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Young Children Monitor the Fidelity of Visual Working Memory

Jessica B. Applin and Melissa M. Kibbe
Boston University

The ability to concurrently maintain representations of multiple objects and their locations in visual working memory is severely limited. Thus, making optimal use of visual working memory requires continual, moment-to-moment monitoring of its fidelity: High-fidelity representations can be relied upon, whereas incomplete or fuzzy representations must be refreshed or ignored. Previous work showed that adults track the fidelity of their visual working memory. Here, we asked whether children, whose capacities for visual working memory are undergoing protracted development, also can do so. We showed 5- and 6-year-olds sets of 2–5 single-feature (Experiment 1) or multifeature (Experiment 2) objects hidden simultaneously in separate locations. We asked children to recall the location of one of the objects, then bet 0–3 resources on whether they were correct. In both experiments, we found that children's confidence in their visual working memory, as indexed by their bets, was correlated with their accuracy on each trial, controlling for task difficulty: Children bet higher when they were correct and lower when they were incorrect. Our results suggest that metacognitive awareness of the representational limits of visual working memory may emerge before working memory reaches stable capacity.

Keywords: metacognition, object cognition, visual working memory, representation, confidence judgments

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Visual working memory allows us to briefly store and manipulate incoming visual information (e.g., Cowan, 2014; Cowan et al., 2003; Gathercole & Baddeley, 1990; Just & Carpenter, 1992; Siegel & Linder, 1984). We rely on visual working memory to keep track of previously viewed information while we gather new information (Henderson & Hollingworth, 2003; Hollingworth & Henderson, 2002). However, visual working memory is severely limited: Adults can store only small amounts of visual information in working memory at once (typically estimated at four or five simple items; e.g., Cowan, 2001; Luck & Vogel, 1997; Phillips, 1974).

Because visual working memory is limited, the ability to monitor the quality of our representations is critical to enable us to make decisions about when to rely on working memory and when not to (Droll & Hayhoe, 2007; Epelboim & Suppes, 2001; Flavell, 1971; Kibbe & Kowler, 2011; Touron, Oransky, Meier, & Hines, 2010). Because the contents of visual working memory are continually updated, successfully tracking the fidelity of our representations requires dynamic, moment-to-moment monitoring. Recent work suggests that adults have this ability (Bona, Cattaneo, Vecchi, Soto, & Silvanto, 2013; Rademaker, Tredway, & Tong, 2012; van den Berg, Yoo, & Ma, 2017). In these studies, adults were briefly shown simple visual stimuli. After a short retention interval, they were asked to rate their confidence in their memory for the stimuli and were also probed on their memory for the stimuli. Adults' confidence ratings in their visual working memory representations predicted their accuracy in both working memory recall (Rademaker et al., 2012; van den Berg et al., 2017) and recognition (Bona et al., 2013) tasks. These results suggest that adults can closely monitor the reliability of the contents of their visual working memories even as the contents change from trial to trial.

Although research has examined adults' metacognitive awareness of representational limits for visual information held in working memory, less is known about the development of this ability in children. In contrast to adults, whose visual working memory capacity is relatively stable (Xu, Adam, Fang, & Vogel, 2018), children's visual working memory undergoes rapid development during early to middle childhood (Cowan, 2016; Pailian, Libertus, Feigenson, & Halberda, 2016; Riggs, McTaggart, Simpson, & Freeman, 2006; Riggs, Simpson, & Potts, 2011; Simmering, 2012). Developmental change in visual working memory adds another layer of uncertainty to the task of monitoring the information stored in one's working memory: Not only is visual working memory limited, but those limitations are changing across developmental time. Furthermore, the process of monitoring cognitive uncertainty itself draws on working memory resources (Coutinho et al., 2015; Geurten, Catale, & Meulemans, 2016; Smith,

Jessica B. Applin, Department of Psychological and Brain Sciences, Boston University; Melissa M. Kibbe, Department of Psychological and Brain Sciences and Center for Systems Neuroscience, Boston University.

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Correspondence concerning this article should be addressed to Melissa M. Kibbe, Department of Psychological and Brain Sciences, Boston University, 64 Cummington Mall, Boston, MA 02215. E-mail: kibbe@bu.edu

Coutinho, Church, & Beran, 2013). This may pose a challenge for children, whose working memory is more limited than adults and who therefore may not have the working memory resources to both maintain representations and adequately monitor their visual working memories. Successfully tracking the fidelity of working memory also involves dynamic monitoring as the contents of visual working memory change, requiring executive functions like set shifting (Mäntylä, Rönnlund, & Kliegel, 2010), which are still developing in young children (Diamond, 2006; Zelazo et al., 2003).

Yet, previous work has shown that some of the cognitive processes necessary for monitoring visual working memory may be in place by age 4. First, children are capable of judging how well they learned studied information (e.g., Allwood, 2010; Destan, Hembacher, Ghetti, & Roebers, 2014; Hembacher & Ghetti, 2014; Liu et al., 2018; Lyons & Ghetti, 2011, 2013; Roebers, Gelhaar, & Schneider, 2004). For example, Destan et al. (2014) gave 5-, 6-, and 7-year-old children a self-paced task in which they were asked to learn the meanings of Japanese characters. They were then asked to identify the correct definition for the learned characters and to provide confidence judgments for their answers. Children's confidence judgments were higher for correctly identified items compared with incorrectly identified items, suggesting they had monitored the quality of their learning for each character.

Second, children can judge the quality of episodic memories. For example, Liu, Su, Xu, and Pei (2018) asked 3- to 5-year-old children to memorize arrays of pictures. Children were allowed to view the arrays until they felt that they had memorized them and were then asked to recognize whether different series of images were part of the study set. Children also were asked to place bets on whether they were correct or incorrect. By age 4.5, children bet high when they were correct and low when they were incorrect, suggesting retrospective monitoring of episodic memories in a self-paced memorization task. Children as young as 3 years have been shown to be capable of retrospective monitoring of episodic memories when the task involves a more implicit measure of metacognitive awareness (accepting or declining to respond to trials during a later recognition task; Balcomb & Gerken, 2008). Together, this work suggests that young children are capable of metacognitive monitoring of longer-term, less limited, and less developmentally volatile memory systems.

