b, and equivalent work in the visual domain (Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2014; 2016), there was again no overall main effect of prioritization, indicating that the direction of attention towards certain items does not itself incur a general processing cost.

Evidence that prioritization boosts emerged in the simple concurrent task condition suggests that effects might involve mechanisms other than rehearsal. Certainly, this would fit with evidence from the visual domain, in which effects persist under articulatory suppression (e.g., Hu et al., 2014, 2016; Sandry et al., 2014) and are unrelated to participants' subjective reporting of rehearsal use (Sandry & Ricker, 2020). An alternative explanation might be found in the form of attentional refreshing, a domain general process (Vergauwe et al., 2010) whereby decaying memory traces are kept active via executive control (Camos et al., 2018; Hitch et al., 2020). Indeed, such an account was posited by Sandry and colleagues to capture prioritization effects in the visual domain (Sandry et al., 2014, 2020), though this was not explored empirically. Experiment 3 therefore examined whether priority effects change when concurrent executive load is increased.

Experiment 3

Experiment 2 demonstrated that boosts to valuable items can be maintained when rehearsal is disrupted. Within the literature a distinction has been drawn between maintenance based on verbal rehearsal, and maintenance based on attentional processes such as refreshing (e.g., Camos et al., 2009). Thus, one possibility is that the more valuable item is retained through attentional refreshing rather than rehearsal (Atkinson et al., 2018; Hu et al., 2014). If so, sufficient executive attentional resources would be needed in order to prioritize the valuable information. Some support for this hypothesis has been provided in the visual domain, with Hu et al. (2016) demonstrating that prioritization boosts were reduced when the complexity of the secondary task was increased (thereby disrupting recruitment of executive control for the main task). This was taken as evidence that effective reward-based prioritization within visual WM requires executive resources.

Experiment 3 therefore investigated how working memory for items in an auditory-verbal sequence that differ in value might change when executive resources are reduced during encoding and maintenance. Participants were instructed to prioritize a valuable digit whilst completing either a simple or a complex verbal task (adapted from Calia et al., 2018). Based on previous research indicating that executive resources are involved in immediate serial recall, an overall main effect of concurrent task was expected, with poorer performance in the complex condition (Baddeley et al., 2009; Calia et al., 2018; St. Clair-Thompson & Allen, 2013). Moreover, if this type of prioritization is critically reliant on executive resources, one might expect an interaction at the more valuable position, whereby the prioritization boost is reduced or abolished under complex concurrent task conditions. It was anticipated that performance would be at floor if nine items were presented in the complex concurrent task condition. As such, the number of items encountered was reduced to seven.

Increased value was allocated to SP4, to ensure that the more valuable item continued to be the middle digit in the sequence (in line with Experiment 2).

Method

Participants.

Twenty-four young adults took part (aged 18-21 years; *M* = 19.34; *SD* = 0.88; 2 males). Participants had not taken part in Experiments 1a, 1b or 2.

Design, materials and procedure.

A 2 x 2 x 7 within-subjects design was employed, which manipulated prioritization (Prioritize-SP4 vs Control), concurrent task (simple verbal vs. complex verbal) and SP (1-7).

The materials and procedure were similar to Experiment 2, with some exceptions. The no concurrent task condition was dropped, and a complex verbal task condition was introduced. In every trial, participants were presented with a randomly selected day of the week and a month of the year (e.g., Monday, July) at the start of each trial. In the simple verbal task condition, participants had to repeat this pair aloud (e.g., *Monday, July, Monday, July, Monday, July…*) until the test probe was displayed, as in Experiment 2. In the complex task condition, participants had to repeat the day of the week and month of the year presented on screen and then cycle through the days of the week and months of the year in chronological order (e.g., *Monday, July, Tuesday, August, Wednesday, September…*).

As the complex concurrent task was designed to disrupt executive control as well as verbal rehearsal, we predicted that overall accuracy would be lower than with the simple concurrent task. Given that some SPs were approaching chance in the previous experiment, the number of digits presented was reduced from nine to seven. However, despite this reduction in memory load, it was anticipated that participants would not perform near ceiling in this experiment due to the absence of a no concurrent task condition. The initial FDR screening tool was therefore not administered[2].

Results

Accuracy across SPs.

Mean proportion correct (and SE) as a function of prioritization, SP, and concurrent task are displayed in Figure 5A. A comparison of each prioritization condition against the equivalent control condition (as baseline) is illustrated in Figure 4B.

A 2 (prioritization) x 2 (concurrent task) x 7 (SP) within-subjects ANOVA revealed no significant effect of prioritization ($F(1, 23) = 2.46$, $MSE = .05$, $p = .131$, $\eta_p^2 = .10$, $BF_{10} = .83$). and a significant effect of SP (GG corrected $F(3.06, 70.43) = 72.80$, $MSE = 0.07$, $p < .001$, $\eta_p^2 = .76$, $BF_{10} > 10{,}000$), characterised by primacy and recency effects, as well as superior performance at SP4. There was also a significant effect of concurrent task ($F(1, 23) = 225.01$, $MSE = .05$, $p < .001$, $\eta_p^2 = .91$, $BF_{10} > 10{,}000$) with participants exhibiting higher accuracy in the simple verbal task condition. No significant interaction emerged between prioritization and concurrent task, ($F(1, 23) < .01$, $MSE = .02$, $p = .951$, $\eta_p^2 <. 01$, $BF_{10} = 0.12$). However, as in the previous experiments, there was a significant interaction between prioritization and SP ($F(6, 138) = 20.17$, $MSE = .02$, $p < .001$, $\eta_p^2 = .47$, $BF_{10} > 10{,}000$). There was also a significant interaction between concurrent task and SP (GG corrected $F(3.45, 79.26) = 31.38$, $MSE = .05$, $p < .001$, $\eta_p^2 = .58$, $BF_{10} = 10{,}000$). Finally, there was also a three-way interaction between prioritization, concurrent task, and SP, though the BF analysis indicated evidence of no effect (*GG corrected* $F(3.92, 90.16) = 2.59$, $MSE = .03$, $p =$

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[2] This was confirmed by observing participants' mean performance across SPs, with the highest proportion correct in any condition being 0.86.

