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Atkinson, AL, Waterman, AH orcid.org/0000-0001-9882-7206 and Allen, RJ orcid.org/0000-0002-1887-3016 (2019) Can children prioritize more valuable information in working memory? An exploration into the effects of motivation and memory load. Developmental Psychology, 55 (5). pp. 967-980. ISSN 0012-1649

https://doi.org/10.1037/dev0000692

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Developmental Psychology (Accepted December 2018)

Can children prioritize more valuable information in working memory? An exploration into the effects of motivation and memory load

Amy L. Atkinson, Amanda H. Waterman*, and Richard J. Allen

School of Psychology, University of Leeds, Leeds, LS2 9JT.

* Corresponding author

School of Psychology, University of Leeds, Leeds, LS2 9JT.

a.h.waterman@leeds.ac.uk

Author notes: The data and task scripts are available at https://osf.io/dczxn/.

Acknowledgements: The authors would like to thank Isobel Connelly, Michaela Lobato, Zoe Thatcher and Felix Tait for assistance with data collection, as well as Lucy Eddy, Alice Kininmonth, and Joyti Panesar for assistance with piloting. We would also like to thank Professor Graham Hitch and Professor Alan Baddeley for useful discussion, Westerton Primary Academy, and all children who participated in the experiments.

Abstract

Recent research found no evidence that children aged 7-10 years are able to direct their attention to more valuable information in working memory. The current experiments examined whether children demonstrate this ability when the reward system used to motivate participants is engaging and age-appropriate. This was explored across different memory loads (3 vs 4 item arrays) and modes of presentation (sequential vs simultaneous). Younger (7-8 years) and older children (9-10 years) were shown three or four colored shapes and asked to recall the color of one probed item following a brief delay. Items were either presented sequentially (Experiment 1) or simultaneously (Experiment 2). Children completed a differential probe value condition, in which the first shape (Experiment 1) or the top-left shape (Experiment 2) was worth more 'points' than the other items, and an equal probe value condition, in which all shapes were equally valuable. Children were told they could use the points collected to play a specially-designed game at the end of the session, and that they would be given a prize if they collected enough points. When items were presented sequentially, significant probe value effects emerged, with children showing higher accuracy for the first item when this serial position was more valuable. This effect was consistent across age group and memory load. When items were encountered simultaneously, both groups showed probe value effects in the higher (4 item) memory load condition. This indicates that children can prioritize more valuable information in working memory when sufficiently motivated to do so.

Keywords: working memory, attention, probe value, prioritization/prioritisation, motivation

Can children prioritize more valuable information in working memory? An exploration into the effects of motivation and memory load

Working memory (WM) refers to a system that allows a limited amount of information to be temporarily stored in a state of heightened accessibility for use in ongoing information processing (Cowan, 1988, 2017). The ability to retain information in WM increases throughout childhood and adolescence, reaching adult-like levels at approximately 15 years of age, depending on the task (Gathercole, Pickering, Ambridge, & Wearing, 2004). Throughout development, there are large individual differences in WM abilities (Alloway, 2006), with approximately 10% of children exhibiting substantial impairments (Alloway, Gathercole, Kirkwood & Elliot, 2009). Such impairments are likely to result in detrimental outcomes, as WM is essential for learning and is highly predictive of academic achievement across a range of key subject areas (Alloway & Alloway, 2010; Alloway, Alloway, & Wootan, 2014; Gathercole, Pickering, Knight & Stegmann, 2004; Holmes & Adam, 2006).

Research has therefore begun to explore how WM can be enhanced in children. As information encountered in learning environments often varies in importance, one approach involves encouraging children to direct their attention to particularly goal-relevant information. This ability has frequently been explored using pre-cue and retro-cue paradigms (Astle, Nobre, & Scerif, 2012; Shimi, Nobre, Astle, & Scerif, 2013; Shimi & Scerif, 2017). In these paradigms, participants are presented with a cue that informs them which item will be tested at retrieval. For example, Shimi et al. (2013; Experiment 1) presented 7-year-olds, 11-year-olds, and adults with simultaneous arrays of four items, and tested memory for one of them following a brief delay. In the cueing conditions, the array was either preceded (pre-cue) or followed (retro-cue) by a cue informing participants which item would be tested at retrieval. These cues were 100% valid and always identified the item that would be later assessed. Performance in these conditions was compared to a neutral condition, in which no cue was presented. All groups significantly benefited from the pre-cues, although retro-cues only enhanced performance in the 11-year-olds and the adults. This suggests that children as young as 7-years-old can, under particular conditions, direct their attention to more-goal relevant information in WM.

Similar findings were reported by Cowan, Morey, AuBuchon, Zwilling and Gilchrist (2010), who demonstrated that children can use probe frequency to enhance performance on WM tasks. In this study, 7-8 year olds, 12-13 year olds, and adults completed a change detection task, which involved remembering the color and location of circles and triangles for a brief period of time. Participants completed various attentional conditions, in which one of the shapes was tested either 100% of the time, 80% of the time, 50% of the time, or 20% of the time. When the array contained four items, all three groups were able to direct their attention based on probe frequency. However, when six items were presented, an interaction emerged between attention condition and age group, with the younger children less able to successfully distribute their attention. This fits with conclusions drawn from the cueing literature, suggesting that 7-8-year-old children can direct their attention to more goal-relevant information in WM, though perhaps not always as efficiently as older children or adults.

Another line of research has investigated whether individuals are able to direct attention in working memory by manipulating the value of items (Atkinson et al., 2018; Berry, Waterman, Baddeley, Hitch, & Allen, 2018; Castel et al., 2011; Castel, Lee, Humphreys, & Moore, 2011; Hitch, Hu, Allen & Baddeley, 2018; Hu, Allen, Baddeley, & Hitch, 2016; Hu, Hitch, Baddeley, Zhang & Allen, 2014; Allen & Ueno, 2018). This has been examined using a probe value paradigm (Atkinson et al., 2018; termed strategic prioritization in some previous literature; Berry et al., 2018; Hitch et al., 2018; Hu et al., 2014; 2016). In this paradigm, participants are typically presented with a series of colored shapes sequentially and asked to recall the color of one probed item following a delay. Before encoding, participants are told that one item is worth more ‘points’, and thus relatively more valuable than the rest. However, these points are notional, and are also unrelated to how often each item is assessed, with each serial position equally likely to be tested. This manipulation was introduced by Hu et al. (2014), who presented young adults with four colored shapes, and instructed them that either the first or the final item was worth more points. Significant probe value effects were observed, with participants exhibiting higher accuracy at the first or the final position when they were told that particular item was more valuable. In addition, regardless of which item was to be prioritized, participants showed a clear recency effect, exhibiting higher accuracy at the final item relative to others presented within the sequence. From this it was argued that the final item and the more valuable item are stored in a privileged state within WM, allowing them to be accessed more easily. Further research in adults has suggested that probe value effects may be reliant on executive resources, whilst recency effects appear to be obtained relatively automatically (Hu et al., 2016).

To date, only one study has examined whether children also exhibit probe value effects in WM (Berry et al., 2018). In this set of experiments, children aged 7-10 years were presented with three colored shapes sequentially. After a brief delay, the outline of one shape was presented, and participants were asked to recall the color. Participants completed a baseline condition, in which all items were worth the same number of points, and a priority condition in which the first item (Experiment 1 and 2) or the final item (Experiment 3) was worth more points and thus more valuable. In line with findings in adults, significant recency effects were observed, demonstrating that children can benefit from relatively automatic memory processes (Hu et al., 2016). Conversely, no probe value effects emerged in any of the experiments, suggesting that children cannot prioritize more valuable information in WM. This absence of an effect was attributed to the possible reliance of probe value effects on executive resources (Hu et al., 2016), which are not fully developed in 7-10-year old children (Berry et al., 2018; Jurado & Rosselli, 2007; Waszak, Li, & Hommel, 2010).

However, there are some methodological features of Berry et al. (2018) which might explain why probe value effects were not observed in these experiments. Firstly, the task was taken from previous literature using adult participants, with the points system purely notional. Whilst this approach appears to motivate adults to prioritize information (e.g. Atkinson et al., 2018; Hitch et al., 2018; Hu et al., 2014; 2016), it might not be sufficiently motivating for children. Indeed, it has been suggested that children may need more motivation to engage fully in psychological experiments compared to adults (Brewer et al., 2013), and that tasks may underestimate children's abilities when they do not sufficiently engage the child or are not presented in an age-appropriate context (Borke, 1975; McGarrigle & Donaldson, 1974; Rose & Blank, 1974). For instance, based on his three-mountains task, Piaget concluded that children younger than 7 years of age were egocentric, and therefore unable to understand that others had a different view of the world (Piaget & Inhelder, 1956). Borke (1975) then developed a more 'child-friendly' version of this task by using a toy model village and introducing a narrative that gave meaning and context to the requests for children to indicate another person's viewpoint. Using this version, it was found that children as young as 3 years were able to pass the task and therefore were not classified as egocentric. Similar findings have been shown for other cognitive constructs, such as conservation of liquid or number, whereby children were able to demonstrate abilities at younger ages when tasks were adapted appropriately (McGarrigle & Donaldon, 1974, Light et al., 1979). As such, it is possible that children might be able to prioritize more valuable information in WM if the reward system was more meaningful and the task was more age-appropriate.

Secondly, in Berry et al (2018) children were only ever presented with three item sequences. However, cueing effects vary as a function of the number of items presented (referred to as memory load hereafter). This effect has been reported in adults (e.g. Astle, Summerfield, Griffin & Nobre, 2011; Kuo, Stokes, & Nobre, 2012; Nobre, Griffin, & Rao, 2008; Souza, Rerko & Oberauer, 2014; van Moorselaar, Olivers, Theeuwes, Lamme, & Sligte, 2015), and more recently in children (Shimi & Scerif, 2017). Based on this, it has been argued that children, like adults, use cues strategically, attending to them more when memory load is increased (Shimi & Scerif, 2017). It is therefore possible that memory load will also influence whether children prioritize more valuable information using the probe value paradigm, and that the 3-item sequences used in Berry et al (2018) might not have tapped into this ability.

These issues were examined in the current experiments. The task was made more age-appropriate by placing it in the context of a story, with children able to use the points collected in a specially-designed game at the end of the session. Children were also told they would win a prize if they collected enough points. In addition, memory load was manipulated, with either three or four items presented per sequence. As in previous research employing the probe value paradigm (Atkinson et al., 2018; Berry et al., 2018; Hitch et al., 2018; Hu et al., 2014; 2016), Experiment 1 displayed items sequentially. This was implemented in order to closely mirror the presentation methodology used by Berry et al. (2018). Experiment 2 then investigated effects using simultaneous arrays, in order to bridge the findings with other paradigms that have used this mode of presentation (Astle et al., 2012; Cowan et al., 2010; Shimi et al., 2013, Shimi & Scerif, 2017). These findings are also likely to have practical importance, as information can be encountered both sequentially (e.g. watching a video clip or reading a book; Berry et al., 2018) and simultaneously (e.g. in wall displays and whiteboards) in educational settings.