Third, there is some evidence that children can monitor moment-to-moment confidence in representational precision during *perceptual* discrimination tasks (Baer, Gill, & Odic, 2018; Vo, Li, Kornell, Pouget, & Cantlon, 2014). For example, Vo and colleagues showed 5- to 8-year-olds two arrays containing different quantities of dots and asked them to select which array had more dots. They manipulated the difficulty of the discrimination task by varying the ratio between the dot arrays. On each trial, after providing their answer, children were asked to place a bet about how certain they were that they were correct. Children could bet either one or three tokens. If they were correct, children would gain the number of tokens they bet; but if they were incorrect, they would lose those tokens. Vo and colleagues found that children bet higher when they were correct and lower when they were incorrect, suggesting that children were monitoring moment-to-moment representational uncertainty in a perceptual domain. Further, even young infants show some ability to monitor moment-to-moment uncertainty: In a task in which infants were asked to retrieve a toy hidden in one of two locations, infants were more likely to ask for help from their parent if they themselves did not see where the toy was hidden (Goupil, Romand-Monnier, & Kouider, 2016).

Can young children monitor the fidelity of their visual working memories? In two experiments, we investigated this question in 5- to 6-year-old children. We chose to test 5- to 6-year-olds because previous work suggested that these children show metacognitive awareness in learning and episodic memory (e.g., Balcomb & Gerken, 2008; Destan et al., 2014; Hembacher & Ghetti, 2014; Liu et al., 2018) and perception (Baer et al., 2018; Vo et al., 2014), but their visual working memory capacities are still developing (Pailian et al., 2016; Simmering, 2012). Children observed sets of two, three, four, or five colored beads being hidden in separate locations. We then probed children's visual working memory for the location of one of the objects in the array. In Experiment 1, the objects were defined by a single feature (color). In Experiment 2, the objects were defined by feature conjunctions (color and shape). To succeed, children needed to bind features to specific locations (Experiment 1) or bind feature conjunctions to specific locations (Experiment 2). Thus, we manipulated the difficulty of the working memory task both within subjects (number of objects hidden: two to five) and between experiments (complexity of the objects: single features or feature conjunctions; see Kibbe, 2015; Kibbe & Leslie, 2013; Riggs et al., 2011; Saiki, 2003; Wheeler & Treisman, 2002) in order to yield variability in children's responses.

To measure children's ability to monitor the fidelity of their visual working memories, we gave children a set of resources (Starburst candies, emoji erasers, or stickers) and told children that they could earn more resources by playing our "hide-and-seek" game. On each trial, after children indicated their response in the visual working memory task, children were given the opportunity to bet zero, one, two, or three of their resources. Children were told that if they were correct, they would gain as many resources as they had bet, but if they were incorrect, they would lose the resources they bet. We opted not to give children feedback on each trial because we did not want children's bets on each trial to be influenced by their remaining resources (i.e., becoming risk averse when resources are running low, becoming more risky when resources are plentiful) or by an emotional response to gaining or losing resources on the previous trial. We predicted that if children can monitor the fidelity of their visual working memories, across both experiments, children's accuracy at the visual working memory task should correlate with their bets, controlling for task difficulty: Children's bets should be higher when they are correct and lower when they are incorrect.

In addition to our primary aim of examining children's ability to monitor their visual working memories, we also were interested in children's performance on our visual working memory task itself. Much of the research on children's visual working memory capacity in this age range has used recognition-based change-detection tasks and computer-generated displays (e.g., Pailian et al., 2016; Simmering, 2012). Our task, in contrast, required children to recall the locations of occluded objects (see Kibbe, 2015, for discussion). We therefore were interested in using children's performance in our task to gain additional insights into capacity limits for tracking multiple occluded objects in this age group. We predicted children's accuracy would be above chance at smaller set sizes and that performance would decline as set size increased, consistent with previous results using change detection. However, we did not have specific predictions about the impact of set size on children's performance. Previous work found that the precision of visual working memory increases with development (Guillory, Gliga, & Kaldy, 2018; Sarigiannidis, Crickmore, & Astle, 2016), as does the ability to bind feature and location information in visual working memory (Kibbe & Leslie, 2013; Simmering & Wood, 2017). Children are estimated to be able to hold anywhere from two to four single-feature items or two multifeature items in visual working memory during a change-detection task by age 5–6 (Pailian et al., 2016; Riggs et al., 2006; Simmering, 2012; Simmering & Wood, 2017) and around three multifeature objects by age 7 (Burnett Heyes, Zokaei, van der Staaij, Bays, & Husain, 2012; Riggs et al., 2011). Our task required children to track objects into occlusion and to recall the locations of objects, which may impose different demands on visual working memory (Kibbe, 2015). We predicted that children's accuracy would be higher in Experiment 1, in which they had to track single-feature objects, versus Experiment 2, in which they had to track feature conjunctions (e.g., Wheeler & Treisman, 2002).

Finally, we were interested in whether children's visual working memory and/or their ability to monitor their visual memories develops across our age range. We predicted that both visual working memory performance and metacognitive monitoring of visual working memory would increase with development.

Experiment 1

Method

Participants. Participants were 25 children, aged 5 to 6 years old (mean [M] age = 69.1 months, range = 60.1–83.6 months; 15 girls). We conducted a power analysis using G*Power 3.1 to determine a sufficient sample to detect a difference in children's bets on trials in which they were correct versus incorrect (paired-samples t test, two-tailed, $\alpha = .05$). A previous article (Vo et al., 2014) that used betting to assess children's representational uncertainty found large effect sizes ($d > .8$) for this comparison. Our power analysis with $1\text{-}\beta = .95$ and $d = .8$ yielded a suggested sample size of $n = 23$. We opted for a target sample size of $n = 24$ children. The final sample of $n = 25$ was the result of overscheduling. One additional child was tested but was excluded from analysis because of a video malfunction that prevented us from being able to code the child's responses.

Parents reported their children as Black (2), Asian (4), Pacific Islander (1), White (16), or declined to report (2). Of these participants, four were Hispanic/Latinx. Twenty-two of the 25 participants came from households with at least one parent who had a college degree or higher. Participants were recruited from the greater Boston area through phoning lists and family events. Children received a small gift for their participation.

Both Experiments 1 and 2 were approved by the Boston University Institutional Review Board. We obtained informed consent from all caregivers.

Materials. Materials for betting (see Figure 1) included two clear jars (10 cm × 7.5 cm), a white dry-erase tag (on which the child's first initial was written during the study), a tag with a piggy bank image, and a black foam-core occluder (20.5 cm × 34 cm). Children could place bets using 2.5 cm × 2.5 cm white foam-core "tokens," which represented the resource they were betting (either

Figure 1. Materials used for betting in Experiments 1 and 2. See the online article for the color version of this figure.