.043, η_p^2 = .10, BF_{10} = .50). The BF analysis indicated that the most likely model included main effects of concurrent task and SP, as well as two-way interactions between prioritization and SP, and concurrent task and SP (BF_{10} > 10,000 relative to a model containing participant only).

[Figure 5 about here]

Analysis of SP4.

A 2 (prioritization) x 2 (concurrent task) within-subjects ANOVA revealed a significant main effect of prioritization ($F(1, 23) = 70.29$, $MSE = .02$, $p < .001$, $\eta_p^2 = .75$, BF_{10} > 10,000), whereby participants exhibited greater accuracy at SP4 in the Prioritize-SP4 condition relative to the Control condition. There was also a significant main effect of concurrent task ($F(1, 23) = 94.04$, $MSE = .02$, $p < .001$, $\eta_p^2 = .80$, BF_{10} > 10,000), with participants exhibiting greater accuracy in the simple verbal task condition. There was no interaction between prioritization and concurrent task ($F(1, 23) = 2.32$, $MSE = .03$, $p = .142$, $\eta_p^2 = .09$, $BF_{10} = .92$). The BF for this interaction indicated entirely equivocal evidence, although it should be noted (based on Figure 5) that there was a numerically larger prioritization boost in the complex task condition. This therefore refutes our initial prediction that prioritisation effects would be reduced under complex concurrent task conditions. The BF analysis indicated that the most likely model included main effects of prioritization and concurrent task ($BF_{10} >$ 10,000 relative to a model containing participant only).

Analysis of less valuable items.

As in the previous experiments, composite scores were calculated for each condition by averaging performance across all SPs except SP4. A 2 (prioritization) x 2 (concurrent task) within-subjects ANOVA revealed a significant main effect of prioritization ($F(1, 23)$ =

16.41, $MSE < .01$, $p < .001$, $\eta_p^2 = .42$, $BF_{10} = 846.41$) with participants exhibiting higher accuracy at these positions in the Control condition ($M = .44$, $SE = .02$) relative to the Prioritize-SP4 condition ($M = .36$, $SE = .02$). There was a significant main effect of concurrent task ($F(1, 23) = 235.33$, $MSE < .01$, $p < .001$, $\eta_p^2 = .91$, $BF_{10} > 10{,}000$), with participants exhibiting reduced accuracy for the less valuable items in the complex condition ($M = .27$, $SE = .01$) relative to the simple condition ($M = .53$, $SE = 0.02$). The interaction between prioritization and concurrent task was not significant ($F(1, 23) = 0.44$, $MSE < .01$, $p = .512$, $\eta_p^2 = .02$, $BF_{10} = .33$). The BF analysis indicated that the most likely model included main effects of prioritization and concurrent task ($BF_{10} > 10{,}000$ relative to a model containing participant only).

Observation of Figure 4A suggests that performance at several of the low value items was near floor in the complex concurrent task condition. This was particularly apparent in the Prioritize-SP4 condition, which might suggest that participants abandoned these items in order to focus on the more valuable digit. To investigate this further, a series of one-sample t-test were conducted to explore whether performance in the complex concurrent task conditions significantly differed from chance guessing rate (1/9 = .11). In the Prioritise-SP4 condition, performance at SP4 ($t(23) = 7.15$, $p < .001$, $d = 1.46$, $BF_{10} > 10{,}000$) and SP7 ($t(23) = 9.51$, $p < .001$, $d = 1.94$, $BF_{10} > 10{,}000$) significantly differed from chance, whilst all other SPs did not ($t \geq -.42$ and ≤ 2.12, $p \geq .226$, $BF_{10} \leq 1.41$). This suggests that performance was at floor for all positions except from the more valuable item and the final item. In the Control condition, accuracy at SP1 ($t(23) = 7.25$, $p < .001$, $d = 1.48$, $BF_{10} > 10{,}000$), SP2 ($t(23) = 3.66$, $p = .005$, $d = .75$, $BF_{10} = 27.71$), SP6 ($t(23) = 4.19$, $p = .002$, $d = .86$, $BF_{10} = 88.93$) and SP7 ($t(23) = 12.56$, $p < .001$, $d = 2.56$, $BF_{10} > 10{,}000$) was significantly greater than chance, whilst performance at SP3, SP4, and SP5 did not differ ($t \geq -.44$ and ≤ 1.51, $p \geq .431$, $BF_{10} \leq .58$).

Discussion

In this experiment, participants attempted to prioritize a more valuable item whilst engaging in a concurrent task that disrupted verbal rehearsal (simple), or verbal rehearsal and executive control (complex). Overall accuracy was lower when participants performed the complex concurrent task (Calia et al., 2018), indicating that executive control resources are involved in immediate serial recall of digit sequences (St. Clair-Thompson & Allen, 2013). Moreover, replicating the previous experiments, prioritization effects were observed, whereby accuracy at the targeted position (SP4) was significantly higher when this item was more valuable. This effect was in fact numerically larger in the complex concurrent task conditions, demonstrating that individuals are able to prioritize information in the current paradigm when executive control resources are diminished.

The overall absence of a main effect of prioritization was again observed in this final experiment. Instead, as in the visual domain, a trade-off pattern emerged with recall improvements for the high value item alongside costs to other items. These costs did not appear to vary as a function of concurrent task. It is, however, worth noting that mean accuracy at the less valuable positions (except the final item) was at floor in the complex concurrent task condition (see Figure 5A). This suggests that disruption to both verbal rehearsal and executive control renders individuals only able to recall the more valuable item and the most recently encountered in the sequence.