Children aged 7-8 and 9-10-years old were recruited in both experiments. Two age groups were tested in order to investigate whether the ability to prioritise valuable information increases with age. Proactive control strategies, in which individuals plan ahead for future responses and maintain task-relevant information before it is required, develop throughout childhood (Chevalier, James, Wiebe, Nelson & Espy, 2014). As such, older children (aged 9-10 years) might be able to prioritise valuable information more effectively than younger children (7-8 years). Further, several relevant constructs develop over this age range, for example, cognitive flexibility and goal setting (Anderson, 2002; Davidson, Amso, Anderson, & Diamond, 2006). The ages selected are also in line with the upper and lower age groups tested in Berry et al. (2018) and are similar to those used in other experiments that have investigated cueing effects in children (e.g. Shimi et al., 2013; Shimi & Scerif, 2017).

Experiment 1

Children completed a visual WM task, in which series of colored shapes were presented sequentially. After a brief delay, the outline of one shape was presented, and participants had to recall the color. Before encoding, participants were either told that the items were of equal value (equal probe value) or that the first item was worth more points than the rest (differential probe value). The points system was made meaningful and age-appropriate through the incorporation of a story and game element. At the start of the session, children were introduced to a friendly alien whose planet had been invaded by 'evil aliens'. They were told they would collect energy points during the memory task which would allow them to 'zap' the evil aliens in a specially-designed game at the end of the session. They were also told that they would be given a prize if they accrued enough points. Memory load was also manipulated, with either three or four items presented in each trial.

Evidence of probe value boosts, whereby performance at the first position is higher in the differential probe value condition, would indicate that children can prioritize more valuable information when they are sufficiently motivated to do so. In addition, if memory load is important in mediating strategic prioritization within the current paradigm, as it appears to be with visual cueing (Shimi & Scerif, 2017), then we would expect to see an interaction between probe value and memory load, whereby larger probe value effects are observed when four items are presented. Given that proactive control strategies may develop throughout childhood, we also predicted that the older children would show larger probe value effects than the younger children. More generally, we expected there to be an effect of memory load, whereby the three item sequences would be remembered more accurately than the four item sequences. We also anticipated an overall effect of age group, whereby the older children would exhibit higher accuracy than the younger children.

Method

Sample size justification. Power analysis was conducted using G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007). In adults, the probe value manipulation yields an effect size (*d*) of 0.70-1.44 (Atkinson et al., 2018; Hu et al., 2016). However, based on previous findings, we might expect any effect observed to be smaller in children (Cowan et al., 2010; Shimi et al., 2013). Estimating an effect size (*d*) of 0.60, 24 participants per group would be required to obtain 80% power for a two-tailed t-test comparing accuracy in the differential and equal probe value conditions at the more valuable position. With a minimum number of 30 participants in each group, the test would have 88.80% power. Combining across the age groups (approximately 60 participants), the test would have 99.55% power. With this number of participants, we would have 80% power to detect an effect ≥ 0.37. This sample size justification was used in both experiments.

Participants. A primary school agreed to participate. The school is in a moderate socio-economic status (SES) neighbourhood, with the index of multiple deprivation (IMD) indicating that the area is amongst the 50% least deprived neighbourhoods in the country

(English Indices of Deprivation, 2015). Children at the school are predominantly White-British and native English speakers. All children who participated spoke fluent English and had no known learning difficulties. Thirty-four younger children completed the experiment (aged 7-8 years; *Mean (M) age = 7.92, Standard deviation (SD) = 0.30;* 21 males). All children in this group were in Year 3 (UK). From this group, two children were removed for failing to engage with the articulatory suppression concurrent task and one child was removed as their performance was below chance. The final analysis was therefore run on data from 31 younger children (*M. age = 7.94, SD = 0.30,* 18 males). Thirty-three older children also participated (aged 9-10 years; *M. age* = 9.93, *SD* = 0.30; 12 males). All children in this group were in Year 5 (UK). One child was absent on the second day of testing and therefore only participated in the 3-item condition. The final analysis for the 4-item conditions was therefore run on 32 older children (*M. age* = 9.93, *SD* = 0.31; 12 males), whilst the analysis for the 3-item conditions was run on all participants in this age group. Ethical approval for both experiments was granted by the School of Psychology Ethics Committee at the University of Leeds (Approval number PSC-210; 'Can children prioritise information in working memory?')

Design, materials and procedure. A 2 (Probe value: differential vs equal) x 2 (Memory load: 3 or 4) x 2 (Age group: younger children vs older children) mixed design was employed. Probe value and memory load were manipulated within-subject, whilst age group was a between-subject variable. The probe value and memory load conditions were blocked. Participants completed the experiment in two sessions, blocked by memory load. The sessions were completed on different days. The order of the memory load sessions, and the order of the probe value blocks within the memory load sessions, was counterbalanced. Within each probe value-memory load block, each serial position (SP) was as likely to be tested. In the 3-item conditions, participants completed three practice trials and 30 experimental trials per block. In the 4-item conditions, participants completed four practice trials and 40 experimental trials per block. Within each block, each SP was tested 10 times.

The task was created using PsychoPy 1.84.2 (Peirce, 2007). The script used to run the experiment is available at https://osf.io/dczxn/. The experimental paradigm used is displayed in Figure 1. Participants were presented with either three or four colored shapes sequentially, with each presented for 500ms. Stimuli were created by randomly pairing one of six colors (red, yellow, green, blue, purple, black) with one of six shapes (circle, triangle, cross, arch, flag, arrow). No color or shape was repeated within the same trial. The shapes were presented on a white background at one of eight positions around a 2º imaginary circle located at the screen centre. All stimuli measured approximately 1.5º, based on a viewing distance of 50cm. After a delay of 1000ms, the outline of one shape was displayed in the centre of the screen and participants were asked verbally to recall the color. Responses were recorded by the experimenter. During encoding and maintenance, participants whispered the word 'la' to prevent (or at least reduce) verbal recoding (Baddeley, 1986). Participants were informed of the probe value manipulation during the instructions. In the differential probe value condition, they were told that correct recall of the first shape would earn them four 'energy points', and that correct recall of any other shape would earn them one 'energy point'. In the equal probe value condition, they were told that correct recall of any item would earn them one 'energy point'.

[Figure 1 about here]

Before the instructions of the memory task, children were introduced to a friendly alien named 'Zorg' and were told a short story about him (see Figure 2A and 2B, and the supplementary material for the full text). They were told that his planet had been invaded by evil aliens, and asked if they would help ‘zap’ them. To zap the aliens, they needed energy points, which could be collected by playing memory games (i.e. the experimental task). They were also told that they would get a prize if they collected enough points.

After every 10 trials, children were shown an energy bar that slowly increased throughout the session. The increase in energy was not linked to their true performance and increased by the same amount for each child (see Figure 2C). This was implemented to ensure that motivation was not affected by prior performance and that children were not discouraged if they performed poorly. Participants were also reminded of the probe value instructions directly after these screens.

At the end of the session, children were told they had accumulated enough energy points from the memory games to play the ‘zap an alien’ game (see Figure 2D). In this game, the ‘evil aliens’ appeared on screen and participants had to click on them before they disappeared in order to ‘zap’ them. Children were told the same story and played the same game in both sessions. At the end of each session, children were told they had collected enough energy points to receive a prize, and chose a piece of stationery as a reward.

[Figure 2 about here]

Data Analysis

The dependent variable was accuracy (proportion of trials answered correctly). Separate analysis was conducted for the 3-item and 4-item conditions as the number of SPs differed between the conditions. As some previous research has suggested that older children can direct their attention in WM more effectively than younger children (Cowan et al., 2010; Shimi et al., 2013), age group was also added as a factor.

Both frequentist and Bayes Factor (BF) analysis were conducted on the data. BF analysis assesses the strength of evidence for the alternative hypothesis against the null hypothesis and provides a test of equivalence between groups/conditions (Barchard, 2015; Mulder & Wagenmaker, 2016). This analysis was conducted in R using the BayesFactor package (Morey et al., 2018; R Core Team, 2016). When conducting Bayesian ANOVAs, the default priors described by Rouder, Morey, Speckman, & Province (2012) were used and the number of iterations was set at 500,000 to reduce computing error. All possible models were assessed, meanings that an interaction could be included in the most likely model even if the main effect was absent. When reporting effects, the most likely model given the data is reported relative to a null model which includes only random effects of participant. Bayes factors for all main effects and interactions are also reported. If an effect/interaction is included in the most likely model, the BF was calculated by comparing the most likely model to one excluding the effect/interaction of interest (Rouder, Morey, Verhagen, Swagman, & Wagenmakers, 2017). If the effect/interaction was not included in the most likely model, the BF was calculated by comparing the model plus the effect/interaction of interest to the most likely model (Rouder et al., 2017). BF_{10} describes how many times more likely the alternative hypothesis is than the null hypothesis (of no effect/interaction). Values above 1 represent evidence for an effect, whereas values below 1 provide values against an effect.

Results

The data analysed in both experiments is available at https://osf.io/dczxn/.

3 items. Mean accuracy (and SE) as a function of probe value, SP and age group is displayed in Figure 3A. Means and SE are also presented in Table 1, collapsed across age groups. A 2 (Probe value; within-subject) x 3 (SP; within-subject) x 2 (Age group; between-subject) mixed ANOVA was conducted. This revealed no significant effect of probe value

(*F*(1, 62) = .42, *MSE* = .02, *p* = .521, η_p^2 < .01; BF_{10} = 0.13), demonstrating that this manipulation did not affect overall performance on the task. There was, however, a significant effect of age group (*F*(1, 62) = 4.43, *MSE* = .08, *p* = .039, η_p^2 = .07; BF_{10} = 1.17), with older children (*M* = .60, *SE* = .02) exhibiting higher accuracy than younger children (*M* = .54, *SE* = .02). There was also a significant effect of SP (*Greenhouse-Geisser corrected F*(1.52, 94.33)= 35.64, *MSE* = .06, *p* < .001, η_p^2 = .37; BF_{10} > 10,000). Bonferroni-Holm pairwise comparisons revealed significant differences between SP1 (*M* = .53, *SE* = .02) and SP2 (*M* = .48, *SE* = .02; *p* = .022), SP1 and SP3 (*M* = .70, *SE* = .02; *p* < .001), SP2 and SP3 (*p* < .001). There was a significant interaction between probe value and SP (*F*(1.71, 106.27) = 13.13, *MSE* = .03, *p* < .001, η_p^2 = .18; BF_{10} = 186.72), but no other interactions (*F* ≤ 2.21, *p* ≥ .123, BF_{10} ≤ 0.34). These findings were corroborated by BF analysis, which indicated that the most likely model included main effects of SP and age group, and an interaction between probe value and SP (*BF* > 10,000 relative to the null model containing only participant).