Starburst candies, emoji erasers, or star stickers). Prior to the experiment, caregivers selected the resource that they thought would be most motivating to their child (without asking their child) by checking a box on a questionnaire.

For the visual working memory task (see Figure 2), we used an 11.5 cm × 57.5 cm × 18 cm black box with six identical 12-oz red plastic cups embedded in it. The box was open in the front so that children could see that each cup was a separate hiding location. The top of the box had six openings, one for each cup, and these openings could be covered by a piece of black felt that was attached to a black bar. Brown felt disks attached to the black felt cover served as place markers for each opening once the openings were covered. On each trial, the experimenter hid two to five different-colored plastic 2.5-cm beads (yellow, green, blue, red, or purple), each in its own cup. To probe children's recall for the locations of the beads, we used a set of five cards, each depicting a color corresponding to each bead.

Procedure. Children were seated at a small table across from an experimenter in a quiet room in the laboratory. The experiment proceeded in three phases: betting introduction, practice trials, and test trials.

Betting introduction. Children were first shown two jars each containing 12 resources (either candies, erasers, or stickers, selected by caregivers before the experiment). The experimenter then said, "See these two jars? Right now, they both have the same amount of [resources]. Which of these do you want to be your jar?" Children were not explicitly told how many resources were in each jar and could not count the resources, but they were able to see roughly how many were in each jar. The experimenter placed the tag with the child's initial on their selected jar and placed the piggy bank tag on the other jar. The experimenter then explained to children, "All these [resources] in your jar, they're yours to take home and keep. But first, I want to give you a chance to earn more [resources] to add to your jar." She then told children that they would play a game in which she would hide different-colored beads and then ask the child to remember where she hid them. She told children that they would then get a chance to bet on their answer.

The experimenter then explained how betting would work. She showed children the three white tokens and told children that they would use the tokens to bet, but that real resources would be transferred between their jar and the bank. Children were told they could bet zero to three resources on each turn and that they should

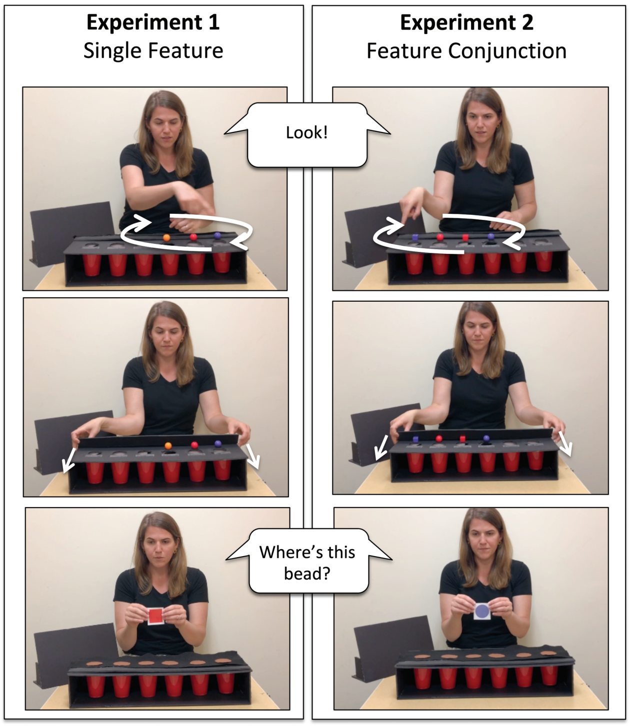

Figure 2. Example test trials from Experiment 1 (left panel) and Experiment 2 (right panel). The left panel depicts a Set Size 3 trial from Experiment 1, in which three different-colored beads were hidden, and children were asked to recall the location of the red bead. The right panel depicts a Set Size 4 trial from Experiment 2, in which four two-feature beads were hidden, and children were asked to recall the location of the Purple + Round bead. After children gave their responses, they were invited to bet on whether they were correct. The experimenter then made the appropriate transfer (either from the bank to their cup if they were correct, or vice versa if they were incorrect) behind the occluder located on the experimenter's right (out of children's view). Children did not receive feedback during test trials. These photographs are published with the consent of the first author. See the online article for the color version of this figure.

bet according to how sure they were about their answer. They were told that if they were correct, they would keep the resources they bet and earn as many more resources, but if they were wrong, they would lose the resources they bet. The full script is available in the online supplemental materials.

Practice trials. Practice trials served both to introduce children to the visual working memory task and give them practice with betting. The experimenter brought out the beads, the bead box, and the color cards. The labeled jars were placed to the right side of the box, in children's view.

The first practice trial was a Set Size 2 trial. The experimenter placed two different-colored beads simultaneously on top of the box in front of two adjacent cups. To ensure that the child observed the beads before they were hidden, the experimenter drew the child's attention to the array by circling her index finger around the beads and saying, "Look!" Then she pushed the felt bar forward, knocking the beads into their respective cups and covering all of the cups at once. The entire array was visible for ~3 s, regardless of set size. After the objects were hidden, the experimenter immediately probed children's memory for the location of one of the beads by showing children a card corresponding to the bead's color and asking, "Where is this bead?" Total retention time was ~2 s. Children selected their response by pointing to a cup. After children gave a response, the experimenter asked, "How many [resources] do you want to bet?" Children indicated their bets using the white tokens.

Children were given feedback during practice trials. The experimenter said, "Let's see if you were right," and retrieved the bead from the selected location. If the child answered correctly, the experimenter said, "You were right! So, because you bet [X resources] and you were right, I am going to take [X resources] from the bank and put them into your jar." If the child answered incorrectly, the experimenter said, "Oops, that's not right. Okay, so because you bet [X resources] and you were wrong, I am going to take [X resources] from your jar and put them into the bank." Transfer of the resources from one jar into the other was done in children's view so that they could directly observe the outcomes of their bets. Twenty-one out of 25 children (84%) selected the correct location. Children's mean bet was 2.04 resources (standard deviation [*SD*] = 1.02).

The second practice trial was a Set Size 4 trial and proceeded similarly to the first practice trial, except that four beads were hidden. Children again were given the opportunity to bet and were given feedback about whether they were correct or incorrect and the outcomes of their bets. Fifteen out of 25 children (60%) answered correctly, and their mean bet was 1.8 resources (*SD* = 1).

