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# THE LIMITS OF VISUAL WORKING MEMORY IN CHILDREN

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# THE LIMITS OF VISUAL WORKING MEMORY IN CHILDREN

## **The limits of visual working memory in children: exploring prioritization and recency effects with sequential presentation**

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## Abstract

Recent research has demonstrated that, when instructed to prioritize a serial position in visual working memory, adults are able to boost performance for this selected item, at a cost to non-prioritized items (e.g. Hu et al., 2014). While executive control appears to play an important role in this ability, the increased likelihood of recalling the most recently presented item (i.e. the recency effect) is relatively automatic, possibly driven by perceptual mechanisms. In three experiments 7 to 10-year-old's ability to prioritize items in working memory was investigated using a sequential visual task (total N = 208). The relationship between individual differences in working memory and performance on the experimental task was also explored. Participants were unable to prioritize the first (Experiments 1 & 2) or final (Experiment 3) item in a 3-item sequence, while large recency effects for the final item were consistently observed across all experiments. The absence of a priority boost across three experiments indicates that children may not have the necessary executive resources to prioritize an item within a visual sequence, when directed to do so. In contrast, the consistent recency boosts for the final item indicate that children show automatic memory benefits for the most recently encountered stimulus. Finally, for the baseline condition in which children were instructed to remember all three items equally, additional working memory measures predicted performance at the first and second but not the third serial position, further supporting the proposed automaticity of the recency effect in visual working memory.

**Keywords:** working memory, visual working memory, executive control, recency effect, sequential memory, attention

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## Introduction

Working memory describes the ability to store and process information over short periods of time. The theoretical accounts of working memory (WM) are numerous but share a view of WM as limited in capacity (Baddeley, 2000; Conway, Jarrold, Kane, Miyake, & Towse, 2007; Cowan, 2009; Oberauer, Farrell, Jarrold, & Lewandowsky, 2016). Theories of WM differ in the emphasis placed on domain-specific components (Baddeley, 1986, 2000, 2012; Logie, 2011) versus domain-general attentional storage (Cowan, 2001, 2005, 2009). In addition, there is debate whether capacity is limited to a fixed number of items (Cowan, 2001; Zhang & Luck, 2008) or represents a continuous but limited resource that can be shared across any number of items (Bays, 2015; Fallon, Zokaei, & Husain, 2016; Ma, Husain, & Bays, 2014).

Performance on tasks designed to measure WM demonstrate a clear developmental trajectory, improving through childhood and into young adulthood (e.g. Alloway, Gathercole, & Pickering, 2006; Gathercole, Pickering, Ambridge, & Wearing, 2004). WM predicts academic attainment, indicating its importance to broader cognitive and intellectual ability (Gathercole, Pickering, Knight, & Stegmann, 2004). WM is closely related to executive control, and indeed, influential models of WM sometimes incorporate executive control mechanisms (e.g. Baddeley, 1986, 2012). These ‘executive functions’ are assumed to reflect a range of abilities required to perform complex cognitive tasks, such as inhibition, set-shifting or maintaining goal information (Baddeley, 2012; Logie, 2016; Smith & Jonides, 1999). Executive functions develop across childhood and have been implicated in key milestones, such as the emergence of theory of mind (Perner & Lang, 1999), in addition to predicting outcomes such as mathematical ability (Cragg & Gilmore, 2014; LeFevre et al., 2013). Whilst stable individual differences in executive functions emerge early in development (Friedman et al., 2007; Friedman, Robinson, & Hewitt, 2012),

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performance does not reach adult-like levels until late adolescence (Jurado & Rosselli, 2007; Waszak, Li, & Hommel, 2010).

Given the apparent limitations in WM capacity and executive control, and the central role these functions play in broader cognition and scholastic attainment, it is important to understand how children's WM performance might be optimized. This could be achieved through both automatic beneficial processes and identifying controlled strategic approaches that children are able to employ. Several factors are likely to be relevant in considering whether children will show similar strategic benefits to adults. For example, identification and implementation of strategic approaches may be effortful and resource-demanding, with children not having the same degree of resources available, relative to adults. Developments in metacognition or 'meta-control' may also be important (Chevalier, 2015; Chevalier, Martis, Curran, & Munakata, 2015); in addition to understanding a task, and having the ability to engage in a strategy, children must have the metacognitive ability to select appropriately among the strategies available to them.

Classic investigations of strategy use in memory have explored whether, for example, children spontaneously support their performance using verbal rehearsal (e.g. Flavell, Beach, & Chinsky, 1966; Hitch, Halliday, Schaafstal, & Schraagen, 1988; Jarrold & Hall, 2013). In an analogous exploration in the visuospatial domain, Morey, Mareva, Lelonkiewicz and Chevalier (2017) identified that children aged 5-7 years show strategic sequential looking in rehearsing spatial locations, though this appears to be reactive in nature, whereas older children and adults demonstrate a more proactive rehearsal approach. Recent work has also started to explore the extent to which children are able to direct their attention towards aspects of a task environment that are particularly goal-relevant (e.g. Cowan, Fristoe, Elliott, Brunner, & Saults, 2006; Cowan, Morey, AuBuchon, Zwilling, & Gilchrist, 2010; Shimi & Scerif, 2015; Shimi, Nobre, Astle, &

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Scerif, 2014). For example, Shimi et al. (2014) presented 7 year-olds, 11 year-olds and young adults with simultaneous four-object arrays, followed by a single recognition probe, while manipulating the timing (before versus after encoding) and location (central versus peripheral) of visual cues orienting participants to a particular item in the array. All three age groups showed a similar boost in performance for pre-cues, whereas 7 year-olds showed a smaller advantage from retro-cues. They also found that individual differences in visuospatial short-term memory and, especially, WM<sup>1</sup> predicted performance on retro-cued trials. Cowan et al. (2010) also demonstrated that children can use context to adjust how much they attend to items. They presented children and young adults with a change detection task manipulating the frequency with which a cued type of item was probed. With set sizes of 4, all age groups showed the same pattern of performance; attention paid to an object reduced as its likelihood of being probed reduced. However, the youngest group (7 to 8 year-olds) failed to appropriately optimize their performance in response to probe frequency under high storage load, while performance remained adult-like for 12 to 13 year-olds. This suggests children can adjust what information

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<sup>1</sup> In the working memory literature it is common to distinguish between short-term and working memory tasks. Short-term memory (hereafter, simple working memory) tasks are thought to have limited executive involvement, compared to working memory (hereafter, complex working memory) tasks. However, we take this distinction to be a matter of degree as even simple serial recall tasks can be thought to tap working memory proper, if strategies such as chunking are prevented (Cowan, 2016). Here, we prefer the distinction between simple and complex WM tasks, where simple tasks primarily involve storage in the absence of concurrent processing. This taxonomy emphasizes our view that all memory for information over short periods of time (i.e. short-term memory) is served by the working memory system, even in the absence of concurrent processing.

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accesses the focus of attention in response to regularities such as probe frequency, though not to the same extent as adults.

One important topic in understanding how limited WM capacity may be allocated concerns the way that participants can be directed to prioritize certain items within a set. This ability has been demonstrated in adults with sequentially presented visual stimuli (Hu, Allen, Baddeley, & Hitch, 2016; Hu, Hitch, Baddeley, Zhang, & Allen, 2014). When presented with 4-item sequences of colored shapes, adults show a boost in performance for the prioritized item when instructed to try especially hard to remember the item in a specified serial position, at a cost to non-prioritized items (Hu et al., 2014, 2016). This prioritization effect is reduced under cognitive load, suggesting it is executive in nature (Hu et al., 2016).

An informative feature of sequential presentation is the ability to investigate performance by serial position. This allows the separation of different mechanisms that contribute to visual WM. A robust finding from such analysis is a large recency effect for the final item in a list (Allen, Baddeley, & Hitch, 2006, 2014; Gorgoraptis, Catalao, Bays, & Husain, 2011; Hu et al., 2014, 2016). Additionally, performance on the final item in a sequence is vulnerable to suffix interference (where a to-be-ignored item drawn from the stimulus set is briefly presented following the final item in a sequence), yet is largely unaffected by cognitive load (Allen et al., 2014; Hu et al., 2014, 2016). Together these findings suggest that the recency effect for the final item is relatively automatic in nature. The relative absence of a cognitive load effect suggests that endogenous executive mechanisms, such as attentional refreshing (Barrouillet, Bernardin, & Camos, 2004; Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009), are not required to maintain this item in visual WM. The selective suffix effect for later items suggests that perceptually driven processing of a to-be-ignored item displaces the final item from a state where

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it is otherwise automatically maintained. This work suggests that there are two ‘routes’ to boosting performance on sequential visual WM tasks (Allen et al., 2014; Hu et al., 2014; see also, Yantis & Jonides, 1990; Yantis, 2000), and more broadly in determining what enters and remains active and accessible in the focus of attention (Cowan, 2005, 2016). One involves ‘top-down’ goal-directed executive control, while the other involves perceptually-driven heightened activation of the most recently encoded item (Allen et al., 2014, Hu et al., 2014).