To investigate the interaction between probe value and SP, a series of paired sample t-tests (corrected using Bonferroni-Holm) were conducted to compare performance in the differential and equal probe value conditions at the various SPs. At SP1, accuracy in the differential probe value condition (*M* = .57, *SE* = .03) was significantly higher than accuracy in the equal probe value condition (*M* = 50, *SE* = .03; *t*(63) = 3.00, *p* = .008, *d* = 0.37; BF_{10} = 7.74). This outcome was also observed at SP2 (*Differential M* = .51, *SE* = .02; *Equal M* = .45, *SE* = .02; *t*(63) = 2.34, *p* = .022, *d* = 0.29, BF_{10} = 1.72). At SP3, the opposite pattern of results was observed, with participants performing significantly better in the equal probe value condition (*M* = .75, *SE* = .02) than the differential probe value condition (*M* = .65, *SE* = .03; *t*(63) = -3.36, *p* = .003; *d* = -0.42, BF_{10} = 20.09).

[Figure 3 about here]

4 items. Mean accuracy (and SE) as a function of probe value, SP and age group is displayed in Figure 3B. Means and SE are also presented in Table 1, collapsed across age groups. A 2 (Probe value; within-subject) x 4 (SP; within-subject) x 2 (Age group; between-subject) mixed ANOVA revealed no significant effect of probe value (*F*(1, 61) = 1.62, *MSE* = .02, *p* = .208, η_p^2 = .03; BF_{10} = 0.16), demonstrating that this manipulation had no effect on overall performance. There was also no main effect of age group (*F*(1, 61) = 2.16, *MSE* = .05, *p* = .147, η_p^2 = .03; BF_{10} = 0.33). There was, however, a significant effect of SP (*Greenhouse-Geisser corrected F*(2.57, 156.84) = 102.64, *MSE* = .05, *p* < .001, η_p^2 = .63; BF_{10} > 10,000). Bonferroni-Holm pairwise comparisons revealed significant differences between SP1 (*M* = .38, *SE* = .02) and SP2 (*M* = .26, *SE* = .02; *p* = .001), SP1 and SP4 (*M* = .68, *SE* = .02; *p* = .001), SP2 and SP3 (*M* = .34, *SE* = .02; *p* = .002), SP3 and SP4 (*p* = .001), and SP3 and SP4 (*p* = .001) A significant interaction between probe value and SP emerged (*F*(3, 183) = 4.06, *MSE* = .03, *p* = .008, η_p^2 = .06; BF_{10} = 1.32), although no other interactions were observed ($F \leq 1.11$, $p \geq .348$, $BF_{10} \leq 0.15$). The BF analysis indicated that the most likely model included main effects of SP and an interaction between probe value and SP (BF_{10} > 10,000 relative to the null model containing only participant).

To investigate the interaction between probe value and SP, a series of paired sample t-tests were conducted to compare performance in the differential and equal probe value conditions at the various SPs (corrected using Bonferroni-Holm). At SP1, performance in the differential probe value condition (*M* = .43, *SE* = .03) was significantly better than performance in the equal probe value condition (*M* = .34, *SE* = .02; *t*(62) = 3.31, *p* = .008; *d* = 0.42, BF_{10} = 17.83). There were no significant differences at the other SPs ($t \geq$ -1.04 and $\leq$ 0.54, $p \geq .906$, $d \geq$ -0.13 and $\leq$ 0.07; $BF_{10} \leq 0.23$).

[Table 1 about here]

Across memory loads. Accuracy at SP1 is displayed in Figure 4A as a function of probe value and memory load. To investigate whether the probe value boosts differed across memory loads, a 2 (Probe value; within-subject) x 2 (Memory load; within-subject) x 2 (Age group; between-subject) mixed ANOVA was conducted at SP1. One participant in the older children's group completed only the 3-item condition and was therefore excluded from this analysis. The analysis was therefore run on data from 31 younger children and 32 older children. This revealed a main effect of probe value ($F(1, 61) = 22.42$, $MSE = .02$, $p < .001$, $\eta_p^2 = .27$; $BF_{10} = 753.71$), whereby performance was higher in the differential probe value condition ($M = .50$, $SE = .02$) than the equal probe value condition ($M = .41$, $SE = .02$). There was also a main effect of memory load ($F(1, 61) = 40.91$, $MSE = .03$, $p < .001$, $\eta_p^2 = .40$; $BF_{10} > 10{,}000$), whereby performance was higher in the 3-item condition ($M = .53$, $SE =$. 02) than the 4-item condition ($M = .38$, $SE = .02$). There was no significant effect of age group ($F(1, 61) = 2.51$, $MSE = .08$, $p = .118$, $\eta_p^2 = .04$; $BF_{10} = 0.69$), and no interactions ($F \leq 1.33$, $p \geq .254$, $BF_{10} \leq 0.42$). BF analysis revealed that the most likely model included main effects of probe value and memory load ($BF_{10} > 10{,}000$ relative to the null model containing only participant).

[Figure 4 about here]

Discussion

This experiment examined whether children could prioritize more valuable information in WM by increasing the motivation and age-appropriate nature of the reward system. In contrast to Berry et al (2018), significant probe value effects emerged. This suggests that children are able to prioritize the more valuable item in a sequence in order to facilitate its later recall, when they are motivated to do so. No interaction between probe value and memory load was observed, indicating that the increased motivational aspects of the task enabled children to prioritize with both 3- and 4-item sequences. Thus, the absence of a probe value effect in Berry et al (2018), using only 3-item sequences, cannot simply be attributed to an explanation based on memory load.

There were relatively few effects involving age. The older children were better overall at the 3-item task than the younger children, but there were no age differences for the 4-item task, and the main effect of age group disappeared in the analysis that collapsed across memory loads. More importantly there were no interactions involving age, indicating that the ability to prioritize information in WM does not undergo developmental changes between the ages of 7-10 years.

Evidence that the probe value boosts did not differ across memory load contrasts with the cueing literature, in which Shimi and Scerif (2017) recently reported that effects of cues are larger in children when more items are presented. However, one key difference between these experiments is the mode of presentation used; Experiment 1 presented items sequentially, whilst Shimi and Scerif (2017) used simultaneous arrays. Experiment 2 therefore examined the impacts of probe value and memory load on visual WM for simultaneously presented arrays of multiple items. This exploration will not only address the claims of Shimi and Scerif (2017), but also connect research on probe value with the broader developmental literature on cueing and probe frequency effects, which has tended to use simultaneous rather than sequential presentation (Cowan et al., 2010; Astle et al., 2012; Shimi et al., 2013; Shimi & Scerif, 2017).

Experiment 2

Experiment 2 explored whether children can prioritize more valuable information in simultaneous arrays, and whether such effects vary as a function of memory load. Previous research has revealed important distinctions between sequential and simultaneous modes of presentation. For instance, rates of forgetting are considerably larger when information is presented sequentially (Allen, Baddeley, & Hitch, 2006; Gorgoraptis, Catalao, Bays, & Husain, 2011; Morales, Calvo, & Bialystok, 2013). Moreover, research in adults has suggested that the direction of attention might be easier when information is presented simultaneously, as one does not need to protect the item from further incoming stimuli (Gorgoraptis et al., 2011), a process that is essential when information is presented sequentially.

Allen and Ueno (2018) recently explored adults' ability to prioritize more valuable information in WM using simultaneous arrays. In their series of experiments, participants were presented with four colored shapes simultaneously. After a short delay, participants were probed with either the color or shape and asked to recall the other feature. In each trial, one or more items were worth more points than the rest, and thus worth a higher reward. In all of the experiments, the more valuable items were recalled more accurately than the less accurate items. Participants were also able to prioritize multiple high-value items concurrently, and grade their attention if each item was associated with a varying level of reward (e.g. between 1-4 points).

However, to date, research has not investigated whether children are also able to prioritize more valuable information in WM when information is encountered simultaneously. Such a skill would be beneficial for children, as the visual environment often contains multiple items that vary in value or importance. Experiment 2 therefore investigated this question. The emergence of probe value effects would replicate Experiment 1, providing further evidence that children can direct their attention to more valuable information in WM.

Also of interest was whether an interaction would emerge between probe value and memory load. Evidence of an interaction, whereby larger probe value effects are observed in the 4-item condition, would be in line with the claims of Shimi and Sherif (2017). It would, however, contrast with Experiment 1, suggesting that mode of presentation is important when considering the effect of memory load on the ability to direct attention. Conversely, equivalent effects across memory loads would replicate Experiment 1, potentially highlighting an important distinction between probe value and cueing effects, when considering the effect of memory load. It was unclear whether the probe value effects would increase with age, as this interaction was not observed in Experiment 1, but might be predicted based on previous findings suggesting that proactive control abilities increase with age (Chevalier et al., 2014). More generally, we expected a significant effect of memory load, with participants exhibiting higher accuracy when three items were presented.

Method

Participants. Children were recruited from the same primary school as in Experiment 1, although no participants had taken part in the previous experiment. Thirty-five younger children took part (7-8 years; Year 3; *M. age* = 8.01, *SD* = 0.29; 15 males). Two children were excluded for not properly engaging in the articulatory suppression task. Due to absence, one child from this group only completed the 4-item conditions. The final analysis for the 3-item conditions was therefore run on 32 younger children (*M. age* = 8.01, *SD* = 0.29; 13 males), whilst the analysis for the 4-item conditions was run on 33 younger children (*M. age* = 8.00, *SD* = 0.29; 13 males). Thirty-four older children (aged 9-10 years; Year 5; *M. age* = 9.82, *SD* = 0.25; 20 males) also participated in both sessions.

Materials, design and procedure. With the exception of a few minor details relating to presentation mode, the materials, design and procedure were identical to Experiment 1.

The script used to run the experiment is available at https://osf.io/dczxn/. The experiment employed a 2 (Probe value: differential, equal) x 3 (Memory load: 3 and 4) x 4 (Spatial location (SL): top-left, top-right, bottom-left, bottom-right) x 2 (Age group: younger children, older children) mixed design. Probe value, memory load and SL were within-subject variables, whilst age group was a between-subject variable. In the differential probe value condition, participants were told that the top-left item was worth 4 points and the other items were worth 1 point. In the equal probe value condition, all of the items were worth 1 point. As in Experiment 1, trials were blocked by probe value and memory load. Children completed two sessions on separate days, blocked by memory load. The order of the memory load blocks, and the order of the probe value blocks within the memory load blocks, was counterbalanced. In each probe value-memory load block, there were 40 trials, with each SL being assessed 10 times.