Test trials. Test trials proceeded similarly to the practice trials, except that children did not receive feedback on their responses, and the outcomes of their bets were hidden. Before beginning the test trials, the experimenter placed the black occluder in front of the betting jars and told children that the rest of the game was going to remain a secret. Children then completed four blocks of three trials each: one block each of Set Sizes 2, 3, 4, and 5. Trial blocks were yoked such that children completed the Set Sizes 2 and 3 blocks first followed by Set Sizes 4 and 5, with block order counterbalanced within each yoked pair, resulting in four possible orders. We opted to present the smaller set sizes first to prevent children from becoming fatigued by task difficulty early in the experiment.

On each trial, the experimenter hid the beads in the outermost cups of the box and alternated the side of placement across trials to limit proactive interference from trial to trial. For example, on one Set Size 2 trial, the experimenter hid the beads in the leftmost two cups, and on a second Set Size 2 trial, the experimenter hid the beads in the rightmost two cups.

Although children believed they were gaining and losing resources across trials, all children received 15 resources at the end of the experiment, regardless of their performance.

Two cameras captured children's behavior (one angled from above and one to the left of the child). These camera images were digitally mixed and recorded. We had two primary measures. To measure visual working memory, we used children's recall accuracy. On each trial, we recorded the location children selected once they completed a pointing gesture toward the location (e.g., their arm stopped moving). Children's responses were later coded "1" (correct) or "0" (incorrect). To measure children's certainty in their responses, we used the number of items children chose to bet on each trial (zero, one, two, or three items). We also measured children's time to respond to the visual working memory probe on each trial. Response time was calculated from the moment the experimenter finished the sentence "Where's this bead?" to the moment at which the child completed pointing to a location.

Results

Visual working memory. To examine visual working memory recall performance, we first averaged children's responses within each set size to yield a proportion correct score for each set size (see Figure 3). Because our task required children to recall the location of a bead, and the number of locations increased with set size, chance levels also varied across set sizes. Therefore, we assessed children's recall accuracy separately at each set size, using two-tailed one-sample *t* tests against chance. To account for four comparisons, we set our alpha criterion for statistical significance to .01. The results of these comparisons are presented in Table 1. Children's recall accuracy was significantly above chance at all set sizes.

We used two approaches to quantify the extent to which children's performance was different from chance at each set size. First, we computed Cohen's *d* effect sizes for each comparison against chance, which showed that the size of the effect decreased as set size increased (see Table 1). In addition, we used Bayes factor analysis to quantify the odds of the alternative hypothesis (that children's proportion correct responses were significantly above chance) versus the null hypothesis (that children's proportion correct responses were not different chance). These analyses yielded "decisive" odds in favor of the alternative for Set Sizes 2, 3, and 4 and "moderate" odds in favor of the alternative for Set Size 5 (see Table 1; see Gallistel, 2009 for information about interpreting Bayes factors). These analyses suggest that children could recall the locations of at least four simple objects, but their recall performance declined as set size increased. See Figure S1 in the online supplementary materials for details on the patterns of children's errors across set sizes.

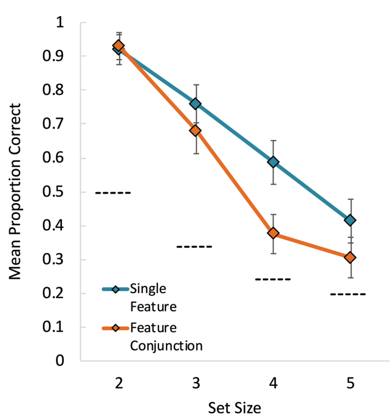

Figure 3. Children's recall accuracy (mean proportion correct) for each set size in Experiments 1 and 2. Dashed lines show the chance level for each set size. Error bars show ±1 standard error of the mean (*SEM*). See the online article for the color version of this figure.

Finally, we asked whether children's visual working memory performance varied with age. We conducted a repeated-measures analysis of variance (ANOVA) on children's mean proportion correct at each set size (Set Size 2, 3, 4, or 5), with age (in months) as a covariate. This revealed a main effect of age, $F(1, 23) = 5.05$, $p = .034$, $\eta_p^2 = .18$; a main effect of set size, $F(3, 69) = 3.05$, $p = .034$, $\eta_p^2 = .117$; and no Age × Set Size interaction, $F(3, 69) = 1.74$, $p = .167$, $\eta_p^2 = .07$, suggesting children's recall accuracy improved with age across all set sizes (see Figure 4).

Metacognitive monitoring of visual working memory. To examine whether children could monitor the quality of representations stored in visual working memory, we first asked whether, overall, children's bets tracked their accuracy across trials. Trials at the lowest set sizes (particularly Set Size 2) were easier for children and contributed fewer incorrect trials than higher set size trials. To account for this, we conducted a partial correlation between children's bets and children's accuracy on each individual trial, controlling for set size and subject. Children's bets were significantly correlated with their accuracy, $r(296) = .20$, $p = .001$, controlling for the difficulty of the task. We then compared children's mean bets on trials in which they were correct versus trials in which they were incorrect. We computed children's mean bets for correct and incorrect trials at each set size and then averaged these to obtain overall mean bets when correct and incorrect. One child was not included in this analysis because the child produced no incorrect answers. Children bet significantly more resources on trials in which they provided correct responses ($M = 2.23$, $SD = 0.70$) compared with trials in which they provided incorrect responses ($M = 1.82$, $SD = 0.88$), $t(23) = 2.15$, $p = .043$, $d = .43$ (see Figure 5, left panel; see Figure 6, left panel, for distributions of each bet type at each set size). See the online supplemental materials for an exploratory analysis of children's patterns of errors in relation to their bets.

Next, we estimated individual children's metacognitive sensitivity in our task (see Kornell, Son, & Terrace, 2007; Liu et al., 2018; Vo et al., 2014). For each child, we computed a Pearson correlation between accuracy and bet on each trial.[1] We were unable to compute this correlation for four children because of a lack of variability in their responses (three children bet the same amount on each trial; one child had no incorrect responses). Scores significantly above 0 suggest accurate assessment of performance on the task, reflecting greater metacognitive sensitivity. We found that children's *r* coefficients were significantly greater than 0 ($M = .21$, $SD = .37$), one-sample *t* test $t(20) = 2.55$, $p = .019$, 95% confidence interval (CI) of the difference [.04, .38]. Next, we

[1] Previous work that used betting to examine metacognitive awareness (e.g., Liu et al., 2018; Vo et al., 2014) computed a phi coefficient for each child (see Kornell et al., 2007). In this previous work, children's responses could be coded as correct or incorrect, and children could place either a low or a high bet, resulting in two binary measures. Because children in our task could choose to bet zero, one, two, or three resources, phi was not appropriate, so we used Pearson correlations, which are closely related to phi. To ensure that our analysis converged with previous work using phi coefficients, we converted children's bets to a binary variable (low = 0 or 1; high = 2 or 3), computed the phi coefficient controlling for reaction time, and performed the same analyses on phi coefficients for both Experiments 1 and 2. These analyses yielded similar results to those obtained using partial *r* coefficients (significant results remained significant, nonsignificant results remained nonsignificant).