Evidence that prioritization boosts emerged under high cognitive load might suggest that these effects do not appear crucially to rely on executive resources in a serial recall, verbal WM task. This would be in line with outcomes reported in the directed-remembering literature (Middlebrooks et al. 2017) but would contrast with research employing a similar type of prioritization in visual WM (Hu et al., 2016). It is, however, important to review this outcome within the broader set of findings. Although prioritization costs did not vary as a function of concurrent task, performance at all of the less valuable positions except the final item was at chance level in the complex concurrent task condition. This suggests that individuals may have abandoned the less valuable digits and only attempted to retain the more valuable item. Building further on this possibility, analysis of omission rates in this experiment (see Supplmentary materials) shows that, at SP4, omissions were more frequent in the Control condition, compared to the Prioritize-SP4 condition, and this difference was reliably increased under complex cognitive load. This pattern was reversed at the less valuable SPs, with participants somewhat more likely to omit responses when prioritizing SP4 under complex load (though the Bayesian analysis did not strongly support the frequentist outcomes). In conjunction then, this combination of outcomes provides some evidence that participants did indeed abandon the less valuable items in order to retain the more valuable digit.

Finally, a very clear recency advantage again emerged in this experiment. This can be seen even in the condition where participants are encouraged to direct their attention to another item and also perform a cognitively demanding concurrent task. Such findings are consistent with claims that the final item is retained automatically in verbal WM (Baddeley & Hitch, 1993) and mirrors effects reported in the visual domain (Allen et al., 2014; Hu et al., 2016).

General Discussion

Individuals can prioritize more valuable information for recall when this is presented visually (Atkinson et al., 2018; Hu et al., 2014; 2016; Hitch et al., 2018; Sandry et al., 2014). The current series of experiments was the first (to our knowledge) to investigate whether attention can be directed to particular items in an auditory-verbal WM task. Experiment 1a revealed that individuals are able to prioritize more valuable information, regardless of whether this appears near the beginning, middle, or end of a verbal sequence. Experiment 1b demonstrated that these effects replicate when discounting an alternative explanation based on distinctiveness. Two follow-up experiments were then completed to explore how these effects are moderated by concurrent performance of a simple (Experiment 2) or complex (Experiment 3) verbal task. The simple task was implemented to disrupt verbal rehearsal, whilst the complex task was designed to disrupt verbal rehearsal and executive control. In Experiment 2, prioritization effects emerged that were, somewhat unexpectedly, significantly larger in the simple concurrent task condition. Significant prioritization effects were also observed when participants completed a more complex verbal task (Experiment 3), although these boosts were accompanied by chance level performance at the majority of the other positions.

Observation of prioritization benefits for high value items in all four experiments provides clear evidence that individuals can direct their attention to particularly valuable information in auditory-verbal WM tasks. Such effects emerged as prioritization x serial position interactions and enhanced recall at the high value position, and not via any main effect of the prioritization manipulation on recall performance overall. This pattern of outcomes is similar to those observed in the visual domain using cued recall of colored shapes (e.g., Hu et al., 2014). Thus, in both the visual and auditory-verbal domains, the process of prioritization involves strategically allocating a limited capacity attentional resource towards an item of relatively greater value, but with a trade-off emerging in the form of some costs to lower value items. Using an analogy from visual perception (Jonides, 1983; Eriksen & Yeh, 1985; Eriksen & James, 1986), it is possible to focus attention in on one or more items (as in the priority conditions of the present experiment, and equivalent visual work) or pull back and distribute attention across a broader set (as we assume is applied in the equal value control condition). The absence of any overall decline in performance suggests that no cognitive cost is incurred when adjusting the focus of this attentional selectivity. Priority instructions alter the way executive resources are deployed, without affecting the total amount of resources available.

Once attention is focused on the higher value item from within a sequence, how is it successfully maintained in order to derive a prioritization boost in recall? The continuing emergence of priority effects under simple verbal load in Experiments 2 and 3 suggest that it does not critically depend on use of verbal rehearsal. This fits with outcomes from the visual domain (e.g., Hitch et al., 2018; Hu et al., 2014) where a verbal concurrent task (usually, a simple task such as repeating a short number) is typically applied to disrupt verbal recoding and rehearsal and thus maintain the focus on visual WM. However, the absence of any reduction in prioritization effects under complex concurrent load in Experiment 3 contrasts with findings from visual WM (Hu et al., 2016). This might indicate that the cognitive mechanisms underlying prioritization in WM differ depending on modality. Visuospatial WM appears to be more vulnerable to dual-task interference (e.g., Morey, 2018; Morey et al., 2013) and more closely associated with central executive control (Gray et al., 2017). Therefore, it may be that at least temporarily maintaining a visual item for priority is somewhat more demanding, compared to the verbal domain. However, it is also worth noting that the fate of low value items differed in Experiment 3 and Hu et al. (2016). Participants in Experiment 3 may have abandoned the less valuable items in order to retain the more valuable digit, as indicated by chance recall performance at the majority of the less valuable positions. Although significant prioritization costs were observed in Hu et al. (2016), memory for the low value items remained above chance for most, if not all, items. Differences in findings between these studies might then partly reflect changes in strategic approach motivated by methodological differences between experiments. The current study used serial recall, in which all items were assessed on every trial. Under these circumstances, a successful approach might be to focus remaining resources on preserving the more valuable digit, as this will be assessed on every trial. In contrast, Hu et al. (2016) employed a cued-recall paradigm, in which each serial position was assessed 25% of the time. In this case, where the more valuable item is relatively unlikely to be tested, participants might abandon a prioritization strategy under high cognitive load, and instead focus on remembering as many items as possible. This approach would reflect the flexible ways in which individuals apply limited-capacity WM and attentional control systems, dynamically shifting strategic approaches to optimize performance and meet task demands (Logie et al., , 2020), and is consistent with the observation that strategy use within a given task varies substantially depending on retrieval method (Morrison et al., 2016), Thus, although the current study was designed to explore prioritization using serial recall, it would be useful for further research to explore how attention can be selectively applied across a range of task contexts.

Indeed, using single digit items as to-be-remembered material involves a closed stimulus set, and so, as is typically the case in digit recall measures, serial order is an important component of the present task. This approach differs from that used by Sandry et al. (2020), for example, in which new words are encountered on every trial, therefore placing a greater requirement on item memory. In contrast, closed sets are typically used in visual working memory explorations of value-directed prioritization (see Hitch et al., 2020), and are useful in emphasizing temporary storage and minimizing contributions from long-term memory. Nevertheless, it would be interesting for future work to systematically examine how strategic prioritization might differentially impact on item vs. order memory, and for material that varies on dimensions such as familiarity, imageability, and meaning. Similarly, given prioritization has typically been explored in the visual domain, in both working memory and episodic LTM, using binding/associative memory tasks that require the association between color and shape, or object and location, it would be worthwhile to explore strategic prioritization within auditory-verbal tasks that involve such analogous demands.