However, children’s ability to prioritize within serial memory has not been explored to date. While previous developmental work has guided attention to a target using external cues or regularities, our prioritization instruction directly encourages participants to increase the attention allocated to one item while also processing the other items in the set. This requires explicit engagement of ‘top-down’ attentional resources without the possibility that participants might simply be responding to regularities in a task in a way that does not involve executive resources. Furthermore, previous studies exploring visual WM in children have typically used arrays of multiple objects encountered simultaneously in a single display. The present study differs by using sequential presentation, allowing for informative analyses of performance by serial position. Assessing performance for prioritized and non-prioritized items encountered in sequence potentially provides a means of examining how visual WM changes over time, and of more clearly differentiating between items that vary in their reliance on different forms of attentional control. It therefore also allows an exploration of whether children show potentially automatic recency benefits for the final item in a sequence.

There has been limited research on children’s memory for visual information across serial positions to date. Memory for an entire list of sequentially presented visual items has been explored in children using nameable line drawings (Hitch et al., 1988) and spatial sequences

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(Pickering, Gathercole, & Peaker, 1998). In both cases primacy effects were observed alongside less pronounced recency effects, though the primacy effects were not always observed for 5-year-olds (Hitch et al., 1988). Others have observed recency effects with children, in the absence of primacy effects, using colored shape stimuli and single item probed recall (Walker, Hitch, Doyle, & Porter, 1994), or orientation judgments (Burnett Heyes, Zokaei, Staaij, Bays, & Husain, 2012). However, these previous studies did not examine children's ability to prioritize specific items in a sequence, or how performance across the sequence varies with working memory ability.

While sequential presentation might seem less similar to the inherently simultaneous nature of real visual scenes, or the strong sequential cues built into verbal stimuli, it can provide a number of insights (Allen et al., 2014). Presenting visual items sequentially allows for the dissociation of processes that contribute to the encoding and maintenance of individual items while additional items are being maintained or subsequently presented. Whereas sequential information is crucial in encoding verbal sequences (e.g. Hughes, Chamberland, Tremblay, & Jones, 2016; Macken, Taylor, Kozlov, Hughes, & Jones, 2016, see Macken, et al., 2015 for a review), spatial cues have a significant influence on visual WM (e.g. C.C. Morey, Cong, Zheng, Price, & R.D. Morey, 2015; Woodman, Vecera, & Luck, 2003). Sequential presentation offers a way to reduce the potential influence of spatial processing on visual memory. Thus, while arguably less 'ecologically valid', sequential visual tasks offer theoretical insights that complement the use of simultaneous presentation (Allen et al., 2014).

In the present study, children aged 7 to 10 years-old completed a sequential visual task near-identical to those previously used with adults (e.g. Hu et al., 2014). Examining performance in this age range is particularly useful as performance on measures of working memory and

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executive function undergoes substantial improvement across these years (e.g. Davidson, Amso, Anderson, & Diamond, 2006; Gathercole, Pickering, Ambridge, & Wearing, 2004; Lee, Bull, & Ho, 2013). These age ranges also reflect previous investigations of visual WM in children (e.g., Burnett Heyes et al., 2012; Cowan, et al. 2010; Shimi et al. 2014; Walker et al., 1994) with similar tasks. Moreover, a number of potentially relevant factors have been proposed to emerge at around this age. For example, children aged 7-9 years may start to show greater cognitive flexibility, goal setting, and information processing (Anderson, 2002; Davidson et al., 2006). It has also been suggested that 7-years-old reflects an age at which children often begin to spontaneously engage proactive control strategies, such as those needed to complete the primary task in the present study (Braver, 2012; Chevalier, 2015; Chevalier, James, Wiebe, Nelson, & Espy, 2014; Chevalier et al., 2015). Relatedly, children in this age range may start to show more effective use of rehearsals (Tam, Jarrold, Baddeley, & Sabatos-DeVito, 2010) and attentional refreshing (Camos & Barrouillet, 2011), which could be usefully applied in sequential visual working memory tasks, particularly for the purposes of prioritization. Thus, our selected age ranges were appropriate and informative both in terms of previous research and theoretical proposals in the literature.

Participants were presented with 3-item sequences of colored shapes before being probed to recall the color of one of the items. All participants completed a baseline condition where they were instructed to try equally hard to remember each item, and a prioritization condition in which they were either instructed to try especially hard to remember the first (Experiments 1 & 2) or third item (Experiment 3). Research with young adults (Hu et al, 2014; 2016) found that their ability to prioritize items in visual WM required executive resources. Given that executive

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resources develop over childhood and into adolescence, we might expect to see a reduced ability to prioritize in children.

A further outcome from the work with adults (e.g. Allen et al., 2014) is the suggestion that performance at the final serial position is relatively automatic. Items at earlier positions, on the other hand, require resources to be maintained in the face of interference or decay. Following this distinction, and based on the assumption that automatic forms of processing should show minimal developmental changes (e.g. Hasher & Zacks, 1979), we would expect a large recency effect for the final item. In addition individual differences in WM should relate to performance at the first two serial positions, but not the third. This prediction flows from the observation in adults that performance at early serial positions, but not the last position, is vulnerable to cognitive load (Allen et al., 2014; Hu et al., 2016). This suggests that performance for the final item is boosted ‘for free’ without drawing on executive resources. In contrast, performance for early items in a sequence draws on executive resources such that it would be expected to relate to individual differences in WM. To our knowledge, the present study is the first attempt to test this hypothesized relationship between individual differences and performance by serial position.

Here this prediction with respect to individual differences in WM was tested by taking both simple and complex verbal and visuospatial measures, i.e. measures where storage was the primary demand versus those where storage and additional processing were required. Given that measures of simple and complex working memory are highly related in children (Alloway et al., 2006; Gathercole et al., 2004), we would expect both our simple and complex measures to relate to performance at early serial positions; children’s ability to simply store information, and their ability to perform concurrent processing alongside storage, will both relate to task performance. In addition, given the visual nature of our primary task, we would expect measures that rely on

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visuospatial storage to relate more strongly to performance than those that rely on phonological storage, assuming storage in working memory is served by modality specific sub-components (Baddeley, 2007).

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## General Methods

### Participants

Participants for all three experiments were 7 to 10 years old and recruited from primary schools in Bradford, UK in a predominantly Pakistani British low-SES neighborhood. Participants were drawn from three consecutive Year Groups, Years 3, 4 & 5, which correspond to ages 7 to 8 (hereafter, “8-year-olds”), 8 to 9 (hereafter, “9-year-olds”), and 9 to 10 (hereafter, “10-year-olds”), respectively. A different group of children participated in each experiment. Consent was obtained from the school in addition to verbal assent from individual participants. The study was approved by the School of Psychology Ethics Committee, University of Leeds, UK (protocol number: 15-0370; project title: Perceptual, perceptual-motor and cognitive development in primary school children). Participants were excluded if they had Special Educational Needs (SEN), were distracted on the primary task, had missing data, or performed below chance on the primary task.

### Sample size justification

The effects of the primary manipulation described below in adults are large with effect sizes ranging from 0.7 to 1.4 (Hu et al., 2016). Power analysis was carried out using G\*Power 3.1.9.2. (Faul, Erdfelder, Lang, & Buchner, 2007). Assuming the effect would be less pronounced in children ( $d = 0.6$ ) we would achieve 80% power for a t-test at the prioritized position with a sample size of 25, as we had in each age group. Combining across age groups ( $Ns \approx 75$ ) gives this test power  $>99\%$ . With a sample size of 75 we would have 80% power to detect an effect size of 0.33 or larger.