The experimental paradigm used is displayed in Figure 5. Participants were shown arrays of three or four colored shapes simultaneously. Shapes appeared at one of four SLs positioned at the corners of a 2° imaginary circle, located at the centre of the screen. The arrays were displayed for 1500ms in the 3-item blocks and 2000ms in the 4-item blocks. In the 3-item conditions, an item was always presented in the top-left location as this is the SL at which the probe value manipulation was targeted. The other SLs were selected randomly. In the 4-item conditions, all SLs were occupied on every trial. The retention interval and the suppression task were identical to Experiment 1.

[Figure 5 about here]

Before the start of each session, children completed a brief paper-based activity to ensure they understood the meaning of ‘top-left’. In each trial, they were presented with four pictures of related objects (e.g. fruit, furniture, stationary) arranged in a 2 x 2 grid and asked to point to the top-left picture. If they responded correctly on three consecutive trials, they immediately progressed onto the main experimental task. If they responded incorrectly on any of the three trials, the experimenter pointed to the top-left picture of three novel sets. The participant was then presented with three new sets and asked to identify to the top-left picture in each. This was repeated a maximum of three times until children correctly selected the top-left picture on three consecutive trials. The same set of images was used in both sessions. 73% of younger children and 94% of older children responded correctly on the first attempt in session 1, whilst all children in both groups answered correctly on the first attempt in session 2. No child required more than two attempts in either session.

Data Analysis

Frequentist and BF analysis was conducted. To mirror the analysis conducted in Experiment 1, separate analysis was conducted for the 3-item and 4-item conditions and age group was included as a factor.

Results

3 items. Mean accuracy (and SE) is displayed in Figure 6A as a function of probe value, SL, and age group. Means and SE are also presented in Table 2, collapsed across age groups. A 2 (Probe value; within-subject) x 4 (SL; within-subject) x 2 (Age group; between subject) mixed ANOVA was conducted. This revealed no significant main effect of probe value, $F(1, 64) = 0.27$, $MSE = .02$, $p = .604$, $\eta_p^2 < .01$; $BF_{10} = 0.10$), but a significant main effect of SL, $F(3, 192) = 7.30$, $MSE = .03$, $p < .001$, $\eta_p^2 = .10$; $BF_{10} = 1094.83$). Bonferroni-holm post-hoc comparisons revealed significantly lower accuracy in the bottom-left position ($M = .68$, $SE = .03$), compared to the top-left position ($M = .78$, $SE = .02$; $p = .001$), the top-right position (M = .76, SE = .02; p = .005), and the bottom-right position (M = .76, SE = .02; p = .005). A significant effect of age group also emerged, $F(1, 64) = 9.32$, MSE = .12, p = .003, η_p^2 =.13; BF_{10} = 10.21, with older children (M = .79, SE = .02) exhibiting higher accuracy than the younger children (M = .70, SE = .02). There was no significant interaction between probe value and SL, $F(3, 192) = 0.99$, MSE = .02, p = 0.400, η_p^2 = .02; BF_{10} = 0.05). No other significant interactions emerged ($F \leq 1.51$, $p \geq .214$, $BF_{10} \leq 0.19$). The BF analysis indicated that the most likely model included main effects of SL and age group (BF_{10} > 10,000 relative to the null model with random effects of participant only).

[Figure 6 about here]

4 items. Mean accuracy (and SE) is displayed in Figure 6B as a function of probe value, SL and age group. Means and SE are also presented in Table 2, collapsed across age groups. A 2 (Probe value; within-subject) x 4 (SL) x 2 (Age group; between-subject) mixed ANOVA revealed no significant effect of probe value $F(1, 65) = 1.66$, MSE = .03, p = .202, η_p^2 = .03; BF_{10} = 0.23). There was, however, a significant main effect of SL, *Greenhouse-Geisser corrected* $F(2.61, 169.44) = 10.70$, MSE = .06, $p < .001$, η_p^2 = .14; BF_{10} > 10,000), with Bonferroni-Holm post-hoc comparisons revealing significantly lower accuracy at the bottom-left position (M = .47, SE = .03), relative to the top-left (M = .62, SE = .02; p = .001), top-right (M = .58, SE = .02; p = .005), and bottom-right positions (M = .55, SE = .02; p = .020). There was also an effect of age group $F(1, 65) = 9.26$, MSE = .16, p = .003, η_p^2 = .13; BF_{10} = 9.94), with older children (M = .61, SE = .02) performing better than the younger children (M = .50, SE = .03). Crucially, a significant interaction between probe value and SL emerged $F(3, 195) = 11.61$, MSE = .03, $p < .001$, η_p^2 = .15; BF_{10} = 244.09). No other interactions emerged ($F \leq 1.96$, $p \geq .131$, $BF_{10} \leq 0.59$). These findings were corroborated by

BF factor analysis which revealed the most likely model contained main effects of SL and age group, and an interaction between probe value and SL ($BF_{10} > 10{,}000$ relative to the null model with random effects of participant only).

To investigate the key interaction between probe value and SL, Bonferroni-holm corrected paired sample t-tests were conducted. There was a significant effect of probe value at the top-left position ($t(66) = 5.30$, $p < .001$; $d = 0.65$; $BF_{10} > 10{,}000$), with participants exhibiting higher accuracy in the differential probe value condition ($M = .69$, $SE = .03$) relative to the equal probe value condition ($M = .55$ $SE = .03$). No significant differences emerged at the other SLs ($t \geq -2.11$ and ≤ 1.26, $p \geq .117$, $d \geq -0.26$ and ≤ 0.15, $BF_{10} \leq 1.07$).

[Table 2 about here]

Across memory loads. Accuracy at the top-left position is presented in Figure 4B as a function of probe value and memory load. A 2 (Probe value; within-subject) x 2 (Memory load; within-subject) x 2 (Age group; between-subject) mixed ANOVA was conducted at the top-left position to explore whether probe value boosts vary across memory loads. One participant in the younger children's group completed only the 4-item condition, and was therefore excluded from this analysis. The analysis was therefore run on data from 32 younger children and 34 older children. A significant effect of probe value emerged $F(1, 64) = 21.22$, $MSE = .02$, $p < .001$, $\eta_p^2 = .25$; $BF_{10} = 3900.50$), with accuracy in the differential probe value condition ($M = .74$, $SE = .02$) higher than the equal probe value condition ($M = .66$, $SE = .02$). There was also a significant effect of memory load $F(1, 64) = 76.19$, $MSE = .02$, $p < .001$, $\eta_p^2 = .54$; $BF_{10} > 10{,}000$) with higher accuracy in the 3-item conditions ($M = .78$, $SE = .02$) relative to the 4-item conditions ($M = .62$, $SE = .02$). No significant effect of age group emerged $F(1, 64) = 0.83$, $MSE = .10$, $p = .365$, $\eta_p^2 = .01$; $BF_{10} = 0.38$). There was a significant interaction between probe value and memory load $F(1, 64) = 9.82$, $MSE = .02$, $p = .003$, $\eta_p^2 = .13$; $BF_{10} = 10.25$), but no other interactions ($F \leq .213$, $p \geq .646$, $BF_{10} \leq 0.25$). The BF analysis yielded similar outcomes, indicating that the most likely model included main effects of probe value and memory load, as well as an interaction between probe value and memory load ($BF_{10} > 10{,}000$ relative to the null model with random effects of participant only).

To investigate the interaction between probe value and memory load, paired sample t-tests were conducted (corrected using Bonferroni-Holm). A significant difference between the probe value conditions emerged in the 4-item conditions, $t(65) = 5.24$, $p < .001$, $d = 0.65$; $BF_{10} = 8673.41$) with participants exhibiting higher accuracy in the differential probe value condition relative to the equal probe value condition. There was, however, no effect of probe value in the 3-item conditions, $t(65) = 1.33$, $p = .189$; $d = 0.16$, $BF_{10} = 0.31$).

Discussion

Experiment 2 examined whether children can prioritize a more valuable item when information is encountered simultaneously, and whether such effects vary as a function of memory load. The results showed that children do prioritize more valuable information, but only under particular memory load conditions. When four items were presented, probe value effects were observed, whereby accuracy at the top-left location was significantly higher when that location was associated with more points (the differential probe value condition) than when all locations were associated with the same number of points (the equal probe value condition). However, when three items were displayed, no significant probe value effects emerged, with BF analysis providing evidence of no effect. Such findings are in line with Shimi & Scerif (2017), who found that children's ability to direct attention increases as more items are presented.

In both the 3- and the 4-item analyses, there was a significant effect of age group, with the older children showing higher accuracy overall relative to the younger children. However, both age groups showed the same pattern in relation to the interaction between memory load and probe value effects. Both younger and older children showed prioritization boosts with the 4-item array, but not the 3-item array, when the top-left item was worth more points.

Finally, an unexpected finding emerged in that children were generally less accurate (in both memory load conditions) when recalling the bottom-left item in the array. Visual WM accuracy may indeed vary with spatial location (e.g. Della Sala, Darling, & Logie, 2010) although the precise patterns reported in that study do not map on to those observed in this experiment. As we had no a priori expectation for performance to vary across spatial locations independently of value, we would refrain from further interpretation, but it may be useful for further work to explore whether such outcomes consistently emerge in developmental and adult populations.

General Discussion

The present experiments investigated whether children are able to direct their attention to valuable items in WM if the reward system underpinning the task is engaging and child-friendly. Items were presented sequentially (Experiment 1) and simultaneously (Experiment 2), as information in real world settings may be encountered in either mode of presentation. In both experiments, probe value effects emerged, demonstrating that children can prioritize items worth a higher reward when sufficiently motivated to do so. These probe value boosts were observed without memory for other items dropping to floor, indicating that children did not simply abandon the other representations in order to retain the more important item. This demonstrates that children as young as 7-8 year olds can distribute their attention across items in a sophisticated manner. Such outcomes are in line with previous findings which have shown that children are able to direct their attention in WM based on cues (Astle et al., 2012; Shimi et al., 2013; Shimi & Scerif, 2017) and probe frequency (Cowan et al., 2010). However, to the best of our knowledge, these experiments are the first to demonstrate that children can prioritize higher reward items in WM, and that they are able to orient their attention when a sequential mode of presentation is used (Experiment 1).

Berry et al. (2018) suggested that 7-10-year-old children cannot direct their attention to more valuable information in WM due to under-developed executive resources. However, the current outcomes demonstrate that, when motivated to do so, children are able to engage executive control in order to prioritise high-reward items. This suggests that children assess the cognitive effort associated with strategies and use this to determine whether to apply them (Chevalier, 2017). When a strategy is cognitively demanding, like prioritization (Hu et al., 2016), individuals might only employ it when they are motivated to perform optimally and believe the reward is worth the cognitive effort it will involve.