It has been suggested that prioritization effects may at least partially reflect more valuable items being retained in an accessible, privileged state (Hitch et al., 2019; Hu et al., 2014). Taken together with findings from the visual domain, these experiments illustrate how information received from either the visual or the auditory modality can be strategically maintained in this way. This may occur as a result of attentional processes, such as preferential consolidation (Ricker et al., 2018) or a biased attentional refreshing process. The latter may be a form of 'online refreshing', in which the high value item is repeatedly refreshed so that it is continuously held in a heightened state of accessibility (Johnson, 1992; Johnson et al., 2002; Sandry & Ricker, 2020; Sandry et al., 2020). Differentiating this from WM consolidation is challenging, and indeed, holding an item in an accessible state from the point of encoding may directly serve to support short-term consolidation (Ricker et al., 2018) and longer term (Sandry et al., 2020). Thus, a single item can be maintained at a high level of activation while novel information is concurrently presented and encoded. The high value item might also, or alternatively, be preferentially but not exclusively refreshed, through what has been termed reactivation refreshing, whereby multiple items are cycled through attention (Ricker et al., 2018). The present methods and outcomes do not enable us to confidently distinguish between these possibilities, though the requirement to only prioritize one item per sequence might suggest that online refreshing of this target to be more likely. This seems to be particularly the case under complex load conditions (Experiment 3), where only recall of the high value item remains intact.

The one notable exception to this was the final sequence item. In all four experiments, there was a clear recency advantage. This was observed even when participants were simultaneously attempting to prioritize an item at an earlier sequence position while also carrying out an attention-demanding concurrent verbal task (Experiment 3). This broadly fits with the patterns of performance observed in visual WM tasks in the area (e.g., Hu et al., 2014, 2016; Sandry & Ricker, 2020). Thus, WM performance reflects a combination of strategic control and more automatically derived effects, in both the visual and auditory modalities. The recency effect has been captured in several ways in computation models of serial order (e.g., Brown et al., 2007; Burgess & Hitch, 1999; Page & Norris, 2008), but in each case appears to reflect a bottom-up process (Sandry et al., 2020; Niklaus et al., 2019), as opposed to top-down strategic control indexed via directed prioritization. In the context of visual WM, it has been linked to automatic registration in the focus of attention as the most recently encountered stimulus, followed by displacement from this privileged state by subsequent stimuli unless it is strategically prioritized (Hu et al., 2014). This general account would fit with the observation in Experiment 3 that the single-item recency effect remains unchanged and intact even under high cognitive load and when attention is being strategically directed elsewhere. Indeed, the present study provides the first concurrent observation of both prioritization and recency effects from within the same trials, in contrast to previous work that has typically used single item probe tasks (e.g., Hitch et al., 2018; Sandry et al., 2020). If we assume that each of these effects reflect privileged maintenance within a focus of attention, this could then represent evidence for at least a two-item capacity to this possible WM component (though see Niklaus et al., 2019). Future work might examine how performance changes with varying numbers of high value items (see Allen & Ueno, 2018, and Hitch et al., 2018, for initial examination of this question in the visual domain) Finally, it is also useful to note that prioritization of early sequence positions in visual WM typically always produces at least a small reduction in the recency advantage, whereas this was not consistently the case in this study. This presumably reflects the impact of echoic memory following auditory-verbal presentation (Crowder & Morton,1969), resulting in a stronger tendency for the last item in a sequence to be automatically retained in a privileged state at the time of recall.

How might we capture the present findings within theoretical frameworks describing working memory? Within the multiple component model (Baddeley & Hitch, 1974; Baddeley, 2012; Baddeley et al., 2020), auditory information automatically enters the phonological store. It can then be rehearsed to keep it active, unless articulatory suppression is applied to prevent subvocal rehearsal (as in the simple verbal tasks applied in Experiments 2 and 3). We assume that participants can strategically direct rehearsal maintenance towards any part of the sequence, including the high value item and those surrounding it, though rehearsal tends to typically be applied in serial recall tasks from the start of a sequence when items are equally valuable, and is limited to around four items (Tan & Ward, 2008). Items also, briefly, occupy a modality general FoA within the episodic buffer as the most recently encountered stimulus. Under this approach, a high value item can receive prioritized maintenance, either through rehearsal to keep the phonological representation intact, or through a process of refreshing within a focus of attention as part of the episodic buffer. Taken together with previous findings in the visual domain (Allen & Ueno, 2018; Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2014; 2016), the present findings are consistent with claims that this privileged state is modality-general in nature (Baddeley, 2000; Cowan, 2005; Hitch et al., 2020; Oberauer, 2013). When attempting to hold multiple items for serial recall, including a particularly high value target, one possibility is that participants engage in a division of labor whereby the high value item is kept active through continual refreshing and held via sustained attention, while other items are maintained via rehearsal. When rehearsal is disrupted and available attentional resources diminished via concurrent tasks, the less valuable items are neglected and lost. The present findings support this claim, as costs to these items were only consistently observed in conditions where rehearsal was disrupted by articulatory suppression.

This account assumes that multiple structures and processing resources can be brought to bear on performance in a WM task such as serial recall (Baddeley, 2000; Craik, 1971; Logie et al., 2020). Indeed, Barrouillet et al. (in press) have recently demonstrated how performance in immediate serial recall tasks can be optimized by directing participants to apply rehearsal and attentional refreshing maintenance mechanisms to different parts of a sequence. This was demonstrated for both visual and auditory presentation of verbal information (letters). Barrouillet et al. (in press) interpreted their results as reflecting storage within articulatory and executive loops, with maintenance through rehearsal or refreshing respectively. This theoretical framework differs from the multiple component approach described above, in allocating storage capability to executive control (cf. Baddeley, 1986, 2000). Nevertheless, a similar division of labor might be spontaneously adopted in the current paradigm, with different maintenance mechanisms applied to items of different value or perceived importance.