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## Materials & procedure

The script for the primary task, as well as the data and analysis scripts for all three experiments, are available at <https://osf.io/xgrnc/>. All tasks were created using PsychoPy 1.83.01 (Peirce, 2007). They were presented on a laptop/tablet computer with a screen 256mm x 144mm. The visual working memory task was presented with the tablet upright plugged into a keyboard. For the other measures the tablet was detached from the keyboard and placed flat on a table. Participants completed two sessions. In the first session they completed one condition of the visual WM task along with forward digit recall (FDR), and backward digit recall (BDR). In the second session they completed the other condition of the primary task and the Corsi and odd-one-out tasks. Visual WM condition order was counterbalanced across participants.

**Visual working memory task.** All stimuli measured approximately 1.5 x 1.5 degrees of visual angle and were presented on a white background. Within each trial the 3 stimuli were presented sequentially at three (randomly selected) corners of an invisible square 4 degrees of visual angle wide around a central fixation. Stimuli were selected from a pool of 6 colors and 6 shapes. Two fixed sets of 30 trials were created with 3 stimuli presented in each trial. Use of these two sets in each condition was counterbalanced across participants. Within a set, each shape and color was presented at each serial position 5 times and probed as the response 5 times. Each serial position was probed for response 10 times within each set.

For each condition, participants completed 6 practice trials followed by 30 test trials. Three shapes were presented before participants had to respond by saying aloud what color the shape was in the trial set (see Figure 1 for detailed timings). The experimenter recorded the participant's response by pressing a key on a second keyboard plugged into the laptop. There was a 1000ms inter-trial interval.

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In the prioritization condition (Exps 1 & 2) participants were instructed to try especially hard to remember the color of the first item in the sequence. They were told that either two (Exp1) or four (Exp2) (purely notional) points would be awarded for successfully recalling this item if it was probed, with one point being awarded for the other items. In the baseline condition participants were instructed to try equally hard to remember each shape in the sequence. In Experiment 3, rather than being asked to prioritize the first item, participants were asked to try especially hard to remember the final item (with 4 notional points attached to a correct answer for this item). Within each experiment, all participants completed both the baseline and the prioritization conditions. For Experiments 2 and 3, participants were rewarded with stickers at the end of each session. They were told they would receive a sticker “if they got enough points” on the primary task, though in fact all participants eventually received this reward.

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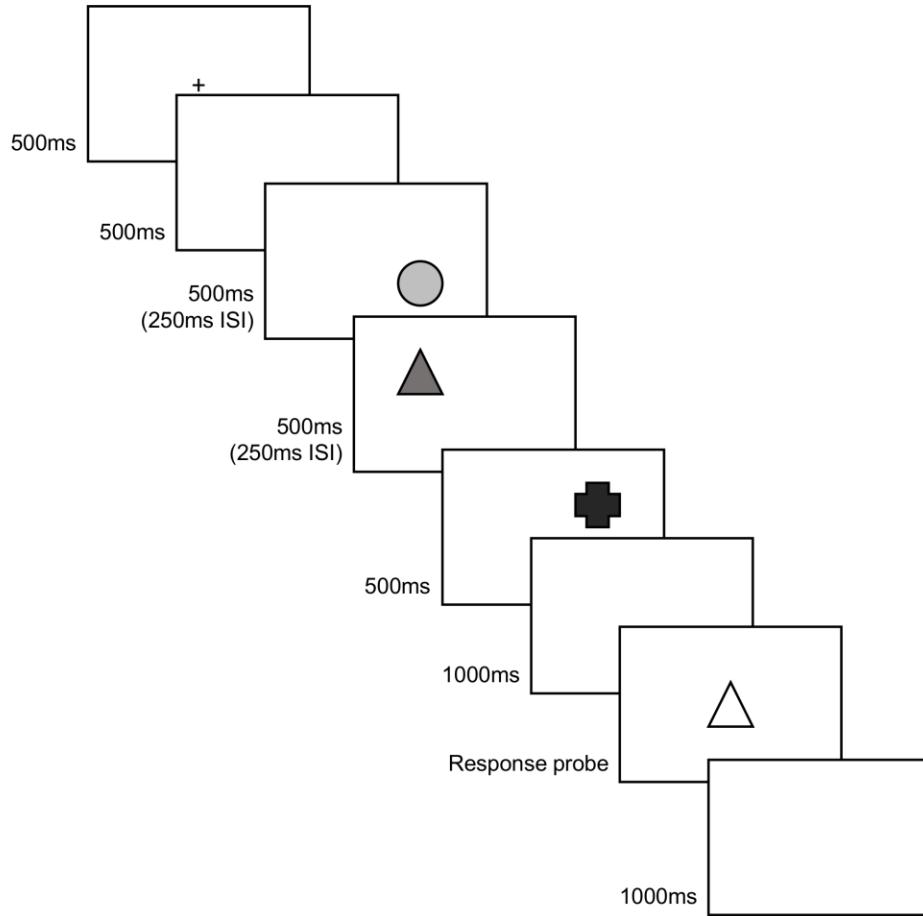


Figure 1. *Schematic for the visual working memory task. Figure is not to scale, and grey shades represent different colors.*

### Additional measures

The tasks described below were selected such that we had both simple and complex verbal and visuospatial tasks. This combination of additional measures is typical in the literature (e.g. Gathercole et al., 2004) allowing the role of verbal versus visuospatial memory, and simple versus complex tasks to be assessed. However, as noted (see Fotenote 1, above), these measures are highly related.

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**Forward digit recall (FDR; simple verbal WM).** For this task participants were presented with sequences of digits via headphones and had to recall them in the same order by pressing response boxes on screen. The digit stimuli were spoken in a neutral voice and each utterance was 350-550ms in length. The response boxes were approximately 1.7cm by 1.9cm and were evenly spaced in a line from 1 to 9. Participants completed 3 practice trials followed by 16 test trials. The test trials were organised into 4 blocks of 4 trials with 3 digits being presented on each trial on the first block building up to 6 digits per trial on the fourth block. All participants completed all 16 trials regardless of performance. The same digit was never presented twice within a trial.

For each trial the word 'Listen' was presented on screen for 1000ms followed by a 1000ms blank screen. The digits were then presented with an ISI of 1000ms, with the final digit followed by a 1250ms retention period. Participants responded at their own pace in the recall phase, followed by a 1000ms inter-trial interval. After the last trial of each block a message was presented stating that the span length would increase.

**Backward digit recall (BDR; complex verbal WM).** This task was identical to the forward digit recall task except that participants had to recall the digits in backwards order from how they were presented. Furthermore, the trials started at a span length of 2 and worked up to a span length of 5.

**Corsi block task (simple visuospatial WM).** Nine boxes (approximately 2.5cm<sup>2</sup>) in a pseudo-random arrangement were displayed on screen. A number of boxes lit up in sequence and participants had to respond by pressing the boxes in the same order that they lit up. As with forward digit recall participants completed 3 practice trials followed by 16 trials split into 4 blocks of 4 trials at spans lengths 3 to 6.

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For each trial a fixation cross was presented for 1000ms followed by a 1000ms blank screen. A sequence of boxes then lit up in yellow with each box remaining yellow for 500ms followed by a 1000ms ISI. After a 1250ms retention interval participants recalled the sequence at their own pace, followed by a 1000ms inter-trial interval.

**Odd-one-out (complex visuospatial WM).** This task was an adaptation of an existing odd-one-out task (Alloway et al., 2006; Russell, Jarrold, & Henry, 1996). Participants were presented with sets of 3 shapes and had to identify the shape that was different from the other two (the 'odd-one-out'), as well as remembering its location. After a series of processing trials, the recall phase commenced, requiring the locations of each odd-one-out to be recalled in order. Eight different shapes were used, each measuring approximately 2.5cm<sup>2</sup>. The shapes were always presented in groups of 3 with one shape serving as the odd-one-out and one serving as the 2 'distractor' shapes. There were 8 possible combinations of the shapes with each shape serving as the odd-one-out and as the distractor once. The same 9 locations as the Corsi task were used for presenting the sets of 3 shapes, with a subset of 5 locations being used within a given trial. The location of the odd-one-out did not repeat within a trial. As with backward digit recall participants completed 3 practice trials followed by 16 trials in 4 blocks from span lengths 2 to 5.

For each trial a 1000ms fixation was presented followed by a 1000ms blank screen. A set of three shapes was then presented simultaneously and participant had to press the shape that was different from the other two. Each set of 3 stimuli was separated by a 1000ms ISI. Following a 1250ms retention interval 5 boxes were displayed on screen at the 5 locations used within that trial. Participant had to recall the location of each odd-one-out by pressing the response boxes in order. There was a 1000ms inter-trial interval.