Table 1
Results of Comparisons of Children's Mean Proportion Correct Against Chance for Each Set Size in Experiments 1 and 2

Experiment	Set size	Chance	*M* (*SD*)	*t*	*p*	BF_{10}	Effect size *d*
1: Single feature	2	.5	.92 (.22)	9.50	<.001*	10,560,442.69	1.90
	3	.33	.76 (.28)	7.66	<.001*	250,000.00	1.53
	4	.25	.59 (.32)	5.21	<.001*	995.02	1.04
	5	.2	.41 (.32)	3.30	.003*	11.93	.66
2: Feature conjunction	2	.5	.93 (.20)	10.76	<.001*	67,490,045.21	2.20
	3	.33	.68 (.33)	5.16	<.001*	795.54	1.05
	4	.25	.38 (.28)	2.16	.041	1.23	.44
	5	.2	.31 (.29)	1.76	.091	.64	.40

Note. *t* and *p* values reflect one-sample *t* tests against chance (two-tailed). To account for multiple comparisons within each experiment, the alpha criterion for significance was set to .01. Bayes factors (BF) are the odds of the alternative over the null hypothesis.
* $p < .01$.

computed the same correlations for each child, this time controlling for children's response time following the memory probe. Children took slightly (but not significantly) longer to respond when incorrect versus correct ($M_{\text{correct}} = 2.89$ s, $SD = 3.48$; $M_{\text{incorrect}} = 3.46$ s, $SD = 2.33$), $t(23) = -1.14$, $p = .266$, 95% CI of the difference [−1.65, .48]. Children could potentially monitor their own response times instead of, or in addition to, monitoring the fidelity of their working memory representations (see Kornell et al., 2007; Vo et al., 2014 for a similar approach). We found that although children's partial *r* coefficients tended to be greater than 0, they were not overall significantly so ($M = .14$, $SD = .39$), $t(20) = 1.72$, $p = .101$, 95% CI of the difference [–.03, .32] (see Figure 6), suggesting that reaction time (RT) may have contributed to children's betting responses. Children's metacognitive sensitivity estimates were not correlated with their age in months, *r* coefficients: $r(21) = -.08$, $p = .723$; partial *r* coefficients controlling for RT: $r(21) = -.104$, $p = .655$ (see Figure 7), suggesting that although visual working memory performance increased with age in our sample, metacognitive sensitivity did not.

Together, these analyses suggested that children's bets tracked their accuracy on our visual working memory task, but the estimates of individual children's metacognitive sensitivity suggested that children's metacognitive accuracy may have been informed, at least in part, by their own response times.

Discussion

In Experiment 1, we asked whether children could monitor the fidelity of their visual working memories for the locations of two to five single-feature objects. We found that, overall, children's bets tracked their accuracy. Children bet more resources on trials in which they had correctly recalled the location of the bead and fewer resources on trials in which they failed to recall the probed bead's location. However, estimates of children's individual metacognitive sensitivity yielded more equivocal results. Children's response times on each trial in the visual working memory task may have contributed, at least in part, to their willingness to bet resources on that trial.

Children's overall performance on the visual working memory task was quite high, even at the largest set sizes. It is possible that children may have some ability to monitor their visual working memory independent of their own response times but that our visual working memory task failed to elicit enough variability in representational fidelity to reveal this ability in children. In Experiment 2, we made the visual working memory task more difficult. Instead of asking children to remember the locations of objects defined by a single feature, we asked children to track the locations of objects defined by two features (color and shape). On each trial, each object shared one feature with at least one other

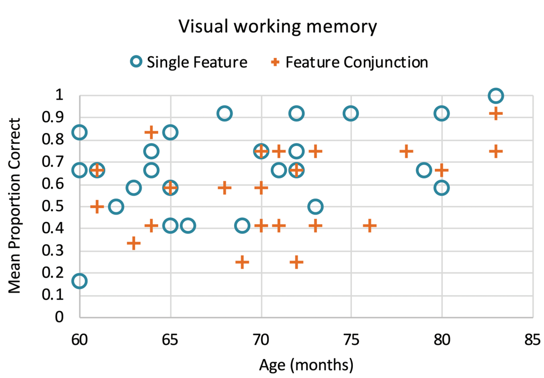

Figure 4. Mean recall accuracy across all set sizes for each child as a function of age for Experiments 1 and 2. See the online article for the color version of this figure.

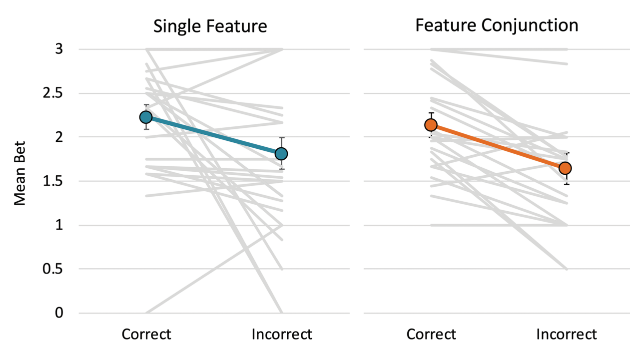

Figure 5. Children's mean bets when they gave correct and incorrect responses in the visual working memory task for Experiment 1 (left panel) and Experiment 2 (right panel). Error bars show ±1 standard error of the mean (*SEM*). Light gray lines represent individual children's paired means. See the online article for the color version of this figure.