These findings might also have some practical implications. In the visual world, individuals can avert their gaze away from less relevant information in order to avoid encoding. However, such mechanisms do not exist with acoustic processing, meaning that verbal information considered irrelevant or less relevant to current goals may be encoded and processed within WM (Macken et al., 2009). The ability to prioritize information in verbal WM is therefore of critical importance. The current experiments demonstrate that individuals can orient attention towards particularly valuable representations in this domain, even under extreme conditions where verbal rehearsal and executive control are disrupted. Importantly, these boosts do not always appear to come at a significant cost to less valuable items, particularly under normal circumstances where individuals are able to refresh or verbally rehearse information.

In summary, these experiments provide clear evidence that individuals can direct their attention to more valuable information in an auditory-verbal WM task. This extends previous findings, which have demonstrated that individuals can prioritize valuable information presented visually (Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2014; 2016; Sandry et al., 2014). In some cases, prioritization boosts were accompanied by costs to other items. This was particularly clear when both rehearsal and attentional mechanisms were disrupted, with performance at the majority of low value items dropping to floor (Experiment 3). These outcomes contrast with previous findings using a cued-recall visual task (Hu et al., 2016), in which prioritization effects were reduced under high load, but memory for other items remained above chance level. These differences in outcomes likely reflect participants taking distinct strategic approaches depending on task factors. Indeed, one view of the current outcomes, and of WM tasks more generally, is that the strategies employed to maintain different items might vary across the sequence. In contrast, a recency advantage for the final sequence item was observed across all experiments and conditions, regardless of where attention was directed in terms of item value or concurrent load, suggesting an automatic, non-strategic basis to this effect. As prioritization provides one way of overcoming the capacity limits of WM, it would be useful to further investigate the fate of high and low value items in a range of different task contexts.

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Figure Legends

Figure 1. Schematic illustration of the experimental paradigm (with Prioritize-SP5 and Control trials as illustrative examples). Participants were first presented with a day of the week and month of the year for 1000ms in Experiment 2 & 3 only. They then heard a series of digits through headphones, with a 1000ms inter-stimulus interval. In the Prioritize-SP3, Prioritize-SP5 and Prioritise-SP7 conditions, a star was displayed on screen when the more valuable item was presented and for 500ms prior to its onset. In the Control condition, a blank screen was displayed during this time.

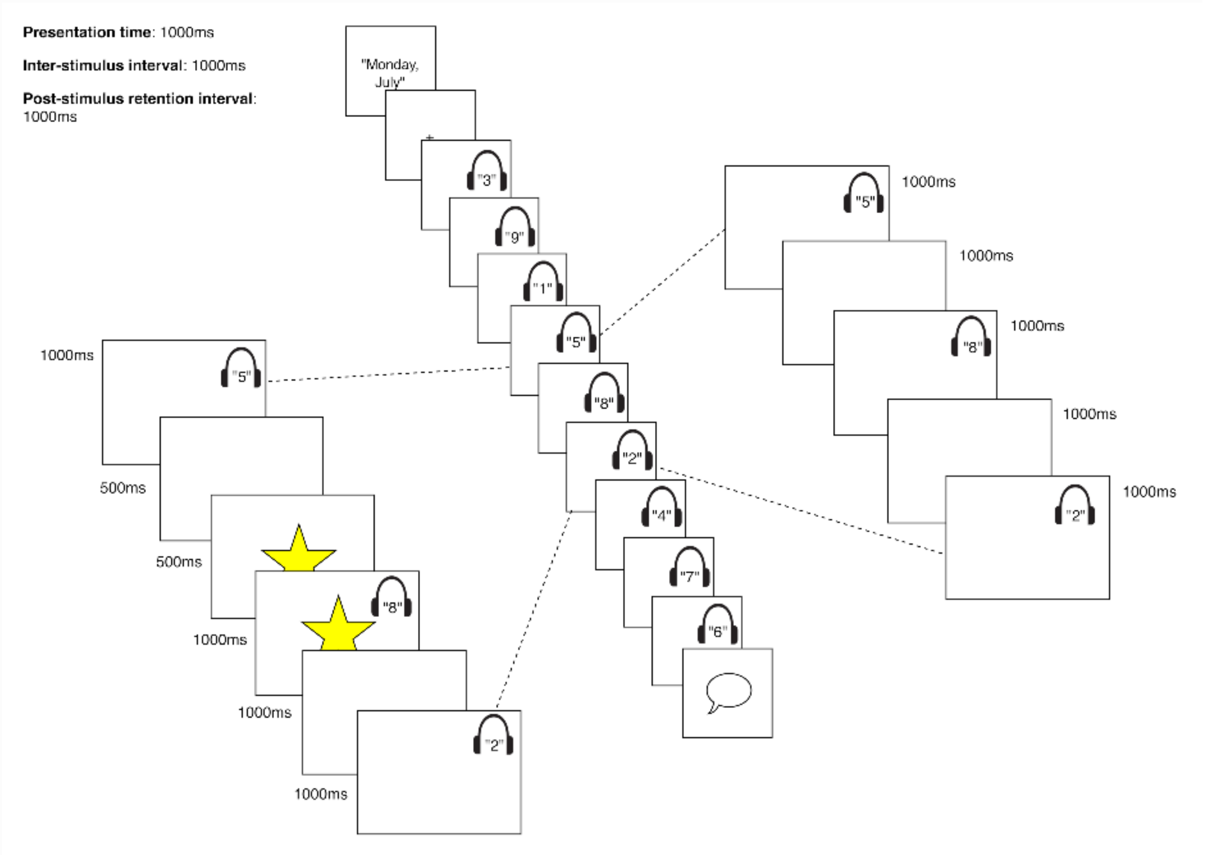
Figure 2. Performance in Experiment 1a. A) Mean proportion correct (and SE) as a function of prioritization and SP. The dotted grey line (at 0.11) indicates chance guessing rate based on the pool of nine digits. B) Comparison between each prioritization condition and the control condition (centred at 0).