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## Analysis plan

**Outcome measures.** For the primary task the outcome measure was proportion correct at the trial level (number of correct trials / total number of trials). For the four additional WM tasks the outcome measure was proportion correct at the item level (number of items correctly recalled/ total number of items presented).

**Primary task analyses.** For the primary task both frequentist and Bayesian analyses are reported. For all three experiments a mixed condition (prioritization, baseline; within) x serial position (1, 2, 3; within) x age group (3, 4, 5; between) ANOVA was carried out. Where main effects were significant follow-up t-tests are reported. These follow-up t-tests were corrected for multiple comparisons using the Bonferroni-Holm method. Degrees of freedom and *p* values for the ANOVAs were Greenhouse-Geisser corrected for sphericity where applicable.

Bayesian ANOVAs with the same structure are also reported. These were carried out using the BayesFactor package in R (Morey & Rouder, 2015; R Core Team, 2016). The default priors described in Rouder, Morey, Speckman, & Province (2012) were used. Bayesian analyses are reported in order to quantify evidence in favor of the null hypothesis, with a Bayes Factor describing the ratio between the likelihood of the data under the alternate model versus the null. More specifically this analysis gives the most likely set of effects given the data. Models with and without particular effects can also be compared to determine how much more (or less) likely a model with a certain effect is.

**Individual differences analysis.** The relationship between performance on the primary task and the additional individual difference measures was explored. This was achieved by looking at how individual differences relate to performance in the baseline condition at each serial position, combining across the three experiments. The baseline condition was identical

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throughout, making this possible. Here we addressed how the relationship between individual differences and working memory might vary by serial position.

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## Experiment 1

For Experiment 1, participants were asked to either try to remember all items equally (baseline condition), or to try especially hard to remember the first item in the sequence (prioritization condition). For the prioritization condition 2 notional points were awarded for correctly recalling the first item, if tested. One point was awarded for the 2<sup>nd</sup> and 3<sup>rd</sup> position as well as all three positions in the baseline condition.

## Method

**Participants.** 87 participants (47 girls) initially took part in Experiment 1 (Mean age = 8.98, SD = 0.95, Range = 7.5 - 10.47). Of this dataset, 15 children were excluded due to having special educational needs, and an additional 3 children were excluded due to being distracted during the primary tasks. Finally, 1 child was excluded due to lacking data for the primary task. The final sample used for primary task analysis had 68 participants (Mean age = 9.02, SD = 0.92, Range = 7.5 - 10.47). There were 21 8-year-olds (Mean age = 7.94, SD = 0.27, Range = 7.5 - 8.43), 22 9-year-olds (Mean age = 8.89, SD = 0.3, Range = 8.5 - 9.43), and 25 10-year-olds (Mean age = 10.05, SD = 0.32, Range = 9.57 - 10.47).

**Materials & Procedure.** See General Methods (above) for a description of the materials, procedure and analysis plan.

## Results

Proportion correct by condition and age group for the primary task is illustrated in Figure 2. A condition (prioritization, baseline; within) x serial position (1, 2, 3; within) x age group (8, 9, 10;

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between) mixed ANOVA was carried out. There was no main effect of condition:  $F(1,65) = 0.65, p = .42, \eta_p^2 < .01, \eta_G^2 < .01$ . The main effect of year was significant:  $F(2,65) = 3.39, p = .040, \eta_p^2 = .094, \eta_G^2 = .035$ . Finally, there was a substantial main effect of serial position:  $F(2,130) = 46.56, p < .001, \eta_p^2 = .42, \eta_G^2 = .18$ . None of the interactions were significant (all  $p > 0.59$ ).

Bayes Factor analysis revealed that the most likely model had effects of age group and serial position (7.01 times more likely than a model with age, serial position, and condition). However, this model was only 1.05 times more likely than a model with effects of serial position only.

Planned pairwise comparisons revealed no significant difference between serial positions 1 and 2 ( $t(67) = -0.77, p = .45, BF = 0.18, d = -0.09$ ). The Bayes Factor analysis shows that the null model is 5.6 times more likely than the alternate model. Positions 1 and 3 significantly differed with performance at position 3 being higher ( $t(67) = -8.09, p < .001, BF > 10000, d = -0.98$ ). Equally, positions 2 and 3 differed significantly with higher performance at position 3 ( $t(67) = -7.60, p < .001, BF > 10000, d = -0.92$ ).

8 year-olds and 9 year-olds did not differ significantly ( $t(40.6) = -1.08, p = .29, BF = 0.48, d = -0.33$ ), nor did years 9 year-olds and 10 year-olds ( $t(44) = -1.45, p = .27, BF = 0.68, d = -0.42$ ). 8 year-olds and 10 year-olds, on the other hand, did differ significantly in performance with 10 year-olds performing better than 8 year-olds ( $t(43.89) = -2.67, p = .037, BF = 4.45, d = -0.78$ ).

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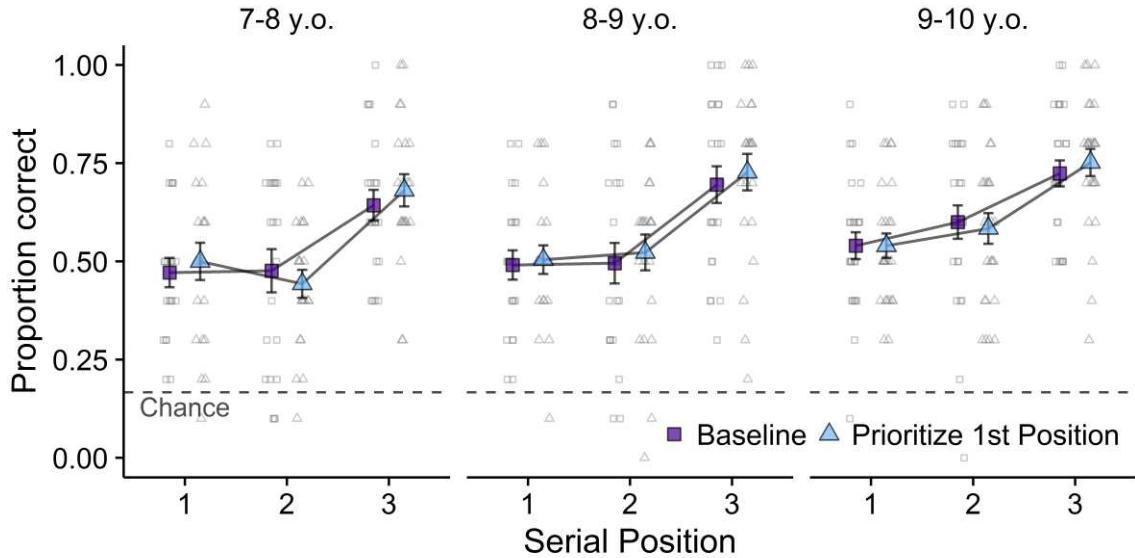


Figure 2. *Serial position curves for Experiment 1 by age group and condition for the primary task. Error bars show standard error. The horizontal dotted line shows chance performance. The unfilled grey shapes show the raw data (see Weissgerber, Milic, Winham, & Garovic, 2015).*

## Discussion

The analyses of the primary visual WM task showed no effect of condition; telling children to try especially hard to remember the first item did not improve memory for that item. There was an effect of year-group driven by the difference between the youngest (7 to 8) and oldest (9 to 10) groups, however, the Bayes Factor analysis did not support including the effect of year. In addition, there were no interactions with age, such that older children were no more able to utilize the instructions than the youngest children. As predicted, there was a large effect of serial position with recall from the final position relatively more accurate than from the first two positions. This recency effect is larger than those observed when an entire visual sequence is recalled (Hitch et al. 1988; Pickering et al., 1998), instead resembling the effects observed using a precision-based single item probe (Burnett Heyes et al., 2012).

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These results provide the first suggestion that, unlike adults (Hu et al., 2014, 2016), 7 to 10 year-olds are unable to prioritize the first item in a sequential visual WM task. In contrast, like adults, they do clearly show improved recall of the final sequence item. These findings might indicate a developmental contrast between controlled, effortful processing on the one hand, and relatively effortless and automatic processing on the other. However, one possible alternative account of the outcomes from Experiment 1 is simply that children were not sufficiently motivated or that they forgot the prioritization instructions. To address this concern and establish whether the Experiment 1 findings replicate, we increased the motivation to prioritize in Experiment 2 by adjusting the notional points rewarded for the prioritized item, and telling participants that if they got enough points they would be given a reward upon completion of the task. In addition, participants were shown an instruction screen every 10 trials reminding them which item in the sequence they should try especially hard to remember.