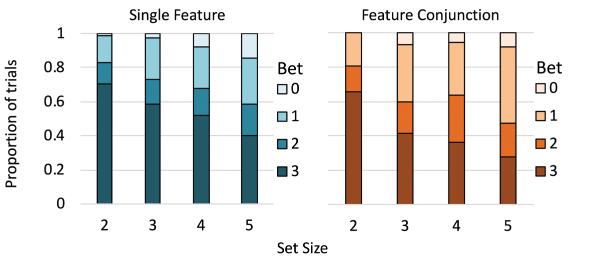

Figure 6. Proportion of trials on which children placed bets of zero, one, two, or three resources for each set size in Experiments 1 and 2. See the online article for the color version of this figure.

object in the array (e.g., a red square, a blue square, and a blue circle on a Set Size 3 trial). Children were then probed to recall the location of one of the objects (e.g., the red square). Success on this task therefore required binding two features to each location, which is more cognitively demanding (Wheeler & Treisman, 2002; Saiki, 2019). We therefore predicted that children's accuracy would be lower in Experiment 2 versus Experiment 1.

We also predicted that children would bet more resources when they were correct versus when they were incorrect, replicating the results of Experiment 1. If children can indeed monitor visual working memory independent of response times, we would expect to see this ability revealed when the visual working memory task is more difficult and children's representational precision is therefore more variable. However, we did not have a strong prediction about whether children's bets would be influenced by the overall greater difficulty of tracking the locations of multifeature objects. On the one hand, children might bet lower overall, reflecting the more challenging nature of tracking feature conjunctions. On the other hand, children's bets might reflect their own assessment of their certainty *on that trial*, regardless of the overall difficulty of the task. In that case, we might expect children's bets to be similar across Experiments 1 and 2.

Experiment 2

Method

Participants. Participants were a new group of 24 children aged 5 to 6 years old (M age = 71.6 months, range = 61.2–83.8 months; 13 girls). Sample size was determined as in Experiment 1. An additional six children were tested but excluded because of a recording malfunction (3), an inability to understand English (2), or parental interference (1). Parents reported their children as Black (1), Asian (3), Native American (1), White (17), or declined to report (1). Of these participants, five were also identified as Hispanic/Latinx. Eighteen of the 24 participants came from households with at least one parent who had a college degree or higher.

Materials. Materials were similar to Experiment 1, except that we used two-feature beads (four circle and four square beads, one each of yellow, red, orange, and purple). To probe children's memory for the location of a bead, we used eight cards, each depicting an image color- and shape-matched to one of the eight beads (four cards showing colored squares and four cards showing colored circles).

Procedure. The procedure was the same as in Experiment 1, with the following exceptions. First, because children would be asked to recall the location of a bead based on a combination of two features, before the practice trials, the experimenter familiarized children with the probe cards, which depicted both a color and a shape. She placed two beads of the same color (one circle and one square) on top of the box and said, "If I show you a card that looks like this (e.g., a card with a red square), I want you to tell me where the red square bead is hiding." She then repeated this instruction for the other bead, then proceeded with the practice trials.

Second, in the test trials, children were shown beads that shared a feature with at least one other bead in the array (see Figure 2, right panel). For example, on Set Size 2 trials, children may have been shown a round bead and a square bead, both of which were red. On Set Size 4 trials, children may have been shown a red square bead, a red round bead, a yellow round bead, and a yellow square bead. Children then had to recall the location of the bead that matched a conjunction of two features, as depicted on the card (i.e., yellow square). Just as in Experiment 1, children were not given feedback about their responses or the outcomes of their bets during test trials.

Results

Visual working memory. As in Experiment 1, we averaged children's responses at each set size and compared these to the chance level for each set size using one-sample t tests. To account for four comparisons, alpha was set to .01. We also quantified the size of the effects using Cohen's d and Bayes factor analysis. The results are summarized in Table 1. We found that children's mean proportion correct scores were significantly above chance only for Set Sizes 2 and 3 and not different from chance for Set Sizes 4 and 5. However, Bayes factor analysis yielded only anecdotal evidence for the null hypothesis for Set Sizes 4 and 5. These results suggested that children could reliably recall up to three multifeature objects but also that they did not reliably fail to recall the locations of multifeature objects at larger set sizes, potentially reflecting variability in working memory for larger sets in this age range. Figure 3 shows children's mean proportion correct at each set size for Experiment 2.

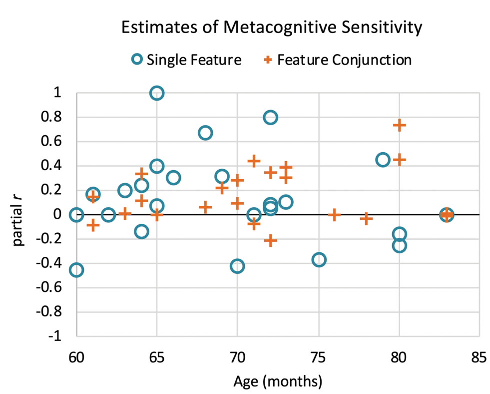

Figure 7. Metacognitive sensitivity estimates (partial r) for each child as a function of age. See the online article for the color version of this figure.

We also explored the nature of children's errors in Experiment 2. Unlike in Experiment 1, in which objects were defined by a single feature, in Experiment 2 the probe object shared features with other objects in the array. We therefore also explored whether, when incorrect, children were more likely to select locations containing a bead that shared its shape with the probe object or that shared its color with the probed object, or whether their errors were more evenly distributed. We restricted this analysis to Set Sizes 3–5, on which children made more frequent errors. The details of this analysis can be found in Table S1 in the online supplemental materials. At Set Size 3, we found that when children made errors, they were more likely to select a location containing an object that shared a feature with the probe (either color or shape) than an object that shared no features with the probe, $\chi^2(2) = 10.12$, $p = .006$. At Set Size 4, children were more likely to select a location containing an object that shared the same shape as the probed object, $\chi^2(2) = 10.13$, $p = .006$. At Set Size 5, children's errors were evenly distributed across locations containing objects that shared color, shape, or no features with the probed object, ($\chi^2(2) = 1.38$, $p = .5$). Although exploratory, this pattern of results suggests that children may track both features at lower set sizes, may prioritize shape as set size increases, but may subsequently fail to reliably remember either feature when the number of hidden objects exceeds their working memory limits. See Figure S1 in the online supplemental materials for further information about the locations of the children's erroneous responses relative to the probed object's location.

Finally, to examine whether children's visual working memory performance varied with age, we conducted a repeated-measures ANOVA on children's mean proportion correct at each set size (Set Size 2, 3, 4, or 5) with age in months as a covariate. We observed a main effect of set size, $F(3, 66) = 3.36$, $p = .024$, $\eta_p^2 = .132$, but no main effect of age, $F(1, 22) = 3.26$, $p = .085$, $\eta_p^2 = .129$, and no Age $\times$ Set Size interaction, $F(3, 66) = 2.62$, $p = .058$, $\eta_p^2 = .106$. Children's accuracy did not improve significantly with age (see Figure 4).