Figure 3. Performance in Experiment 1b. A) Mean proportion correct (and SE) as a function of prioritization and SP. The dotted grey line (at 0.11) indicates chance guessing rate based on the pool of nine digits. B) Comparison between each prioritization condition and the control condition (centred at 0).

Figure 4. Performance in Experiment 2. A) Mean proportion correct (and SE) as a function of prioritization, concurrent task and SP. The dotted grey line (at 0.11) indicates chance guessing rate, based on the pool of nine digits. B) Comparison between Prioritize-SP5 and Control condition (centred at 0) as a function of concurrent task and SP.

Figure 5. Performance in Experiment 3. A) Mean proportion correct (and SE) as a function of prioritization, concurrent task and SP. The dotted grey line (at 0.11) indicates chance guessing rate, based on the pool of nine digits. B) Comparison between Prioritize-SP4 and Control condition (centred at 0) as a function of concurrent task.

Figure 1



Presentation time: 1000ms

Inter-stimulus interval: 1000ms

Post-stimulus retention interval: 1000ms

Figure 2

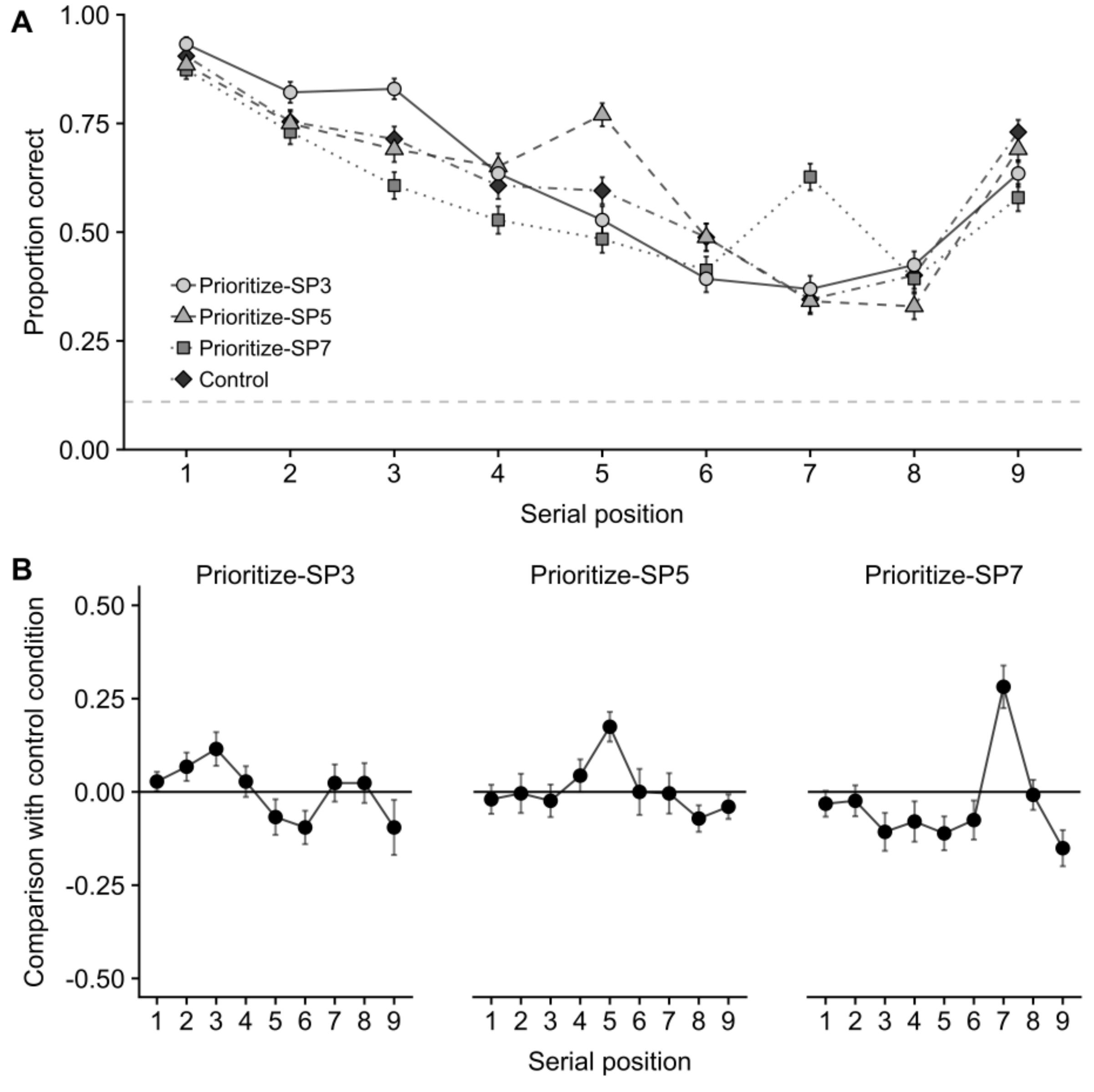

A
1.00
0.75
0.50
0.25
0.00
Proportion correct
Prioritize-SP3
Prioritize-SP5
Prioritize-SP7
Control
1
2
3
4
5
6
7
8
9
Serial position
B
Prioritize-SP3
Prioritize-SP5
Prioritize-SP7
0.50
0.25
0.00
-0.25
-0.50
Comparison with control condition
1 2 3 4 5 6 7 8 9
1 2 3 4 5 6 7 8 9
1 2 3 4 5 6 7 8 9
Serial position