The disparate outcomes between the current experiments and Berry et al. (2018) are in line with previous research which has demonstrated that children may show cognitive abilities earlier if the task is engaging and the context is age-appropriate (Borke, 1975; McGarrigle & Donaldson, 1974; Rose & Blank, 1974; Light et al., 1979). It also suggests that children may need more motivation to complete experimental studies to the best of their ability (Brewer et al., 2013), and that researchers should exert caution when extending experimental paradigms used in adults to a developmental context. As such, these findings may have broad implications for psychologists, educators, and other professionals who wish to understand how cognitive abilities develop across childhood.

This pair of experiments also examined whether probe value effects vary as a function of memory load, as has been reported in the cueing literature (Shimi & Scerif, 2017). When information was encountered sequentially (Experiment 1), no interaction emerged. However, when simultaneous arrays were used (Experiment 2), significant effects of probe value were only observed in the 4-item condition. Why might this distinction have emerged? Whether probe value effects vary as a function of memory load might depend on the mode of presentation used. If items are presented sequentially, children might prioritize information regardless of how many items are presented. Conversely, if the task uses simultaneous arrays, children may not be able to direct their attention in WM if fewer than four items are presented. However, it is not clear why this pattern of finding would emerge as the direction of attention is thought to be easier when information is encountered simultaneously (Gorgoraptis et al., 2011). Indeed, in the 4-item conditions, the effect size for the probe value comparison was larger at the targeted item when information was displayed simultaneously (*Sequential (Experiment 1)* d = 0.42, *Simultaneous (Experiment 2)* d = 0.65).

Therefore, a more likely possibility is that children selectively orient their attention in WM when the amount of information presented is at, or above, capacity limits (Shimi & Scerif, 2017). Across both experiments, mean accuracy was highest when three items were presented simultaneously (see Figure 4). In this condition, children might therefore have judged that additional strategies were not necessary to maximise performance (Shimi & Scerif, 2017), or not worth the cognitive effort they would require (Chevalier, 2017). However, when four items were presented simultaneously (Experiment 2), or three or four items were presented sequentially (Experiment 1), children might have found the task more challenging and thus strategically applied the prioritization information in order to boost performance.

Across both experiments, no age group interactions emerged. This indicates that the ability to prioritize valuable information in WM does not substantially increase between 7-10 years of age. It is, however, important to note that the effects observed were considerably smaller than those reported in previous studies employing the same paradigm in adults (d = 0.42 in the 4-item condition of Experiment 1 relative to 0.70-1.44 reported in Atkinson et al., 2018 and Hu et al., 2016). Further developmental changes must therefore occur between the ages of 10 years old and adulthood. It would therefore be beneficial for research to explore the developmental trajectory of this ability across late childhood and adolescence. As probe value effects are thought to rely on executive control (Hu et al., 2016), increases in the size of probe value effects beyond the ages of 10 years of age might reflect the development and maturation of executive resources in late childhood and adolescence (Jurado & Rosselli, 2007; Waszak, Li, & Hommel, 2010).

It would also be useful for research to investigate whether probe value effects emerge in younger children. It has been suggested that at approximately 6-8 years of age, children begin to use more proactive control strategies (Blackwell & Munakata, 2014; Chatham, Frank, & Munakata, 2009; Chevalier et al., 2014; Elke & Wiebe, 2017). Before this, children tend to rely on more reactive strategies, responding to events only when they occur and retrieving information only when required at that specific moment in time (Chatham et al., 2009; Chevalier et al, 2014). As such, it is unclear whether younger children would be able to make use of probe value information, or indeed direct their attention in response to any information that identifies a particular item as being more important or goal-relevant (e.g. visual cues or probe frequency; Chevalier et al., 2014).

The current study, as with other work examining reward-based prioritisation (e.g. Allen & Ueno, 2018; Atkinson et al., 2018; Berry et al., 2018; Hitch et al., 2018; Hu et al., 2014), used a primary task assessing memory for binding between features (color and shape). Although there has not yet been a systematic examination of changes in binding ability throughout childhood, the temporary retention of color-location bindings has been demonstrated in infants as young as 7.5 months (Oakes, Ross-Sheehy, & Luck, 2006).

Working memory for different types of feature bindings (e.g. color-location, object-background, verbal-spatial, or visual-auditory) appears to show some developmental improvement as children get older and is less accurate than in young adults (e.g. Brockmole & Logie, 2013; Cowan, Naveh-Benjamin, Kilb, & Saults, 2006; Cowan, Saults, & Morey, 2006; Darling, Parker, Goodall, Havelka, & Allen, 2014; Wang, Allen, Lee, & Hsieh, 2015). However, at least when considering the kind of visual feature binding examined in the present study, such changes primarily reflect broader improvement in working memory function, rather than clear and distinct developmental trajectories for the bindings themselves. Overall, we observed moderate age group differences (between 7-8, and 9-10 years) in at least some of our experimental conditions, though without accompanying tasks measuring feature memory, it is not possible to clearly ascertain whether such effects are binding-specific. Regarding the primary focus of the current study, we would not necessarily expect prioritization effects to vary between feature and binding conditions, as attentional control appears to be of equivalent importance across such tasks (e.g. Allen et al., 2006, 2014). It would nevertheless be informative to explore how value-based selective attention might influence working memory across a range of different paradigms assessing different types of feature and conjunction, in children and in adults.

As part of the motivational context within the current experiments, children were presented with feedback that did not accurately reflect their true performance on the task. This was implemented in order to ensure that all children received the same feedback and that this did not affect their behaviour in subsequent trials. For instance, if a child was told multiple times that they were performing poorly, they may give up on the task and simply guess. Similarly, if a child was told that they were answering correctly on all of the trials, they may decide that it is not worth trying to prioritise the more valuable item. Either of these responses would have introduced additional error variance, making it more difficult to assess whether children are able to prioritize valuable information. It would, however, be useful for additional research to investigate the effects of prioritisation when true feedback is provided, and to examine the impacts of true versus false feedback on children's working memory performance more generally.

In many real-world tasks, information is presented which can differ in value or importance. For instance, in classroom settings, children often have competing demands on their attention, and will need to prioritise information or instructions that will enable them to complete tasks efficiently and successfully. For example, children are often given sequences of instructions to remember and implement, where they may have to prioritise certain steps within the sequence before successful completion of other aspects of a task (Gathercole, Durling, Evans, Jeffcock, & Stone, 2008; Gathercole, Lamont, & Alloway, 2006; Jaroslawska, Gathercole, Logie, & Holmes, 2016; Waterman, Atkinson, Aslam, Holmes, Jaroslawska, & Allen, 2017) Investigating how and when children are able to engage in prioritisation is therefore of potential interest to teachers and other educational professionals. Future research using more naturalistic paradigms would be useful to see how these findings might apply in more applied contexts.

In conclusion, the experiments presented here reveal that children aged 7-10 years can prioritize more valuable information in WM provided that they are sufficiently motivated to do so. This ability was observed across both sequential and simultaneous displays, with boosts of a similar size across younger (7-8-year-old) and older (9-10-year-old) children. When information was encountered sequentially, significant probe value effects were observed regardless of whether three or four items were presented. However, when information was encountered simultaneously, probe value boosts were only obtained when arrays contained four items. This suggests that children as young as 7-years-old selectively apply encoding strategies when they believe such approaches are likely to considerably improve performance and are worth the cognitive effort involved. Moving forward, it would be useful for research to investigate the effects in other age groups across childhood and adolescence, and to use examine whether effects emerge in more naturalistic settings where true feedback is provided.

References

Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2006). Is the binding of visual features in working memory resource-demanding? *Journal of Experimental Psychology: General, 135(2)*, 298–313. http://doi.org/10.1037/0096-3445.135.2.298

Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2014). Evidence for two attentional components in visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(6), 1499-1509. http://dx.doi.org/10.1037/xlm0000002

Allen, R. J., & Ueno, T. (2018). Multiple high-reward items can be prioritized in working memory but with greater vulnerability to interference. *Attention, Perception & Psychophysics*. Advanced online publication. https://doi.org/10.3758/s13414-018-1543-6

Alloway, T. P., & Alloway, R. G. (2010). Investigating the predictive roles of working memory and IQ in academic attainment. *Journal of Experimental Child Psychology*, *106*(1), 20-29. https://doi.org/10.1016/j.jecp.2009.11.003

Alloway, T. P. (2006). How does working memory work in the classroom? *Educational Research and Reviews*, *1*(4), 134-139.

Alloway, T. P., Alloway, R. G., & Wootan, S. (2014). Home sweet home: Does where you live matter to working memory and other cognitive skills? *Journal of Experimental Child Psychology*, *124*, 124-131. https://doi.org/10.1016/j.jecp.2013.11.012

Alloway, T. P., Gathercole, S. E., Kirkwood, H., & Elliott, J. (2009). The cognitive and behavioral characteristics of children with low working memory. *Child Development*, *80*(2), 606-621. https://doi.org/10.1111/j.1467-8624.2009.01282.x

Anderson, P. (2002). Assessment and development of executive function during childhood. *Child Neuropsychology : A Journal on Normal and Abnormal Development in Childhood and Adolescence*, *8*(2), 71–82. http://doi.org/10.1076/chin.8.2.71.8724

Astle, D. E., Nobre, A. C., & Scerif, G. (2012). Attentional control constrains visual short-term memory: Insights from developmental and individual differences. *Quarterly Journal of Experimental Psychology*, *65*(2), 277-294. http://dx.doi.org/10.1080/17470218.2010.492622

Atkinson, A. L., Berry E. D. J., Waterman, A. H., Baddeley, A. D., Hitch, G. J., & Allen, R. J. (2018). Are There Multiple Ways to Direct Attention in Working Memory? *Annals of the New York Academy of Science*. Advanced online publication. https://doi.org/10.1111/nyas.13634

Baddeley, A. D. (1986). *Working memory*. Oxford: Oxford University Press.