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## Experiment 2

Here we wanted to replicate the result of Experiment 1 while ensuring it was not the result of a simple lack of motivation or forgetting of instructions. Children aged 7 to 12-years-old have been shown to adapt their performance in response to points and small rewards (e.g., Chevalier, 2017).

## Method

**Participants.** A new sample of 88 participants initially took part in Experiment 2 (Mean age = 9.19, SD = 0.85, Range = 7.68 - 10.62). 15 children were excluded due to having special educational needs, and 4 children due to lacking data for both conditions of the primary visual WM task. The final sample used for primary task analysis included 69 participants (Mean age = 9.19, SD = 0.8, Range = 7.68 - 10.62). There were 22 8-year-olds (Mean age = 8.3, SD = 0.37, Range = 7.68 - 9.55), 25 9-year-olds (Mean age = 9.16, SD = 0.33, Range = 8.72 - 9.65), and 22 10-year-olds (Mean age = 10.12, SD = 0.31, Range = 9.67 - 10.62).

**Materials & Procedure.** The materials and procedure were identical to Experiment 1 except that in the prioritization condition participants were told that 4 points would be awarded for successfully recalling the first item, rather than the 2-points in Experiment 1. Participants were also told that they would get a reward if they got sufficient points (though in fact all participants were rewarded at the end of the study). The instructions for the baseline condition were identical to Experiment 1. In addition, to ensure that children remembered the priority instructions and remained motivated to follow them, a screen was displayed every 10 trials containing a reminder to try especially hard to remember the first shape (prioritization condition) or to remember all three shapes equally (baseline condition).

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## Results

A condition (prioritization, baseline; within) x serial position (1, 2, 3; within) x age group (8, 9, 10; between) mixed ANOVA was carried out. There was no main effect of condition:  $F(1,66) = 0.64, p = .43, \eta_p^2 < .01, \eta_G^2 < .01$ , nor of year:  $F(2,66) = 1.06, p = .35, \eta_p^2 = .031, \eta_G^2 < .01$ . There was a significant main effect of serial position:  $F(1.73, 114.5) = 21.28, p < .001, \eta_p^2 = .24, \eta_G^2 = .13$ . None of the interactions were significant (all  $p$ s  $> 0.19$ ).

Bayes Factor analysis revealed that the most likely model given the data had a main effect of serial position. This model was 7.41 times more likely than a model with effects of condition and serial position, and 9.16 times more likely than one with effects of year and serial position.

Planned pairwise comparisons revealed a non-significant difference between serial positions 1 and 2 ( $t(68) = 0.97, p = .34, BF = 0.21, d = 0.12$ ). The Bayes Factor shows that the null model of no-difference is 4.8 times more likely than the alternative. Positions 1 and 3 significantly differed with performance at position 3 being higher ( $t(68) = -4.44, p < .001, BF = 567.6, d = -0.53$ ). Equally, positions 2 and 3 differed significantly with higher performance at position 3 ( $t(68) = -7.18, p < .001, BF > 10000, d = -0.86$ ).

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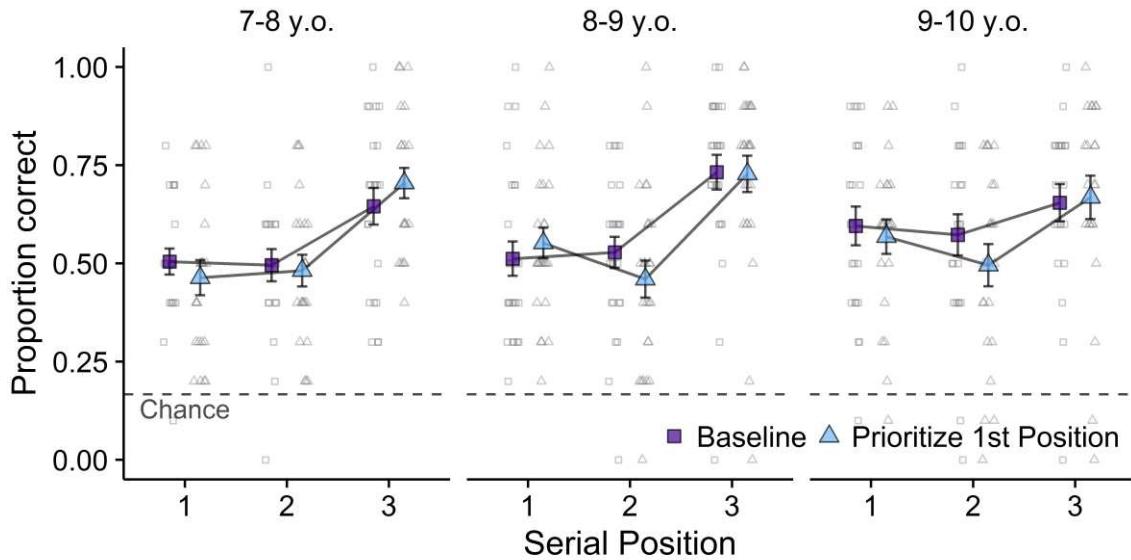


Figure 3. *Serial position curves for Experiment 2 by age group and condition for the primary task. Error bars show standard error. The horizontal dotted line shows chance performance, and unfilled grey shapes show the raw data.*

## Discussion

The analyses of the primary task showed, as with Experiment 1, no effects of condition, alongside a large recency effect for the final item. Unlike Experiment 1, no effect of year group was found. This is unsurprising given the size of the effect and the lack of support from Bayes Factor analysis observed in Experiment 1.

Experiment 2 suggests that children's inability to prioritize the first item in a sequence is not the result of auxiliary factors such as motivation or instructions. In line with this, informal questioning of participants following the experiment indicated no difficulties with understanding the task or the priority instruction. Combining the data from Experiments 1 & 2, Bayes Factor analysis show that the null hypothesis of no difference in performance at serial position 1 for the two conditions is 10.4 times more likely than the alternative. Thus we do not simply observe an uninformative absence of a priority instruction effect. Rather, we have strong evidence for the

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lack of a difference. This runs counter to the consistently observed priority boost that has been observed at the first sequence position in young adults on an essentially identical WM task (Hu et al., 2014, 2016), and suggests children are unable to engage in effortful, goal-directed attention to prioritize items.

However, so far, we have only examined whether children show a priority boost at the *first* position in a short sequence of visual stimuli. Adults also show a prioritization effect for the *final* item in a sequence, supplementing relatively automatic boosts for this recency item via controlled attention (Hu et al., 2014, 2016). It is possible that children cannot achieve a measurable boost in performance for the first item in a sequence in addition to processing subsequent items, as required by the primary task in Experiments 1 and 2. In contrast, processing the first two items in the sequence followed by prioritizing the final item may represent a less demanding and complicated form of goal-directed working memory resource management. Children may therefore be able to engage in this more easily, with observable boosts to performance at the prioritized final position. Thus, in Experiment 3 we investigated this possibility by asking participants to prioritize the final item in a sequence.

### **Experiment 3**

Adults can prioritize the final item in sequential visual WM tasks, with the resulting boost to performance further improving the already accurate recall of this recency position (Hu et al., 2016). Here we used a procedure identical to Experiment 2 to ask whether children are able to prioritize the final item in a sequence. This allows us to address whether the absence of an effect in Experiments 1 & 2 results from the relatively complex task of having to prioritize an item while processing subsequent items. If we observed a prioritization effect for the final serial position we would also expect a drop in performance at the non-prioritized positions, as is

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observed with adults (Hu et al., 2014). Alternately, if the outcomes of Experiments 1 & 2 represent a more general under-development of executive resources in children that undermines the ability to prioritize any item, then the absence of a prioritization effect would be expected to remain in Experiment 3.