Figure 3

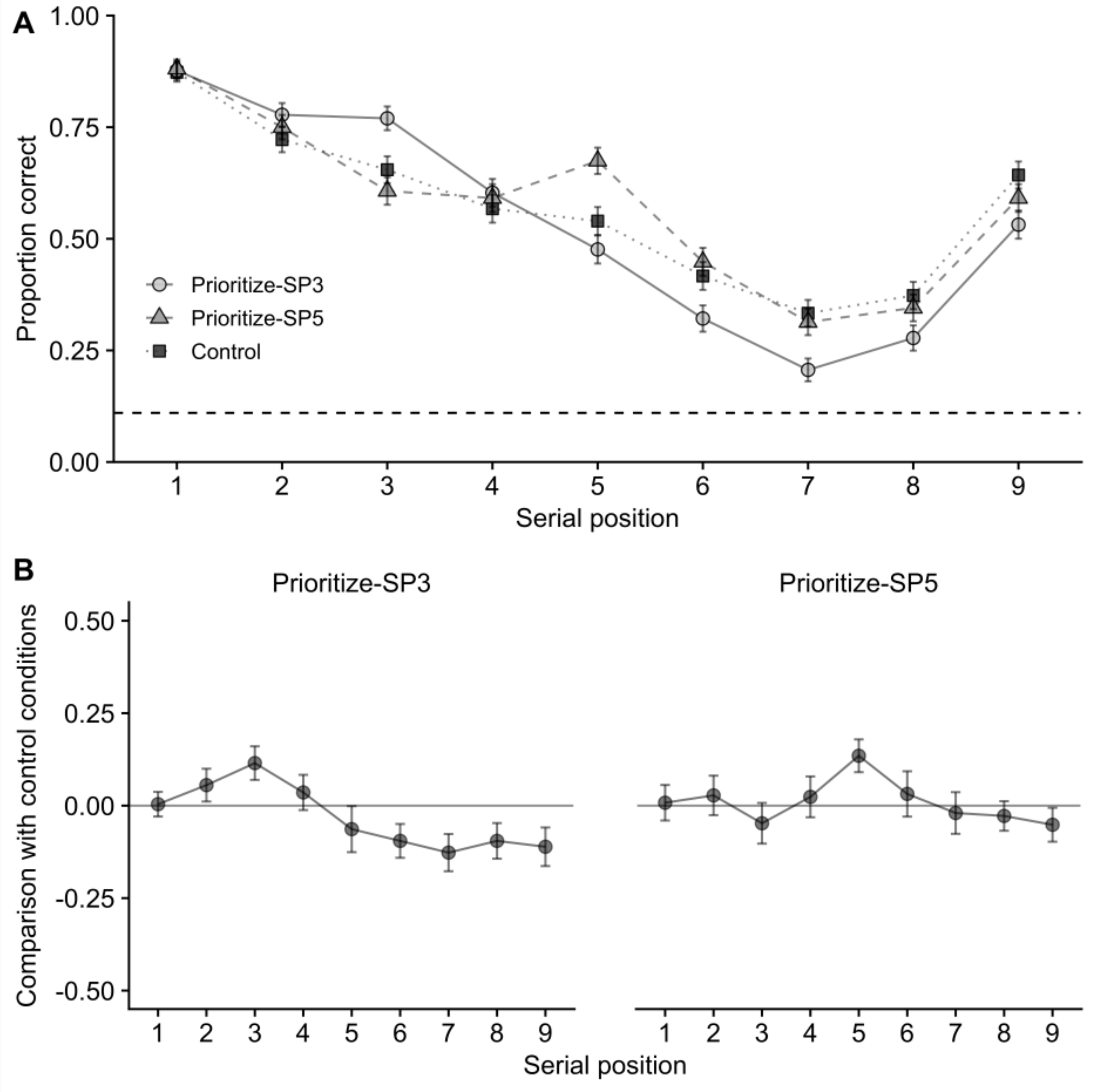

A
1.00
0.75
0.50
0.25
0.00
Proportion correct
Prioritize-SP3
Prioritize-SP5
Control
1 2 3 4 5 6 7 8 9
Serial position
B
Prioritize-SP3
Prioritize-SP5
Comparison with control conditions
0.50
0.25
0.00
-0.25
-0.50
1 2 3 4 5 6 7 8 9
1 2 3 4 5 6 7 8 9
Serial position