Metacognitive monitoring of visual working memory. Children's bets on each trial were significantly correlated with their accuracy on each trial, controlling for set size and subject, partial correlation ($r(284) = .121$, $p = .041$). Children bet significantly more resources on trials in which they accurately recalled the probe's location ($M = 2.14$, $SD = .57$) compared with trials in which they failed to recall the probe's location ($M = 1.64$, $SD = 0.67$), $t(23) = 4.86$, $p < .001$, $d = .99$ (see Figure 5, right panel; see Figure 6, right panel, for distributions of each bet type at each set size). Variability in children's patterns of errors (distance from target and shared vs. nonshared feature-based errors) was not related to their bets (see the online supplemental materials for details).

As in Experiment 1, we computed an r coefficient for each child, correlating accuracy and bets on each trial. We were unable to compute r for three children because of a lack of variability in these children's responses (these children bet the same amount on each trial). We found that children's r coefficients were significantly above 0 ($M = .30$, $SD = .23$), $t(20) = 5.84$, $p < .001$, 95% CI [.19, .40]. The children in Experiment 2 took longer to respond after the memory probe on trials in which they were incorrect versus when they were correct ($M_{\text{correct}} = 2.43$ s, $SD = 1.69$; $M_{\text{incorrect}} = 3.55$ s, $SD = 1.47$), $t(23) = -3.32$, $p = .003$, 95% CI of the difference [−1.82, −.42]. We therefore also computed partial r coefficients controlling for response time and found that children's partial r coefficients were significantly greater than 0 ($M = .18$, $SD = .23$), $t(20) = 3.65$, $p = .002$ (see Figure 7), suggesting that the children in Experiment 2 were monitoring the fidelity of their visual working memories, not simply monitoring their own response times. Children's r coefficients were not correlated with their age in months for either measure, r coefficients: $r(21) = .24$, $p = .297$; partial r coefficients controlling for RT: $r(21) = .20$, $p = .396$ (see Figure 7).

Experiments 1 and 2 Compared

Visual working memory. We first examined whether children's recall accuracy differed between Experiments 1 and 2, whether children's accuracy varied as a function of children's age (in months), and whether this differed between the experiments. We conducted a repeated-measures ANOVA on children's mean proportion correct with set size (Set Size 2, 3, 4, or 5) as a within-subjects factor, experiment (1: single feature or 2: feature conjunction) as a between-subjects factor, and age (in months) as a covariate. This revealed a main effect of set size, $F(3, 138) = 3.79$, $p = .012$, $\eta_p^2 = .076$; a main effect of experiment, $F(1, 46) = 5.70$, $p = .021$, $\eta_p^2 = .110$; and a main effect of age, $F(1, 46) = 8.48$, $p = .006$, $\eta_p^2 = .156$. None of the interaction terms were significant. Children performed worse overall in Experiment 2, in which they had to recall feature conjunctions, versus Experiment 1, in which they had to recall single-feature objects. Although children's age was not a statistically significant factor in their performance in Experiment 2, analysis of the combined data suggested that visual working memory performance improved with age, regardless of experiment.

Metacognitive monitoring of visual working memory. We first asked whether children's patterns of betting differed across Experiments 1 and 2 and/or with age. A repeated-measures ANOVA on children's mean bets at each set size with set size (Set Size 2, 3, 4, or 5) as a within-subjects factor, experiment (1: single feature or 2: feature conjunction) as a between-subjects factor, and age as a covariate revealed no significant main effects or interactions: Children's bets did not vary as a function of set size, $F(3, 138) = .50$, $p = .68$, $\eta_p^2 = .011$; experiment, $F(1, 46) = 1.72$, $p = .196$, $\eta_p^2 = .036$; or age, $F(1, 46) = .39$, $p = .572$, $\eta_p^2 = .007$.

Next, we examined whether children bet differently across the two experiments on trials in which they accurately recalled the location of the probed object and on trials in which they failed to recall the probe's location. We first compared children's mean bets on correct versus incorrect trials using a 2 (Accuracy: Correct or Incorrect) $\times$ 2 (Experiment: 1 or 2) repeated-measures ANOVA. This yielded a main effect of accuracy, $F(1, 46) = 18.05$, $p < .001$, $\eta_p^2 = .282$, but no main effect of experiment, $F(1, 46) = .45$, $p = .505$, $\eta_p^2 = .010$, and no Accuracy $\times$ Experiment interaction, $F(1, 46) = .26$, $p = .615$, $\eta_p^2 = .006$; children bet more on trials in which they were correct, regardless of experiment. Children's bets on each trial were significantly correlated with their responses on the working memory task (correct or incorrect), controlling for experiment, set size, and subject, $r(583) = .16$, $p < .001$. Together, these analyses suggest that children's bets tracked whether they were correct or incorrect, but children did not necessarily modulate their bets based on the overall difficulty of the task.

Although children's individual *r* coefficients were somewhat lower in Experiment 1 versus Experiment 2, there were no significant differences between the two experiments, *r* coefficients: $t(40) = -.97$, $p = .34$, 95% CI of the difference [–.29, .10]; partial *r* coefficients controlling for RT: $t(40) = -.38$, $p = .707$, 95% CI of the difference [–.23, .16], suggesting similar metacognitive sensitivity across the two groups of children, regardless of task difficulty. Metacognitive sensitivity estimates also did not correlate with age in months, controlling for experiment (*r* coefficients: $r = .05$, $p = .781$; partial *r* coefficients: $r = .01$, $p = .945$).

Discussion

In Experiment 2, we again found that children bet more resources when they correctly recalled the location of the probed object and fewer when they were incorrect. Analyses of children's metacognitive sensitivity suggested that children were monitoring the fidelity of their visual working memories and not simply monitoring their time to respond following the memory probe. Although children's ability to recall feature conjunctions was poorer than their ability to recall single-feature objects, children's bets did not differ between the two experiments, suggesting that children's bets may reflect trial-by-trial monitoring of visual working memory rather than overall task difficulty. Across both experiments, children's visual working memory performance improved with age, but metacognitive sensitivity did not.