### Method

**Participants.** 85 participants initially took part in Experiment 3 (Mean age = 9.11, SD = 0.9, Range = 7.68 - 10.64). 7 children were excluded due to having special educational needs. An additional child was excluded due to being distracted during the primary visual WM task. 5 children were excluded due to lacking data for the primary task. Finally, one participant was excluded due to having an overall accuracy of less than chance (16%) on the primary visual WM task. The final sample used for primary task analysis had 71 participants (Mean age = 9.15, SD = 0.87, Range = 7.68 - 10.64). There were 23 8-year-olds (Mean age = 8.11, SD = 0.29, Range = 7.68 - 8.64), 25 9-year-olds (Mean age = 9.19, SD = 0.3, Range = 8.67 - 9.6), and 23 10-year-olds (Mean age = 10.13, SD = 0.36, Range = 9.67 - 10.64).

**Materials & Procedure.** The materials and procedure were identical to Experiment 2 except that in the prioritization condition participants were instructed to try especially hard to remember the final item in the sequence rather than the first.

### Results

A condition (prioritization, baseline; within) x serial position (1, 2, 3; within) x year group (3, 4, 5; between) mixed ANOVA was carried out. Unlike Experiments 1 and 2 there was a main effect

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of condition:  $F(1,68) = 6.94, p = .010, \eta_p^2 = .093, \eta_G^2 < .01$ . No main effect of year was observed:  $F(2,68) = 3.03, p = .055, \eta_p^2 = .082, \eta_G^2 = .032$ . As with Experiments 1 and 2 there was a large main effect of serial position:  $F(2,136) = 58.37, p < .001, \eta_p^2 = .46, \eta_G^2 = .22$ . No interactions were significant (all  $p > 0.09$ ). Bayes Factor analysis revealed that the most likely model had effects of condition and serial position. However, this model was only 1.05 times more likely than a model with an effect of serial position only.

Planned pairwise comparisons revealed a non-significant difference between serial positions 1 and 2 ( $t(70) = -1.46, p = .12, BF = 0.4, d = -0.17$ ). Positions 1 and 3 significantly differed with performance at position 3 being higher ( $t(70) = -8.99, p < .001, BF > 10000, d = -1.07$ ). Equally, positions 2 and 3 differed significantly with higher performance at position 3 ( $t(70) = -8.78, p < .001, BF > 10000, d = -1.04$ ). Finally, given the effect of condition that was observed overall, we looked at the difference between the prioritization and baseline conditions at each serial position. There were not significant differences at serial positions 1 ( $t(70) = -2.02, p = .095, BF = 0.90, d = -0.24$ ), or 3 ( $t(70) = 0.47, p = .64, BF = 0.15, d = 0.06$ ). Performance in the prioritization condition was significantly lower than the baseline condition at position 2 ( $t(70) = -2.53, p = .041, BF = 2.52, d = -0.3$ ). Despite this comparison being significant the Bayes Factor analysis supports a difference by a factor of only 2.5. For position 3 the null model is 6.7 times more likely than the alternative.

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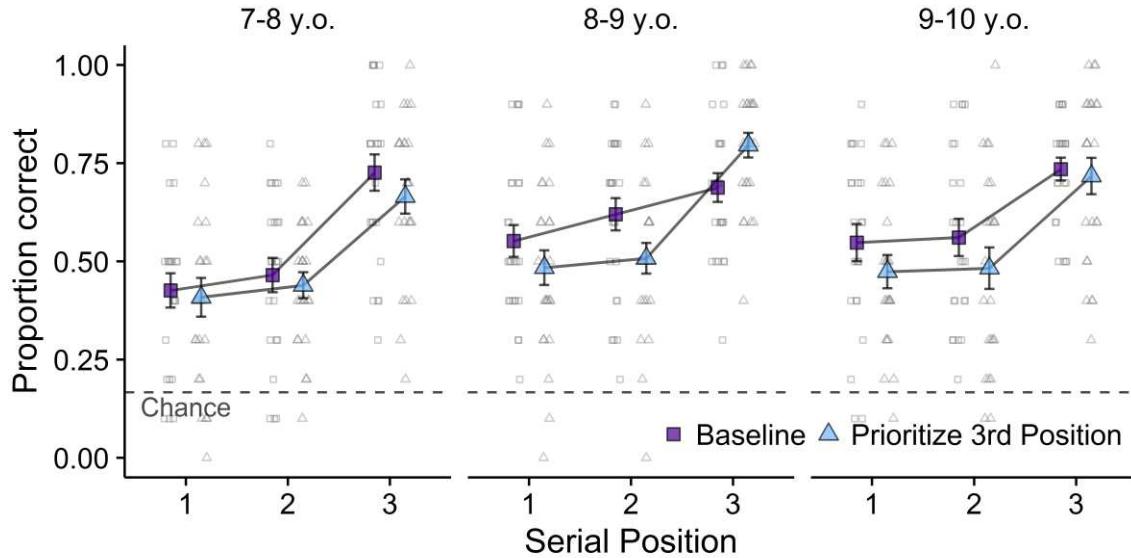
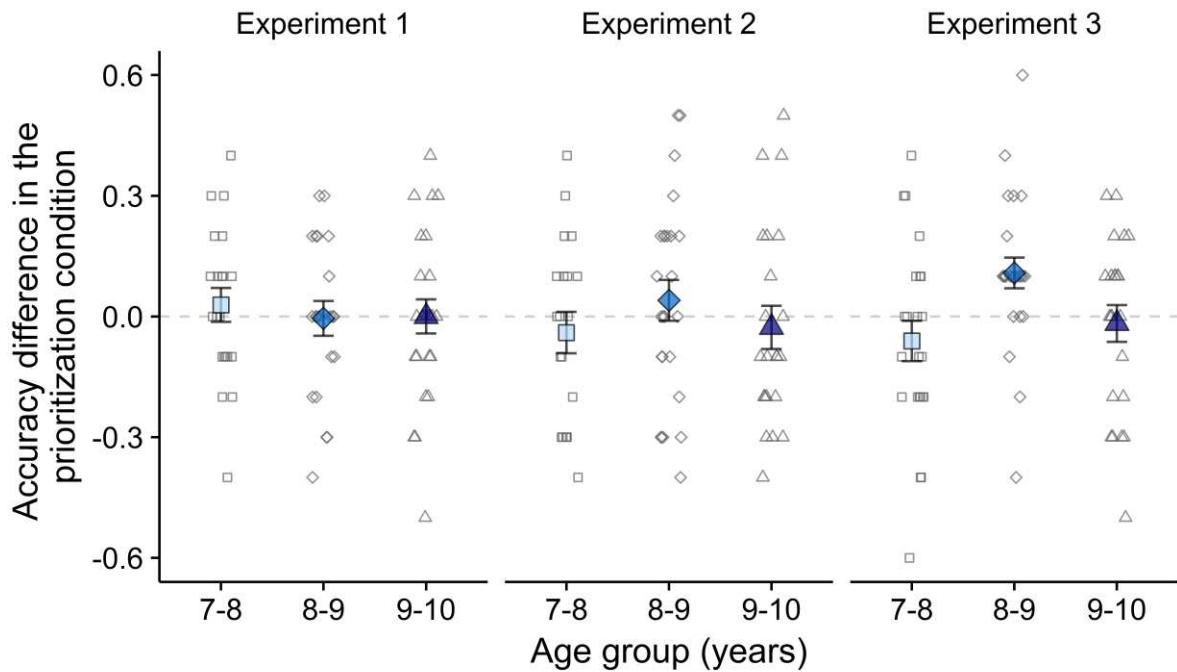


Figure 4. Serial position curves for the primary task in Experiment 3 by condition and age group. Error bars show standard error. The horizontal dotted line shows chance performance, and unfilled grey shapes show the raw data.

Figure 5 shows the difference between performance in the prioritization and baseline condition for each experiment, at the prioritized serial positon (position one, Exp 1 & 2; or position three, Exp 3). An analysis of the relationship between our additional WM measures and the prioritization boost at the relevant serial position was carried out. However, none of the measures predicted the prioritization boost. This analysis is therefore not considered further.

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*Figure 5. The difference between performance in the prioritization condition and the baseline condition at the prioritized serial position for each experiment. Unfilled grey shapes show the raw data, and error bars show standard error.*

## Discussion

In line with the outcomes from Experiments 1 and 2, we observed large effects of serial position with a substantial advantage for the final item over positions 1 and 2, across both instruction conditions. This adds further weight to the conclusion that children demonstrate relatively automatic recency benefits in visual working memory. The question posed by this experiment was whether children are then able to effectively supplement this improved performance by deliberately prioritizing the final item, as observed in adults (Hu et al., 2014, 2016). Unlike the primacy-focused instruction used in Experiments 1 and 2, here we found a small effect of condition when instructing children to prioritize the final item. However, this reflected *lower* performance for the non-prioritized items in the prioritization condition compared with the

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baseline, with no measurable concomitant increase in accuracy for the final item. Follow-up comparisons showed that the effect was driven by performance at the second position. Finally, as with Experiment 2 there was no effect of year.

