Quantifying attentional effects on the fidelity and biases of visual working memory in young children

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ABSTRACT

Attentional control enables us to direct our limited resources to accomplish goals. The ability to flexibly allocate resources helps to prioritize information and inhibit irrelevant/distracting information. We examined developmental changes in visual working memory (VWM) fidelity in 4- to 7-year-old children and the effects that a distracting non-target object can exert in biasing their memory representations. First, we showed that VWM fidelity improves from early childhood to adulthood. Second, we found evidence of working memory load on recall variability in children and adults. Next, using cues to manipulate attention, we found that older children are able to construct a more durable memory representation for an object presented following a non-target using a pre-cue (that biases encoding before presentation) compared with a retro-cue (that signals which item to recall after presentation). In addition, younger children had greater difficulties maintaining an item in memory when an intervening item was presented. Lastly, we found that memory representations are biased toward a non-target when it is presented following the target and away from a non-target when it precedes the target. These bias effects were more pronounced in children compared with adults. Together, these results demonstrate changes in attention over development that influence VWM memory fidelity.

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Introduction

Navigating and problem solving in a dynamic environment requires maintaining and continually updating representations. Underlying these abilities are working memory and goal monitoring, which are in constant interaction with attentional mechanisms (Badre, 2011; Lenartowicz, Kalar, Congdon, & Poldrack, 2010). Visual working memory (VWM) is the ability that allows the maintenance of visual information in the absence of sensory input (Baddeley, 2003; Courtney, Ungerleider, Keil, & Haxby, 1997; Todd & Marois, 2004). During childhood, there is continued development of brain structures subserving these processes (Casey, Tottenham, Liston, & Durston, 2005). To fully understand the mechanisms of VWM, it is important to determine the sources contributing to developmental change. Although several prominent models in the adult cognitive neuroscience literature have focused on the nature of VWM limitations, few incorporate developmental constraints by applying these models to both adults and children.

VWM capacity is severely limited (Alvarez & Cavanagh, 2004; Baddeley, 1992; Bays, Catalao, & Husain, 2009; Cowan, 2010; Luck & Vogel, 1997). Classic studies with adults using change detection paradigms revealed a limit of three or four objects (or "slots") (Awh, Barton, & Vogel, 2007; Luck & Vogel, 1997; for a recent review, see Luck & Vogel, 2013). Age-related improvement in capacity limits between 3 and 11 years of age suggests a slow gradual improvement over childhood (Cowan et al., 2005; Riggs, McTaggart, Simpson, & Freeman, 2006; Simmering, 2012). Prominent developmental theories embrace a slot-based model that assumes that objects are stored with high fidelity or forgotten completely and where changes over development encompass increases in the absolute storage capacity of the VWM system (Cowan, Morey, Chen, Gilchrist, & Saults, 2008).

An alternative model suggests that although memory is a limited resource, it can be flexibly distributed among items, where some items can be maintained with high resolution and others at a lower resolution in memory. Recent studies, mostly with adults, have turned toward a continuous analog measure of memory by computing the variance of the responses around the actual value rather than the number of items to be remembered (Bays & Husain, 2008; for a recent review, see Ma, Husain, & Bays, 2014).

Biases of memory

According to the resource model, memory representations are noisy reconstructions of the memoranda that are susceptible to distortions. In the adult VWM literature, there have been efforts to analyze and quantify the different sources of noise (e.g., Huang & Sekuler, 2010; Marshall & Bays, 2013; Sekuler & Kahana, 2007). These models attribute the imprecision of recalled information to systematic factors such as interference from previously encoded items and task-irrelevant information, in contrast to noise resulting from guessing due to inattention. In these studies, the parametric nature of the stimulus features enabled researchers to quantify the differential contributions of these various sources of error.

One source of error is long-term knowledge. Brady, Konkle, and Alvarez (2011) reviewed evidence for how representations in VWM are influenced by previous experiences, where prior expectations bias judgments. It has been proposed that there is a mechanism in visual processing that identifies objects and a second one that computes and stores their average properties, disposing details for efficiency (see, e.g., Alvarez, 2011). This bias can be conceptualized within a Bayesian framework of memory, where the prior serves as a representation of a weighted average of a memory trace (Hemmer & Steyvers, 2009). Indeed, Huang and Sekuler (2010) reported a prototype effect, where the current memory representation was pulled in the direction of an average feature representation of previously viewed stimuli. Similar reports of temporal dependence of VWM contents on previously viewed information have been demonstrated and quantified in various other contexts (Alvarez & Oliva, 2008, 2009; Fischer & Whitney, 2014; Haberman, Harp, & Whitney, 2009).

Selective attention can be another systematic source of bias. Classic paradigms using spatial orienting cues show benefits in processing by directing attention in space and time to certain stimuli (Posner, 1980; Posner & Cohen, 1984). Cues allow for the prioritization of information leading to greater recall precision (Gorgoraptis, Catalao, Bays, & Husain, 2011). Attention can be drawn to a particular object to be remembered using either a pre-cue preceding the memoranda or a retrospective cue (or retro-cue) following an array of memoranda. Items that have been pre- or retro-cued are less susceptible to interference from the presence of non-target[1] objects (Griffin & Nobre, 2003; Huang & Sekuler, 2010; Rademaker, Bloem, De Weerd, & Sack, 2015). Indeed, the ability to select relevant information and ignore distractions is a predictor of VWM capacity (Fukuda & Vogel, 2009; Shimi, Nobre, & Scerif, 2015; Vogel, McCollough, & Machizawa, 2005). For instance, Astle et al. (2014) found that low-VWM-capacity adults performed similarly to 10-year-old children in a change detection paradigm by processing non-target distractor objects.