Figure 4

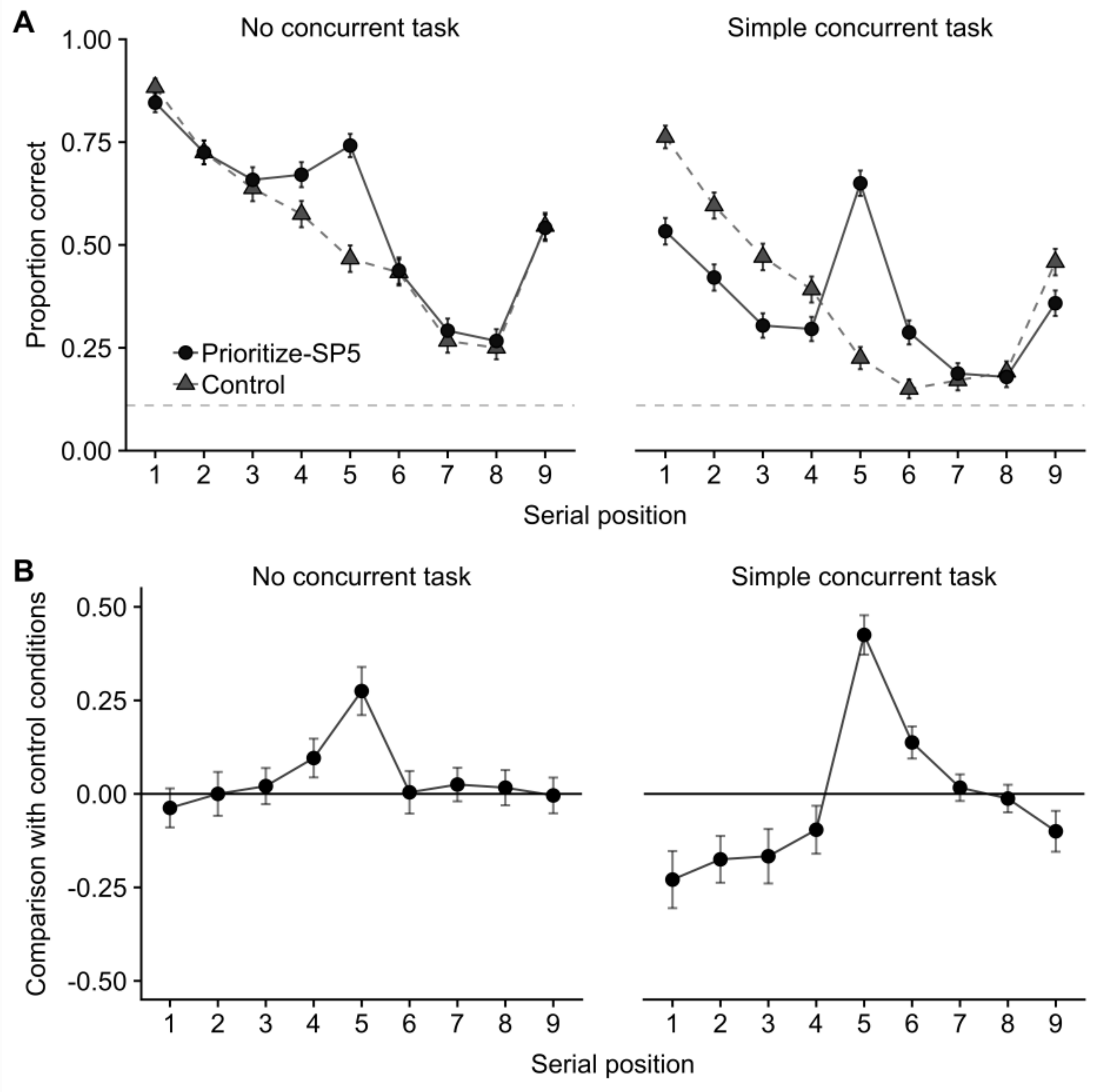
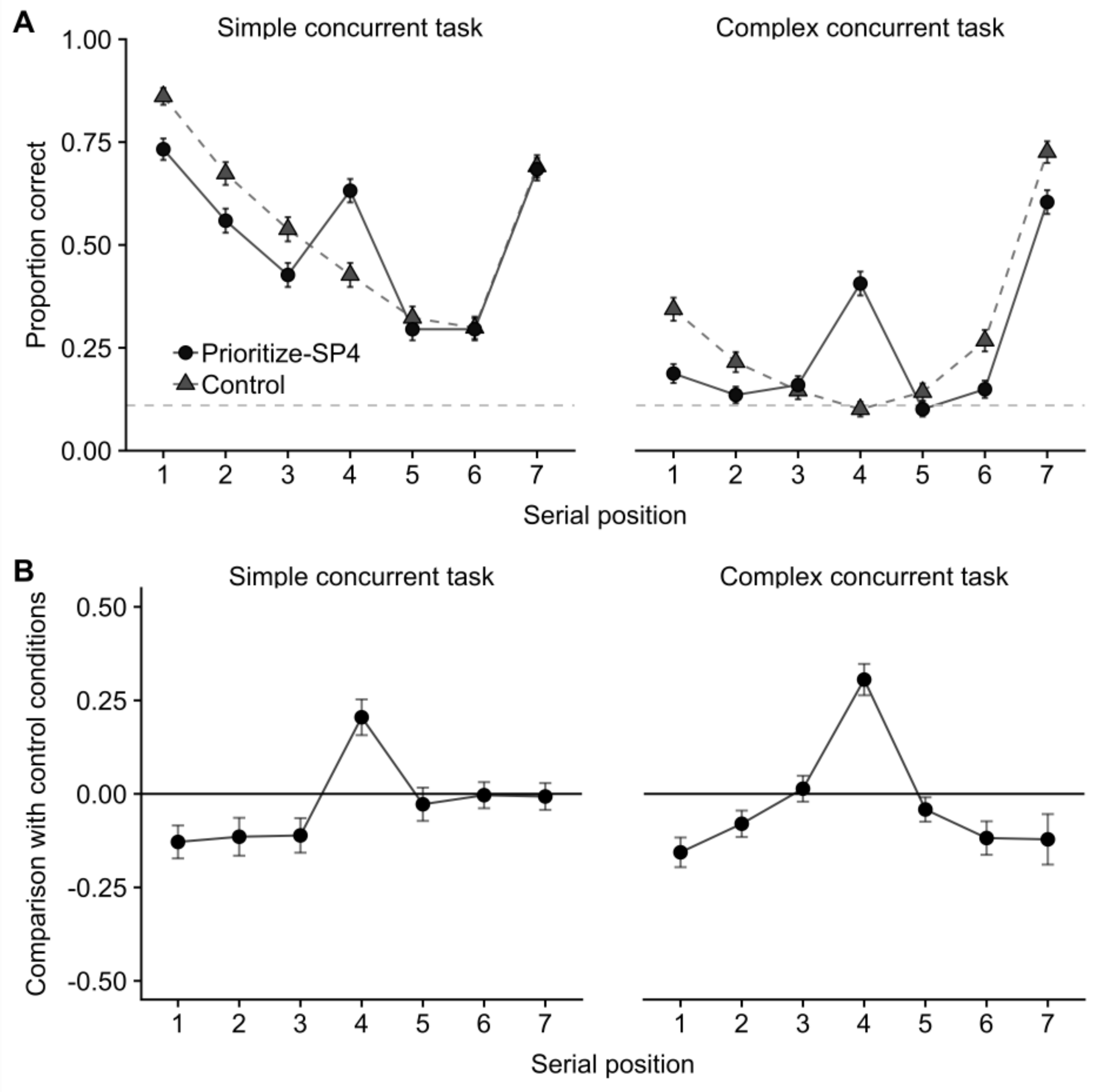

A
No concurrent task
Simple concurrent task
Proportion correct
1.00
0.75
0.50
0.25
0.00
Prioritize-SP5
Control
1 2 3 4 5 6 7 8 9
Serial position
B
No concurrent task
Simple concurrent task
Comparison with control conditions
0.50
0.25
0.00
-0.25
-0.50
1 2 3 4 5 6 7 8 9
Serial position

Figure 5


A
Simple concurrent task
Complex concurrent task
Proportion correct
1.00
0.75
0.50
0.25
0.00
Prioritize-SP4
Control
1
2
3
4
5
6
7
Serial position
B
Simple concurrent task
Complex concurrent task
Comparison with control conditions
0.50
0.25
0.00
-0.25
-0.50
1
2
3
4
5
6
7
Serial position