Given the effect size, the significant effect of condition should be treated with caution. Nevertheless, if genuine it could reflect an unsuccessful attempt by children to prioritize the final position resulting in a drop in performance at the first two serial positions. In adults, increases in accuracy for the priority item are accompanied by declines in performance at non-prioritized positions, relative to a baseline condition (Hu et al., 2014, 2016). In the present study, despite the possible drop in performance at position 2, we did not see a boost in performance for the final item. The difference in performance between the two conditions speaks against the idea that children simply do not understand the prioritization instructions and thus perform equivalently to baseline in that condition. Nevertheless, they remain unable to achieve a boost in performance at the prioritized position.

### **Serial Position and Working Memory: A Cross-Experiment Individual Differences Analysis**

Increased accuracy for the final item in a sequence, as observed across Experiments 1-3 in the present study, may indicate it is stored in a different state to earlier items (Allen et al., 2014). Whereas earlier items require executive resources to be actively maintained, the most recent item may be automatically maintained in a privileged state. This claim would lead to two predictions about the relationship between individual differences in WM and performance in the baseline condition: (i) those children with better working memory will also perform better at serial positions one and two; (ii) working memory will not predict performance at the final serial position. Importantly, ‘working memory’ will be captured by both simple and complex measures

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because of their interrelatedness at the level of constructs and specific measures (Alloway et al., 2006; Gathercole et al., 2004). Furthermore, our primary task predominantly involves storage, rather than processing. Finally, given the visual nature of the primary task, we would also expect our visuospatial additional measures to be more strongly related to performance than our verbal measures.

### Method and Results

The data from the baseline condition of the primary task was combined for each serial position as the task and instructions for this condition were identical across the three experiments ( $N = 210$ ). Tables 1, 2 and 3 show the coefficients for predicting performance at the first, second, and third serial positions, respectively. Correlations and descriptive statistics for the predictor variables can be found in the Appendix.

For serial position 1 (Table 1), Corsi, and odd-one-out significantly predicted performance whereas FDR, BDR, and age did not. The  $R^2_{\text{adj}}$  for this model was 0.25. Bayes Factor analysis revealed that the most likely model given the data included FDR, Corsi and odd-one-out as predictors. The inclusion of FDR in the most likely model reflect the fact the  $\beta$  coefficient for FDR was 0.14, despite not reaching significance. This model was 1.6 times more likely than a model that also included age as a predictor, and over 1000 times more likely than the intercept only model.

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Table 1.

*Standardised and unstandardised coefficients for predicting performance at the first serial position in the baseline condition.*

	B	SE	$\beta$	p value
Intercept	-0.16	0.13		.25
Forward digit recall	0.18	0.096	0.14	.057
Backward digit recall	0.072	0.091	0.065	.43
Corsi	0.29	0.11	0.22	.01
Odd-one-out	0.17	0.077	0.18	.026
Age	0.022	0.015	0.095	.14

For serial position 2 (Table 2), FDR, BDR, Corsi and odd-one-out significantly predicted performance, with  $R^2_{\text{adj}} = 0.3$ . The most likely model given the data includes FDR, BDR, Corsi, and odd-one-out as predictors. This model was over 1000 times more likely than the intercept only model but only 1.3 times more likely than a model without BDR as a predictor.

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Table 2.

*Standardised and unstandardised coefficients for predicting performance at the second serial position in the baseline condition.*

	B	SE	$\beta$	p value
Intercept	-0.13	0.14		.35
Forward digit recall	0.24	0.1	0.16	.022
Backward digit recall	0.19	0.098	0.16	.049
Corsi	0.33	0.12	0.22	.007
Odd-one-out	0.17	0.082	0.16	.038
Age	0.0061	0.016	0.024	.7

For the final serial position (Table 3), none of the individual difference measures significantly predicted performance ( $R^2_{\text{adj}} < .01$ ). Analysis using Bayes Factor showed that the intercept-only model was 1.58 times more likely than any alternative.

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Table 3.

*Standardised and unstandardised coefficients for predicting performance at the third serial position in the baseline condition.*

	B	SE	$\beta$	p value
Intercept	0.48	0.15		.0014
Forward digit recall	0.12	0.11	0.092	.28
Backward digit recall	-0.015	0.1	-0.014	.88
Corsi	0.082	0.12	0.065	.51
Odd-one-out	0.0065	0.084	0.0069	.94
Age	0.0093	0.016	0.042	.57

For serial positions 1 and 2 the Bayes Factor analysis consistently supported the inclusion of Corsi, odd-one-out and, to a lesser extent, FDR as predictors of performance. Thus, we calculated the likelihood of our data under a model assuming a relationship between these predictors and performance at the final serial position. The intercept-only model, where none of our predictors are assumed to relate to performance at the final position, was 17 times more likely than the model that included Corsi, odd-one-out and FDR as predictors.

## Discussion

Both predictions with respect to individual differences in WM and performance by serial position were supported, with simple and complex WM measures predicting visual WM recall at serial positions 1 and 2, but not position 3. Importantly, the Bayes Factor analysis provided evidence against those WM abilities that relate to performance at the first and second positions

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relating to performance at the final serial position. This suggests that the recency effect for the final item is indeed automatic and does not draw on executive resources. Not only is this recency effect present in children but also, like in adults, it does not relate to executive attention. This finding therefore extends evidence from dual-task methods in adults (Allen et al., 2014; Hu et al., 2016) to an individual differences approach with children.

### General Discussion

Across three experiments, we found strong evidence that children more effectively recall items when they were encountered in the final sequence position, relative to earlier positions. In contrast, we also found strong evidence that they were unable to effectively prioritize particular serial positions in visual WM. In Experiments 1 and 2 children were unable to prioritize the first serial position; the combined data provided strong support for the absence of a priority effect for the first item. In Experiment 3 we observed a small effect overall, with children being unable to prioritize the final serial position, but showing a small drop in performance at the second position. This could suggest an attempt to prioritize the final item leading to a reduction in accuracy at earlier positions, but with no concurrent boost for the final position.

Thus, it appears that children aged 7 to 10 years old are unable to selectively attend to a serial position. This runs counter to consistent observations of this ability in young adults using near-identical procedures (Hu et al., 2014, 2016). One possible explanation for the contrasting findings between these age groups might lie in the observation that young adults show a substantially diminished or abolished priority boost when the availability of executive control resources is reduced by concurrent performance of a more attention-demanding verbal task (Hu et al., 2016). This would suggest that the strategic prioritization in visual WM of items within a

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sequence draws heavily on executive resources, which are known to develop through childhood and not reach adult-like levels until late adolescence (Jurado & Rosselli, 2007; Waszak, Li, & Hommel, 2010). Thus, children may lack the necessary executive control abilities to be able to effectively prioritize items within a sequence; carrying out this task might be analogous to adult performance under high cognitive load. In line with this, the effect of condition at position two in Experiment 3 could suggest that children are trying to prioritize the final item by diverting executive resources away from other items, while being unable to boost performance for this final item.

In contrast to the absence of a priority boost at either the first or final sequence position, the substantial recency advantage for the final item observed in all three experiments is in line with similar effects observed in adult studies (e.g. Allen, Baddeley, & Hitch, 2006, 2014). This extends limited previous work with children using different visual stimuli (Burnett Heyes et al., 2012; Hitch et al. 1988; Pickering et al. 1998) to the current task and stimulus sets. In addition, and in line with our initial predictions, recall accuracy for this final item was not related to individual differences in WM, while performance at serial positions 1 and 2 did relate to these measures. These outcomes were supported by Bayesian analysis, with strong support for a model containing WM ability for positions 1 and 2, contrasting with strong support for the intercept-only model for the third serial position. The observation that our visuospatial tasks (Corsi and odd-one-out) more strongly relate to performance at the first and second serial positions is in line with the primarily visual nature of the experimental task, though the additional relationship with verbal tasks (particularly FDR) might indicate a degree of verbal recoding. However, as our WM measures correlate (see Appendix 1), in line with a view of WM as a set of highly related

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constructs (Alloway et al., 2006; Gathercole et al., 2004), the relationships with the primary experimental task are likely to reflect both domain-general and modality-specific functions.