General Discussion

In two experiments, we asked whether 5- to- 6-year old children could monitor the fidelity of their visual working memories. We asked children to maintain the locations of sets of two, three, four, or five single-feature (Experiment 1) or multifeature (Experiment 2) objects in visual working memory and to recall the location of one of the objects. We then asked them to place bets on whether they accurately remembered the location of the object, a measure of metacognitive awareness. We found that children's accuracy at recalling the location of the probed object decreased as the number of hidden objects increased and when the objects were more complex. Children's overall accuracy also increased across our age range, consistent with previous work showing visual working memory development between 5 and 7 years of age (e.g., Pailian et al., 2016; Riggs et al., 2006; Simmering, 2012). Importantly, we found evidence that children could monitor the fidelity of their visual working memories: Children bet higher when they were correct and lower when they were incorrect. Note that children did not receive feedback about whether they were correct or incorrect during test trials. Instead, children's bets reflected their own confidence rather than their objective task performance. Metacognitive sensitivity estimates did not vary as a function of task difficulty, nor did they vary as a function of age. Despite the development of visual working memory across our age range, children's ability to monitor visual working memory did not appear to undergo development, at least in the context of our task.

Our results also suggested that children might have incorporated other sources of information about their own uncertainty when gauging their confidence in their visual working memory representations. In Experiment 1, when the task was somewhat easier, we found that children's metacognitive sensitivity estimates were influenced by their response times during the working memory task (children in Experiment 2 may also have incorporated response time in their decisions about how many resources to bet, but this was not observed statistically). We speculate that when the fidelity of visual working memory is relatively high, children may make use of other sources of information about their own accuracy in the task. When the task is more difficult, and the fidelity of visual working memory is lower, monitoring visual working memory may be a reliable enough source of information for children to gauge their own accuracy in the task. Further work is needed to understand the sources of information that children incorporate into their confidence judgments and the conditions under which they do so.

These results contribute to a growing picture of metacognitive awareness in young children. Previous work showed that children can monitor the quality of their learning in tasks requiring episodic memory (e.g., Destan et al., 2014; Hembacher & Ghetti, 2014; Liu et al., 2018) and that they can monitor moment-to-moment representational precision in a perceptual domain (Baer et al., 2018; Vo et al., 2014). Our results show that children, like adults (Bona et al., 2013; Rademaker et al., 2012; van den Berg et al., 2017), can monitor uncertainty in representations of the locations of visual objects stored in working memory, a severely capacity-limited and developmentally volatile memory system.

What processes are children monitoring when they show sensitivity to their own visual working memory accuracy? To succeed in our task, children had to *encode* representations of feature–location bindings (Experiment 1) or feature–feature–location bindings (Experiment 2) in visual working memory and *maintain* those representations in visual working memory. When probed, children had to *retrieve* from working memory the location of the probed object, activating stored representations (Nairne, 2002; Sprague, Ester, & Serences, 2016). Children also had to *inhibit* information that they may have retained from previous trials, retrieving only the information relevant to the current trial, which is challenging for children (Lloyd, Doydum, & Newcombe, 2009) and places demands on episodic memory in addition to visual working memory (Delogu, Nijboer, & Postma, 2012; Hollingworth, 2007; Simmering, 2012). As set size increases, the demands on these processes increase as well: When more objects are hidden, there is more relevant information to encode and maintain within each trial and more irrelevant information to inhibit across trials. Children could be monitoring one or more of these processes when making decisions about their confidence in their responses, but our task was not designed to allow us to disentangle these processes. Future work will investigate the contributions of encoding, maintenance, and retrieval processes in visual working memory and episodic memory processes to children's metacognitive monitoring of visual working memory.

It is also worth noting that although children's bets tracked their accuracy at the task, children's overall bets across both experiments were relatively high, even for larger set sizes (see

Figure 6). This result is consistent with previous work finding that children tended to be overconfident in their judgments of their own perceptual precision (Vo et al., 2014) and in their acquisition of new knowledge or memories (see, e.g., Destan et al., 2014). Children's overconfidence may reflect that their ability to monitor working memory is still developing. Indeed, adults' confidence in their visual working memory representations is fairly accurate (e.g., Rademaker et al., 2012), suggesting maturation in metacognitive monitoring abilities with development. However, children's overconfidence could also be a function of the way in which we probed children's confidence: Children may be willing to take more risks to obtain rewards, even if it means the possibility of losing rewards (e.g., Rivière, Stomp, Augustin, Lemasson, & Blois-Heulin, 2018). Further work is needed to adjudicate between these possibilities.

Our results also yield some insights into the development of visual working memory itself. Previous work used change-detection tasks that required children to recognize whether an array of items was the same as an array stored in working memory (Pailian et al., 2016; Riggs et al., 2006; Simmering, 2012) and found that 5-year-olds could recognize changes in arrays of two to three items. In our task, children were asked to bind features to multiple moving objects and to track and maintain the locations of those objects as they moved into occlusion, placing different demands on attention and working memory (Kibbe, 2015). We found that children's overall recall accuracy was reliably above chance for at least four single-feature objects and at least three multifeature objects (although effect sizes decreased with set size, reflecting the more challenging nature of remembering more objects), suggesting a larger capacity in this task than is typically observed in change-detection tasks. Our task's emphasis on recalling spatial location—rather than recognizing a change to features at a location—may have supported children's visual working memory by providing consistent spatial structure across trials (Simmering & Wood, 2017). The use of real, persisting objects hidden in physical spatial locations, as opposed to items on a computer screen that vanish and reappear, may also have played a role in supporting children's ability to track more information because physical locations serve as external placeholders for persisting objects (Kibbe, 2015; Kibbe & Leslie, 2011, 2013). Our results highlight the need to assess visual working memory using varieties of different stimuli (e.g., two-dimensional physically implausible items, three-dimensional physical objects) and a variety of tasks (recognition, recall) in order to gain a more complete picture of this critical cognitive process across development.

Our results also have potential implications for our understanding of the role of working memory in academic outcomes. Previous work has found a predictive relationship between visual working memory and academic success (e.g., Cowan et al., 2003) and between metacognitive awareness and learning outcomes (e.g., Flavell, 1971). Future work will investigate whether individual differences in metacognitive monitoring of visual working memory predict academic success in children. More work also is needed to investigate the relationship between working memory strategy use and metacognitive monitoring of working memory. Indeed, despite our best efforts to use short display times to discourage the use of recoding strategies (e.g., phonological recoding), it is possible that at least some children in our task engaged in some type of strategy use. An open question is whether children with higher metacognitive awareness of their working memory limits also are more likely to engage in working memory strategies. Better metacognitive awareness of representational limits could allow children to recognize where their memory is breaking down and select a strategy that can bolster their working memory. Future work will investigate this possibility.

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