Barchard, K. A. (2015). Null Hypothesis Significance Testing Does Not Show Equivalence. *Analyses of Social Issues and Public Policy*, *15*(1), 418-421. https://doi.org/10.1111/asap.12095

Berry, E. D., Waterman, A. H., Baddeley, A. D., Hitch, G. J., & Allen, R. J. (2018). The limits of visual working memory in children: Exploring prioritization and recency effects with sequential presentation. *Developmental Psychology*, *54*(2), 240-253. http://dx.doi.org/10.1037/dev0000427

Blackwell, K. A., & Munakata, Y. (2014). Costs and benefits linked to developments in cognitive control. *Developmental Science*, *17*(2), 203-211. https://doi.org/10.1111/desc.12113

Borke, H. (1975). Piaget's mountains revisited: Changes in the egocentric landscape. *Developmental Psychology*, *11*(2), 240-243. http://psycnet.apa.org/doi/10.1037/h0076459

Brewer, R., Anthony, L., Brown, Q., Irwin, G., Nias, J., & Tate, B. (2013). Using gamification to motivate children to complete empirical studies in lab environments. In *Proceedings of the 12th International Conference on Interaction Design and Children*, 388-391. http://dx.doi.org/10.1145/2485760.2485816

Brockmole, J. R., & Logie, R. H. (2013). Age-related change in visual working memory: a study of 55,753 participants aged 8–75. *Frontiers in Psychology*, *4*, 12. https://doi.org/10.3389/fpsyg.2013.00012

Castel, A. D., Humphreys, K. L., Lee, S. S., Galván, A., Balota, D. A., & McCabe, D. P. (2011). The development of memory efficiency and value-directed remembering across the life span: A cross-sectional study of memory and selectivity. *Developmental Psychology*, *47*(6), 1553-1564. https://doi.org/10.1037/a0025623

Castel, A. D., Lee, S. S., Humphreys, K. L., & Moore, A. N. (2011). Memory capacity, selective control, and value-directed remembering in children with and without attention-deficit/hyperactivity disorder (ADHD). *Neuropsychology*, *25*(1), 15-24. https://doi.org/10.1037/a0020298

Chevalier, N. (2017). Willing to think hard? The subjective value of cognitive effort in children. *Child Development*. Advanced online publication. https://doi.org/10.1111/cdev.12805

Chevalier, N., James, T. D., Wiebe, S. A., Nelson, J. M., & Espy, K. A. (2014). Contribution of reactive and proactive control to children’s working memory performance: Insight from item recall durations in response sequence planning. *Developmental Psychology*, *50*(7), 1999-2008. http://dx.doi.org/10.1037/a0036644

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychological Bulletin*. 104, 163-191. http://psycnet.apa.org/doi/10.1037/0033-2909.104.2.163

Cowan, N. (2017). The many faces of working memory and short-term storage. Psychonomic Bulletin & Review, 24(4), 1158-1170. https://doi.org/10.3758/s13423-016-1191-6

Cowan, N., Morey, C. C., AuBuchon, A. M., Zwilling, C. E., & Gilchrist, A. L. (2010). Seven-year-olds allocate attention like adults unless working memory is overloaded. *Developmental Science*, *13*(1), 120–133. http://doi.org/10.1111/j.1467-7687.2009.00864.x

Cowan, N., Naveh-Benjamin, M., Kilb, A., & Saults, J. S. (2006). Life-span development of visual working memory: When is feature binding difficult? *Developmental Psychology*, *42*(6), 1089-1102. http://dx.doi.org/10.1037/0012-1649.42.6.1089

Cowan, N., Saults, J. S., & Morey, C. C. (2006). Development of working memory for verbal–spatial associations. *Journal of Memory and Language*, *55*(2), 274-289. https://doi.org/10.1016/j.jml.2006.04.002

Darling, S., Parker, M. J., Goodall, K. E., Havelka, J., & Allen, R. J. (2014). Visuospatial bootstrapping: Implicit binding of verbal working memory to visuospatial representations in children and adults. *Journal of Experimental Child Psychology*, *119*, 112-119. https://doi.org/10.1016/j.jecp.2013.10.004

Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia*, *44*(11), 2037–2078. http://doi.org/10.1016/j.neuropsychologia.2006.02.006

Della Sala, S., Darling, S., & Logie, R. H. (2010). Items on the left are better remembered. *The Quarterly Journal of Experimental Psychology*, *63*(5), 848-855. https://doi.org/10.1080/17470211003690672

Donaldson, M., & McGarrigle, J. (1974). Some clues to the nature of semantic development. *Journal of Child Language*, *1*(2), 185-194. https://doi.org/10.1017/S0305000900000635

Elke, S., & Wiebe, S. A. (2017). Proactive control in early and middle childhood: An ERP study. *Developmental Cognitive Neuroscience*, *26*, 28-38. https://doi.org/10.1016/j.dcn.2017.04.005

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*, 175-191. https://doi.org/10.3758/BF03193146

Gathercole, S. E., Durling, E., Evans, M., Jeffcock, S., & Stone, S. (2008). Working memory abilities and children's performance in laboratory analogues of classroom activities. *Applied Cognitive Psychology, 22*(8), 1019-1037. http://doi.org/10.1002/acp.1407

Gathercole, S. E., Lamont, E., & Alloway, T. P. (2006). Working Memory in the Classroom. In *Working Memory and Education,* 219–240. http://doi.org/10.1016/B978-012554465-8/50010-7

Gathercole, S. E., Pickering, S. J., Ambridge, B., & Wearing, H. (2004). The structure of working memory from 4 to 15 years of age. *Developmental Psychology*, *40*(2), 177-190. http://dx.doi.org/10.1037/0012-1649.40.2.177

Gathercole, S. E., Pickering, S. J., Knight, C., & Stegmann, Z. (2004). Working memory skills and educational attainment: Evidence from national curriculum assessments at 7 and 14 years of age. *Applied Cognitive Psychology*, *18*(1), 1-16. https://doi.org/10.1002/acp.934

Gorgoraptis, N., Catalao, R. F., Bays, P. M., & Husain, M. (2011). Dynamic updating of working memory resources for visual objects. *Journal of Neuroscience*, *31*(23), 8502-8511. https://doi.org/10.1523/JNEUROSCI.0208-11.2011

Hitch, G. J. Hu, Y., Allen, R. J. & Baddeley, A. D. (2018). Competition for the Focus of Attention in Visual Working Memory: Perceptual Recency vs Executive Control. *Annals of the New York Academy of Science*. Advanced online publication. https://doi.org/10.1111/nyas.13631

Holmes, J., & Adams, J. W. (2006). Working memory and children's mathematical skills: Implications for mathematical development and mathematics curricula. *Educational Psychology*, *26*(3), 339-366. https://doi.org/10.1080/01443410500341056

Hu, Y., Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2016). Executive control of stimulus-driven and goal-directed attention in visual working memory. *Attention, Perception, & Psychophysics*. http://doi.org/10.3758/s13414-016-1106-7

Hu, Y., Hitch, G. J., Baddeley, A. D., Zhang, M., & Allen, R. J. (2014). Executive and perceptual attention play different roles in visual working memory: evidence from suffix and strategy effects. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(4), 1665–1678. http://doi.org/10.1037/a0037163

Jaroslawska, A. J., Gathercole, S. E., Logie, M. R., & Holmes, J. (2016). Following instructions in a virtual school: Does working memory play a role? Memory & Cognition, 44(4), 580–589. http://doi.org/10.3758/s13421-015-0579-2

Jurado, M. B., & Rosselli, M. (2007). The elusive nature of executive functions: a review of our current understanding. *Neuropsychology Review*, *17*(3), 213-233. https://doi.org/10.1007/s11065-007-9040-z

Light, P. H., Buckingham, N., & Robbins, A. H. (1979). The conservation task as an interactional setting. *British Journal of Educational Psychology*, *49*(3), 304-310. https://doi.org/10.1111/j.2044-8279.1979.tb02430.x

Matsukura, M., Luck, S. J., & Vecera, S. P. (2007). Attention effects during visual short-term memory maintenance: protection or prioritization? *Perception & Psychophysics*, *69*(8), 1422-1434. http://dx.doi.org/10.3758/PP.70.3.571

Ministry of Housing, Communities & Local Governments. (2015). English indices of deprivation 2015. Retrieved from https://www.gov.uk/government/statistics/english-indices-of-deprivation-2015

Morey, R. D., Rouder, J. N., Jamil, T., Urbanek, S., Forner, K., & Ly, A. (2018). Package 'BayesFactor' (Version 0.9.12-4.2. Retrieved from https://cran.r-project.org/web/packages/BayesFactor/BayesFactor.pdf

Mulder, J., & Wagenmakers, E. J. (2016). Editors' introduction to the special issue "Bayes factors for testing hypotheses in psychological research: Practical relevance and new developments". *Journal of Mathematical Psychology*, *72*, 1-5. https://doi.org/10.1016/j.jmp.2016.01.002

Nobre, A. C., Griffin, I. C., & Rao, A. (2008). Spatial attention can bias search in visual short-term memory. *Frontiers in Human Neuroscience*, *2*, 4. https://doi.org/10.3389/neuro.09.004.2007

Oakes, L. M., Ross-Sheehy, S., & Luck, S. J. (2006). Rapid development of feature binding in visual short-term memory. *Psychological Science*, *17*(9), 781-787. https://doi.org/10.1111/j.1467-9280.2006.01782.x

Piaget, J., & Inhelder, B. (1956). The child's conception of space. London: Routledge & Regan Paul.

Peirce, J. W. (2007). PsychoPy-Psychophysics software in Python. *Journal of Neuroscience Methods*, 162(1-2), 8–13. https://doi.org/10.1016/j.jneumeth.2006.11.017

R Core Team. (2016). R: a language and environment for statistical computing. Accessed July 7, 2018.

Rouder, J. N., Morey, R. D., Speckman, P. L., & Province, J. M. (2012). Default Bayes factors for ANOVA designs. Journal of Mathematical Psychology, 56(5), 356–374. http://doi.org/10.1016/j.jmp.2012.08.001

Rouder, J. N., Morey, R. D., Verhagen, J., Swagman, A. R., & Wagenmakers, E. J. (2017). Bayesian analysis of factorial designs. *Psychological Methods*, *22*(2), 304-321. http://dx.doi.org/10.1037/met0000057

Shimi, A., Nobre, A. C., Astle, D., & Scerif, G. (2014). Orienting Attention Within Visual Short-Term Memory: Development and Mechanisms. *Child Development*, *85*(2), 578–592. http://doi.org/10.1111/cdev.12150

Shimi, A., & Scerif, G. (2017). Towards an integrative model of visual short-term memory maintenance: Evidence from the effects of attentional control, load, decay, and their interactions in childhood. *Cognition*, *169*, 61-83. https://doi.org/10.1016/j.cognition.2017.08.005

Wang, S., Allen, R. J., Lee, J. R., & Hsieh, C. E. (2015). Evaluating the developmental trajectory of the episodic buffer component of working memory and its relation to word recognition in children. *Journal of Experimental Child Psychology*, *133*, 16-28. https://doi.org/10.1016/j.jecp.2015.01.002

Waszak, F., Li, S. C., & Hommel, B. (2010). The development of attentional networks: Cross-sectional findings from a life span sample. *Developmental Psychology*, *46*(2), 337-349. https://doi.org/10.1037/a0018541

Waterman, A. H., Atkinson, A. L., Aslam, S. S., Holmes, J., Jaroslawska, A., & Allen, R. J. (2017). Do actions speak louder than words? Examining children’s ability to follow instructions. *Memory & Cognition*, *45*(6), 877-890. https://doi.org/10.3758/s13421-017-0702-7

Figure Legends

Figure 1. The experimental paradigm used in Experiment 1, with a 4-item trial as an illustrative example. Figure not to scale.