To our knowledge, this is the first demonstration of the shifting relationship between memory across different positions in a sequence, and broader WM ability. This finding supports the suggestion that incoming items are automatically processed but require additional resources to be maintained once they have been displaced from an active and accessible ‘privileged state’ by subsequent items, with the most recently encountered item automatically remaining in this state at least for a brief period (Allen et al., 2014; Hu et al., 2014, 2016).

Why do no priority effects emerge in the present study, when previous work has identified evidence that children are able to direct attention in certain contexts? To understand the limitations of children's executive abilities it is useful to consider the differences between this paradigm and others that have been used. With simultaneous presentation, children as young as 7 can allocate attention in response to visual cues (Shimi et al., 2014) and probe frequency in visual WM (Cowan et al., 2010). However, it is possible that children are unable to actively prioritize visual items within a temporal sequence. One reason for this could be the inability to resist interference from subsequent items. Perhaps children are trying to prioritize the first item but find it difficult to resist interference caused by the following items in the sequence. In adults prioritized items are particularly vulnerable to suffix interference from a to-be-ignored item presented after the test sequence, suggesting a cost to the heightened accessibility that results from prioritizing an item (Hu et al., 2014, 2016). Sequential presentation, in general, also infers costs compared to simultaneous presentation (Gorgoraptis et al. 2011) particularly at earlier positions in a sequence. This appears to be driven by the fact that sequentially presented items are more vulnerable to interference from subsequent items (Allen, Baddeley, & Hitch, 2006;

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Gorgoraptis et al. 2011). Support for an interference account of our findings comes from Shimi et al. (2014)'s suggestion that resisting interference drives the ability to use a retro-cue to selectively attend to an item in an array; interference from the other items in an array must be managed to direct attention onto the cued item. However, such an explanation struggles with the absence of a prioritization effect for the final item in Experiment 3, as there are no subsequent to-be-remembered items that might cause retroactive interference. A response could be that the prioritization boost for the final item is too small in children to be detected by this paradigm, over and above the substantial recency effects that are observed. Indeed, it is noteworthy that the prioritization effect for the final item is slightly smaller in adults than for the first item in a sequence (Hu et al., 2014, 2016). This could be tested in future work using a paradigm that allowed for continuous responses (Burnett Heyes et al., 2012; Sarigiannidis, Crickmore, & Astle, 2016), and indeed, Gorgoraptis et al. (2011) observed improvements in the visual memory precision of adult participants for more frequently cued items at all positions in a sequence, including the final one.

One possible account of our findings could depend on the differences between sequential and simultaneous presentation, as spatial organization, which is emphasized by simultaneous presentation, plays an important role in visual WM (e.g. Pertzov & Husain, 2014; Woodman et al., 2003). Nevertheless, children experience the sequential presentation of visual information in everyday life when, for example, turning the pages of a picture book. If, as our results suggest, children are less able to flexibly allocate attention when information is presented sequentially this would represent an interesting finding even if such tasks are less ecologically valid. The ability to allocate attention over abstract or unfamiliar objects remains an important skill that adults possess (Hu et al. 2014, 2016).

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General developmental changes in availability of executive control resources provide one strong candidate for accounting for the absence of prioritization effects in sequential visual WM observed in the present study. Studies tracking developmental changes in working memory and executive control show clear trajectories between 7-10 years of age, but also that children continue to demonstrate substantial improvement in these abilities beyond age 10, up to adulthood (e.g. Davidson et al., 2006; Gathercole et al., 2004; Lee et al., 2013; Zelazo et al., 2013). As such, these abilities may not be sufficiently developed in our 7-10 year-old sample to enable effective implementation of prioritization. The developmental mechanisms underpinning children's performance on visual WM tasks could also be framed in terms of a distinction between reactive and proactive control strategies (Braver, 2012; Chevalier, 2015; Chevalier et al., 2014, 2015; Morey et al., 2017). Proactive control involves planning prospectively for future responses. Reactive control, on the other hand, is simply a response to currently presented information. Under this approach, a developmental shift can be observed in which younger children primarily demonstrate reactive control strategies, responding to the stimulus at hand and only planning ahead when the nature of the task makes reactive control less useful. In contrast, older children and adults show proactive control, planning their recall of items to optimize performance (Chevalier et al., 2014, 2015). This suggests that in addition to a developmental increase in executive control abilities, children also show an increased metacognitive ability to flexibly engage appropriate control strategies with age (Chevalier, 2015; Chevalier et al., 2015). These 'meta-control' abilities are crucial for children to appropriately select from a range of abilities in response to specific task dynamics. Importantly, control strategies will vary in their associated cognitive costs, meaning that choice of strategy is likely to be influenced by a child's available executive resources (Chevalier et al., 2015).

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While proactive abilities have previously been observed in the age-range used in the current study, they continue to develop over a prolonged period (Chevalier, 2015). Speculatively, our sequential task might encourage a reactive control style whereby participants attempt to remember all the items before making a retrospective search of memory following the probe. Crucially, while proactive control strategies might emerge for some tasks at 7-years-old we should not expect development to involve monolithic shifts that immediately apply to all tasks (Seigler, 1994; 2007). Rather, proactive control should *develop* over time, perhaps being applied to tasks such as ours, where the cues to the optimal strategy are less salient, later in development (Chevalier et al., 2014; Chevalier, 2015).

One noteworthy feature of our sample is that the majority of children were from low socioeconomic (SES) neighborhoods. While the evidence is mixed as to whether SES relates to WM ability as such (Aran-Flippetti, 2013; Hackman, Betancourt, Gallop, Romer, Brodsky, Hurt, & Farah, 2014; Noble, Norman, & Farah, 2005; Noble, McCandliss, & Farah, 2007; but see, Engle, Santos, & Gathercole, 2008; Alloway, Alloway, & Wootan, 2014), it is relevant to the development of general cognitive abilities (Farah, Shera, Savage, Betancourt, Brodsky, & Hurt, 2006; Hackman & Farah, 2009). When comparing across other studies, it is important to be mindful of the possible role of extraneous factors such as SES on task performance. Indeed, future research could investigate potential influences of socio-economic factors on tasks involving executive control.

This study represents the first attempt to delineate the boundaries of children's ability to selectively attend to items in visual WM by using sequential presentation and explicit prioritization instructions. Across three experiments, we observe no evidence that children aged 7-10 years can selectively prioritize an item within a sequence. This runs counter to repeated

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observations using the highly similar methodology in young adults (Hu et al., 2014, 2016), suggesting the ability (or proclivity) to do so emerges after 10 years of age. In contrast, we provide convergent evidence for the automaticity of the recency effect in visual WM, robustly demonstrating this boost for the final item in a different population to the previous work with adults (Allen et al., 2014; Hu et al., 2014, 2016), and providing evidence for the absence of a relationship with cognitive control using individual difference rather than dual-task methodology. Thus, children do show the same overall profile as adults concerning the relative effortful and automatic processing of earlier versus final sequence items. However, unlike adults, they appear unable to selectively allocate more attentional resources to particular items in a sequence.

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## Appendix

Table A1 shows the correlations between our additional working memory tasks and age. The correlations within modality are larger than those between modalities. Nevertheless, there are significant correlations between tasks that require storage of information in different modalities, including for ‘simple’ tasks.

*Table A1. Correlations between the additional working memory measures and age*

	Age	FDR	BDR	Corsi	Odd-one-out
Age					
FDR		0.183**			
BDR		0.283***	0.555***		
Corsi		0.298***	0.418***	0.555***	
Odd-one-out		0.251***	0.306***	0.459***	0.622***

**Note.** \*\*  $p < .01$ ; \*\*\*  $p < .001$ ; FDR = forward digit recall; BDR = backward digit recall

Table A2 shows the descriptive statistics for the additional working memory measures expressed as the proportion of items correctly recalled combined across sequence lengths (see General Methods).

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Table A2. *Descriptive statistics for proportion correct on the additional working memory measures*

Task	Mean	SD	Min	Max
Forward digit recall	0.72	0.15	0.11	1.00
Backward digit recall	0.64	0.18	0.09	1.00
Corsi	0.68	0.15	0.25	1.00
Odd-one-out	0.51	0.21	0.12	0.96
Age	9.13	0.87	7.50	10.64