Figure 2. Sample images from the alien story and game used in each experiment. Before the start of the task, children were told a story about an alien (e.g. A and B; see supplementary material for the full story). After every 10 experimental trials, the alien would appear and tell the child how much energy they had collected (C). They then played the 'zap an alien' game at the end of each session (D).

Figure 3. Mean proportion correct in Experiment 1 as a function of probe value, serial position, and age group in the 3-item (A) and 4-item conditions (B). Error bars denote standard error, and the dotted line indicates chance performance.

Figure 4. Accuracy at SP1 in Experiment 1 (A) and the top-left position in Experiment 2 (B) as a function of probe value and memory load. Performance is collapsed across age groups, as there were no interactions containing this factor in either experiments.

Figure 5. The experimental paradigm used in Experiment 2, with a 4-item trial as an illustrative example. The array was presented for 1500ms in the 3-item blocks and 2000ms in the 4-item blocks. Figure not to scale.

Figure 6. Mean proportion correct (and SE) in Experiment 2 as a function of probe value, spatial location and age group in the 3-item (A) and 4-item (B) conditions.

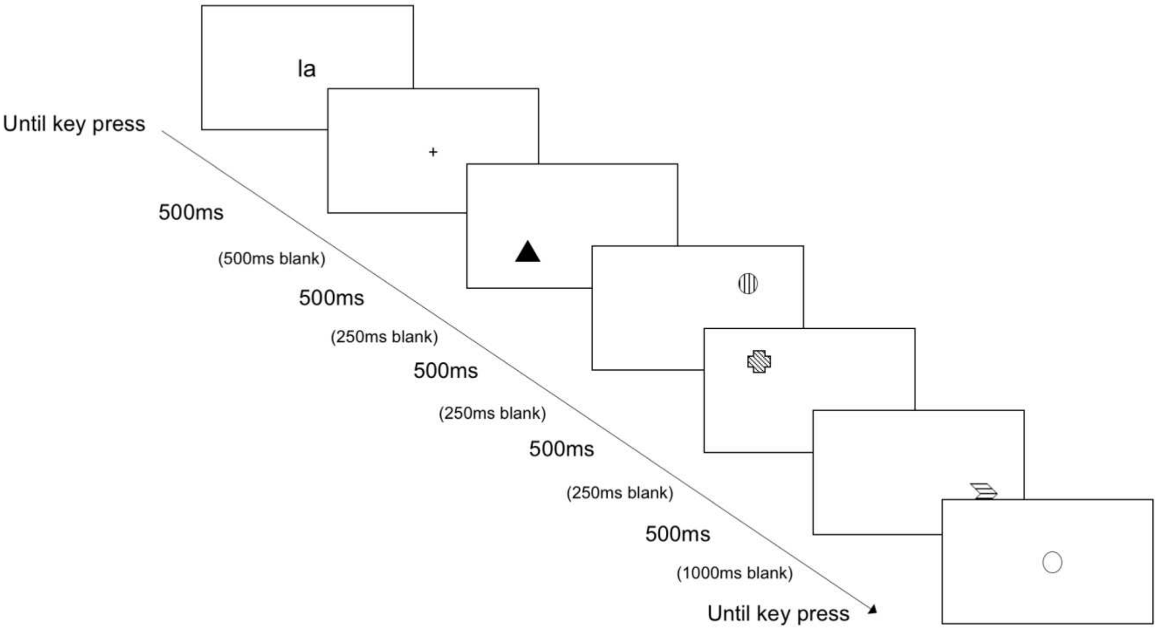
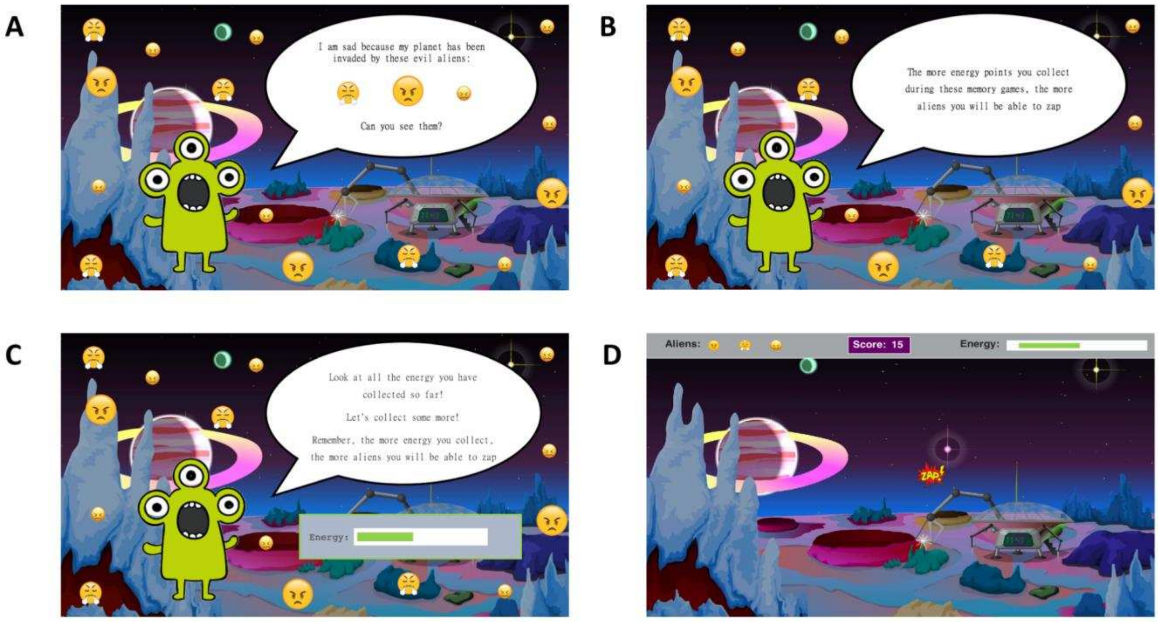

la
Until key press
+
500ms
(500ms blank)
500ms
(250ms blank)
500ms
(250ms blank)
500ms
(250ms blank)
500ms
(1000ms blank)
Until key press

Figure 1



I am sad because my planet has been invaded by these evil aliens:

Can you see them?

The more energy points you collect during these memory games, the more aliens you will be able to zap

Look at all the energy you have collected so far!

Let's collect some more!

Remember, the more energy you collect, the more aliens you will be able to zap

Figure 2

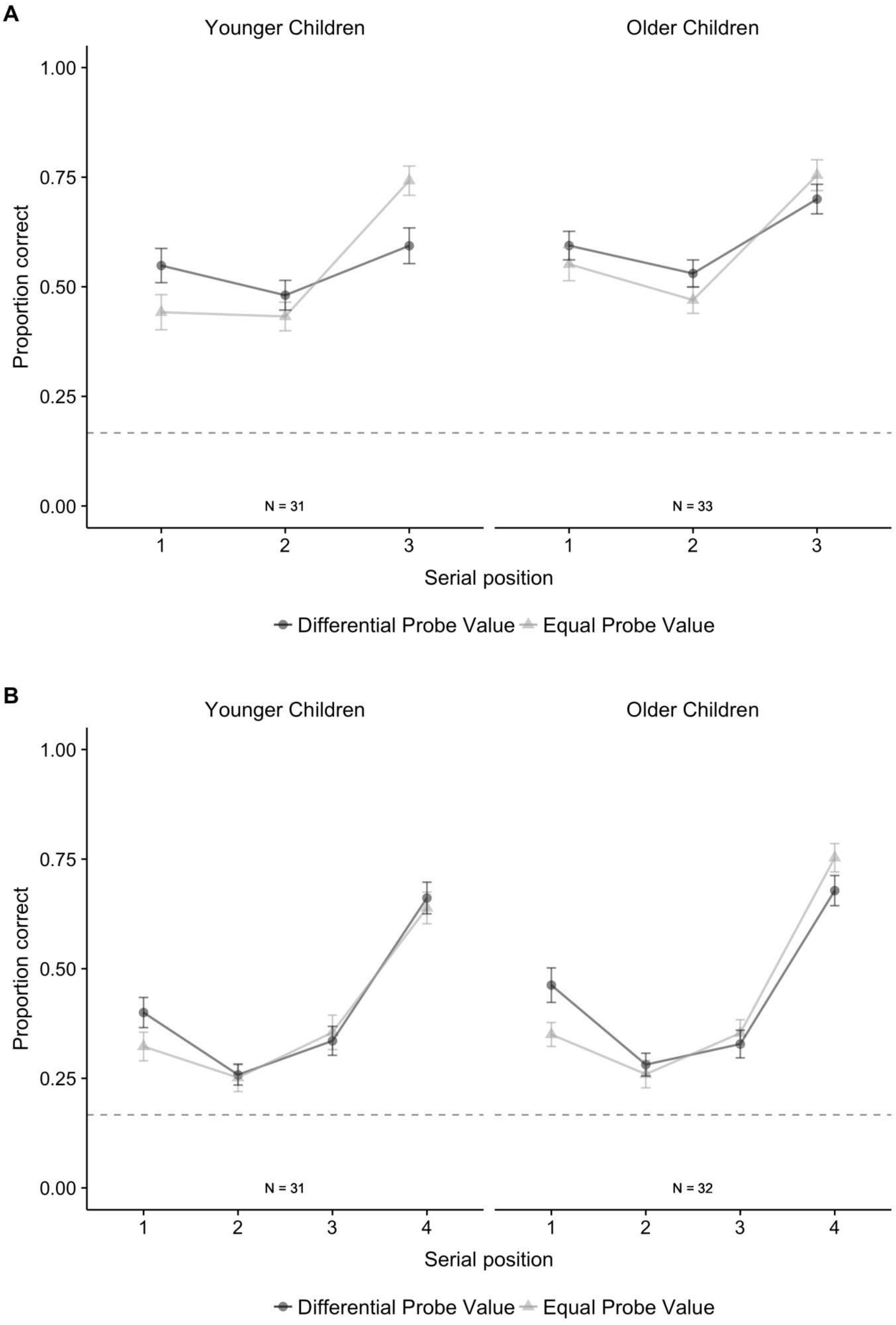

A
Younger Children
Older Children
Proportion correct
1.00
0.75
0.50
0.25
0.00
N = 31
N = 33
1
2
3
Serial position
Differential Probe Value
Equal Probe Value
B
Younger Children
Older Children
Proportion correct
1.00
0.75
0.50
0.25
0.00
N = 31
N = 32
1
2
3
4
Serial position
Differential Probe Value
Equal Probe Value

Figure 3

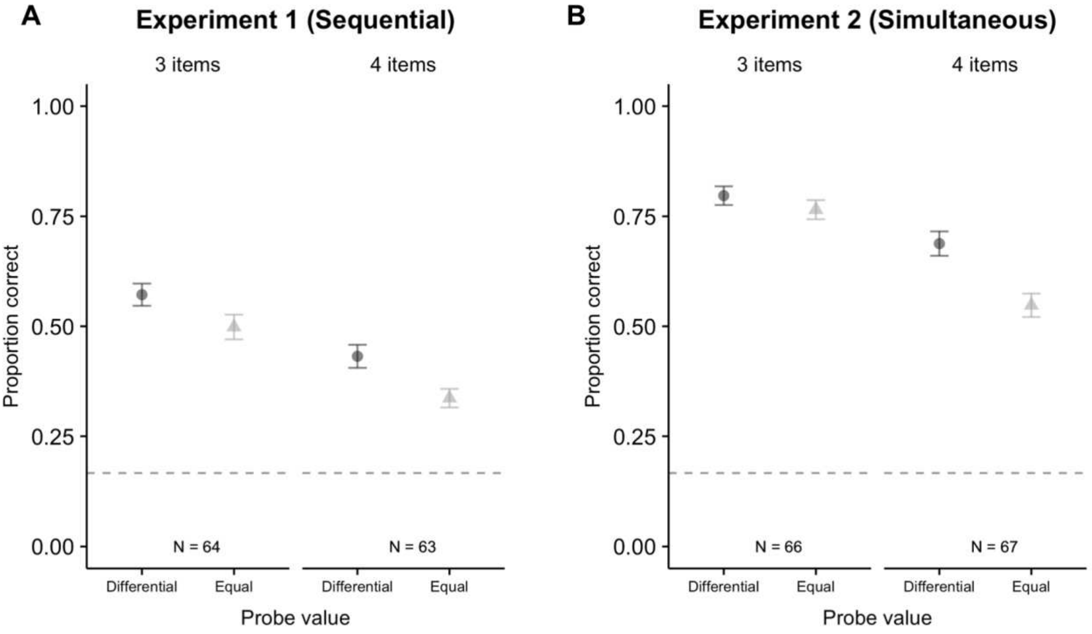

A
Experiment 1 (Sequential)
3 items
4 items
B
Experiment 2 (Simultaneous)
3 items
4 items
Proportion correct
1.00
0.75
0.50
0.25
0.00
N = 64
N = 63
N = 66
N = 67
Differential
Equal
Probe value

Figure 4

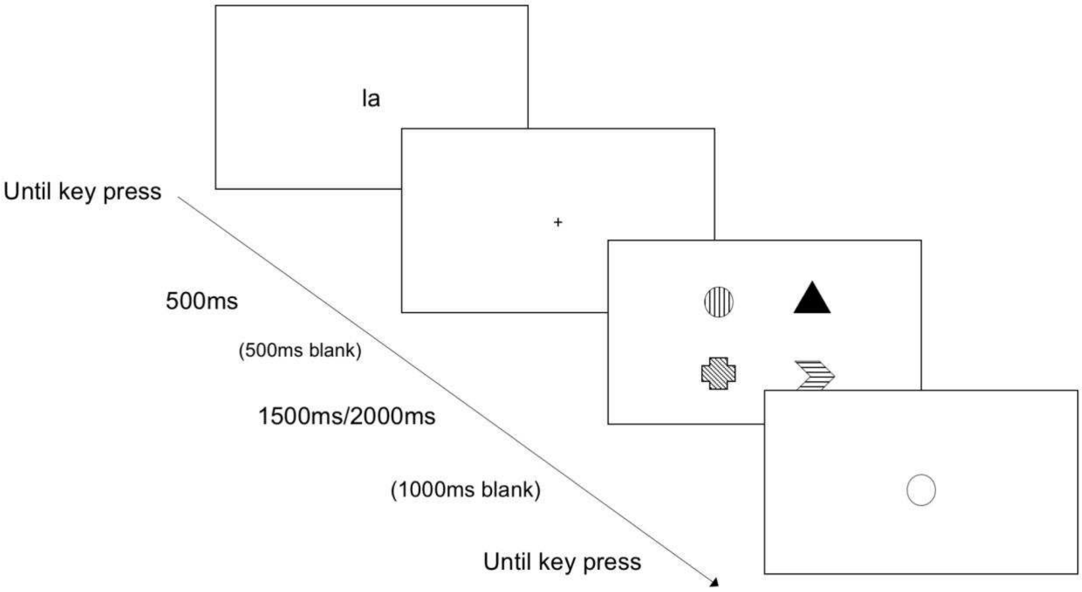

la
+
Until key press
500ms
(500ms blank)
1500ms/2000ms
(1000ms blank)
Until key press

Figure 5

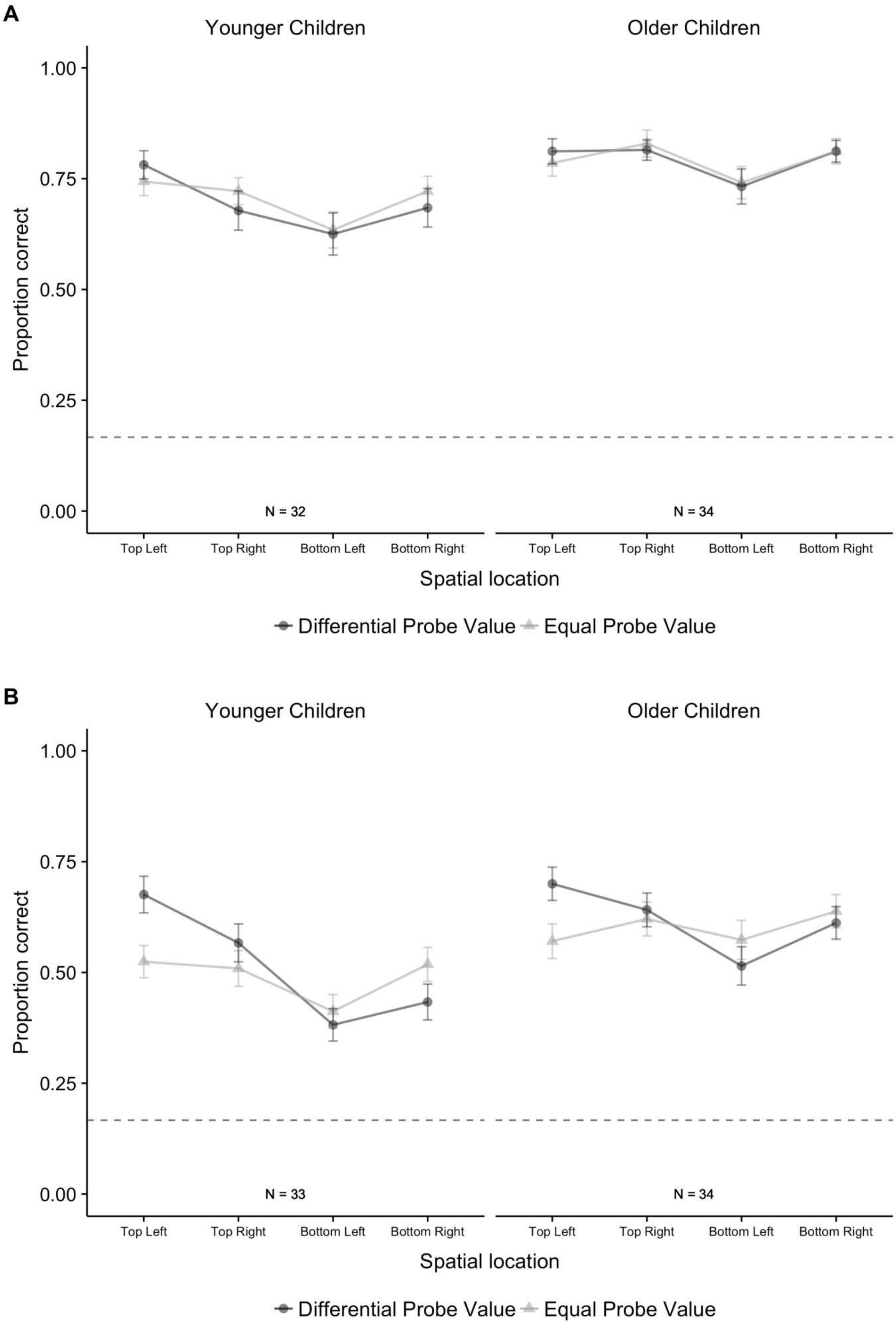

A
Younger Children
Older Children
Proportion correct
1.00
0.75
0.50
0.25
0.00
N = 32
N = 34
Top Left
Top Right
Bottom Left
Bottom Right
Spatial location
Differential Probe Value
Equal Probe Value
B
Younger Children
Older Children
Proportion correct
1.00
0.75
0.50
0.25
0.00
N = 33
N = 34
Top Left
Top Right
Bottom Left
Bottom Right
Spatial location
Differential Probe Value
Equal Probe Value

Figure 6

Table 1

Table 1. Mean accuracy (and SE) in Experiment 1 as a function of probe value, memory load and SP, collapsed across age group. N = 64 for the 3-item conditions and N = 63 for the 4-item conditions.

		SP1	SP2	SP3	SP4
3 items	Differential probe value	.57 (.03)	.51 (.02)	.65 (.03)	-
	Equal probe value	.50 (.03)	.45 (.02)	.75 (.02)	-
4 items	Differential probe value	.43 (.03)	.27 (.02)	.33 (.02)	.67 (.02)
	Equal probe value	.34 (.02)	.26 (.02)	.35 (.02)	.70 (.03)

Table 2

Table 2. Mean accuracy (and SE) in Experiment 2 as a function of probe value, memory load and SL, collapsed across age group. N = 66 for the 3-item conditions and N = 67 for the 4-item conditions.

		TL	TR	BL	BR
3 items	Differential probe value	.80 (.02)	.75 (.03)	.68 (.03)	.75 (.03)
	Equal probe value	.77 (.02)	.78 (.02)	.69 (.03)	.77 (.02)
4 items	Differential probe value	.69 (.03)	.60 (.03)	.45 (.03)	.52 (.03)
	Equal probe value	.55 (.03)	.57 (.03)	.49 (.03)	.58 (.03)

TL = top-left, TR = top-right, BL = bottom-left, BR = bottom-right