VWM development

Developmental studies of VWM have established general improvements in capacity throughout childhood (Cowan et al., 2005; Gathercole, Pickering, Ambridge, & Wearing, 2004); however, there are still many open questions regarding the underlying mechanisms that drive these improvements (see Cowan, 2016; Simmering & Perone, 2013).

Only a few recent studies have examined developmental changes in VWM precision (Burnett Heyes, Zokaei, & Husain, 2016; Burnett Heyes, Zokaei, van der Staaij, Bays, & Husain, 2012; Sarigiannidis, Crickmore, & Astle, 2016; Simmering & Patterson, 2012). Burnett Heyes, Zokaei, van der Staaij, Bays, and Husain (2012) and Burnett Heyes, Zokaei, and Husain (2016) found that the precision of information maintained in VWM increased between 7 and 13 years of age. Simmering and Patterson (2012) found a similar effect between 4- and 6-year-olds using slightly different methods. In a study combining measures of precision with probabilistic modeling, Sarigiannidis et al. (2016) found decreases in the probability of random guessing in a sample of 7- to 12-year-olds. The most extensive model to explain developmental changes in VWM fidelity is based on dynamic field theory (DFT; Schöner, Spencer, & DFT Research Group, 2015; Simmering, 2016). A prominent computational model of VWM, DFT (Schutte, Spencer, & Schöner, 2003; Simmering, 2016) has recently aimed at providing an explanation to limits on both the number and resolution of VWM representations. Although most of this work has focused on VWM for locations, a few studies have addressed VWM for features (Simmering & Miller, 2016; Simmering & Patterson, 2012). Both of these studies found increasing VWM precision for color in children between 4–6 and 5–8 years of age using the method of constant stimuli with a staircase procedure.

Among the various aspects of visual attention that are changing in development, the ability of suppressing irrelevant information and flexibility in allocating attention prospectively and retrospectively are especially important. Studies of 7- and 10-year-old children found that they benefited less from retro-cueing compared with adults, implying that children have trouble in shifting their attention within already stored items (Astle, Nobre, & Scerif, 2012; Roome, Towse, & Jarrold, 2014; Shimi, Nobre, Astle, & Scerif, 2014). In the current study, we measured the effect that a non-target item can exert on VWM representations using a paradigm with pre-cues and retro-cues (similar to Huang & Sekuler, 2010) in adults and 4- to 7-year-old children.

Although most studies have focused on children over 7 years of age with few exceptions (Schutte, Keiser, & Beattie, 2017), when examining attention–VWM interactions, we extend the developmental trajectories of VWM fidelity into a period up to 3 years younger. This age range is particularly important in development because it spans the transition period into elementary school (which has been termed the "five- to seven-year shift"; Sameroff & Haith, 1996), where children enter a more structured environment in which they are challenged with various cognitive tasks with higher attentional demands. Recent neuroimaging studies have demonstrated rapid changes during this period in the mechanisms of attention and VWM (Brod, Bunge, & Shing, 2017; Kharitonova, Winter, & Sheridan,

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[1] The "target" object refers to the probed object, and the "non-target" refers to the items that are not probed.

2015), in contrast to the reported minimal changes in cerebral volume after 5 years of age (Reiss, Abrams, Singer, Ross, & Denckla, 1996).

In this study, two different experimental outcomes were computed and compared across age groups and experimental tasks: the variability and the central tendency of the distribution of responses. The variability in participants' reproduction error was used as a measure of working memory fidelity, where low values (measured as the variance, σ^2) indicate less variability. Measures of the central tendency of error responses reflect a bias in the memory representation of the target. For this measure, the median reproduction error for each participant, which is influenced less by extreme values, is used.

Our hypothesis is that the ability to suppress non-target information and exert top-down attentional control develops considerably from childhood into adulthood. Therefore, we expected (a) improvements in VWM variability as a function of age, (b) increases in recall errors as a function of memory load, (c) increases in VWM variability with the introduction of a non-target item in all three age groups, and (d) a greater shift toward the non-target in the central tendency in children compared with adults.

Method

Materials

In four tasks, participants reproduced the line orientation of a target object's texture using a delayed estimation technique and child-friendly stimuli (Fig. 1). In these tasks, participants responded either while the target object was still visible (Task 1), after a brief delay between target and response (Task 2), or when a distractor was presented concurrently with the target (Tasks 3 and 4). A pre-cueing (Task 3) and retro-cuing (Task 4) manipulation examined the role and flexibility of top-down selective attention. Grating orientations were used as the relevant feature to minimize the effects of semantic associations that rely on other memory systems (Baddeley, 1992). A delayed estimation technique was used to provide a continuous measure of memory recall performance.

Participants

In total, 30 adults (24 women; ages 18.0–46.0 years, mean = 25.5 years, SD = 5.25) and 28 children (10 girls; ages 4.05–7.45 years, mean = 5.7 years, SD = 1.29; see Table 1) with normal or corrected-to-normal visual acuity participated in all four experimental conditions. Adults gave informed consent, and parental consent was obtained in the case of the children. Two children did not complete the fourth task and were excluded from retro-cue analysis.

Stimuli and apparatus

The test and tasks (color-naming test and perceptual matching, 1-item, 2-item pre-cue, and 2-item retro-cue VWM tasks) were presented on a 19-in. computer monitor with a resolution of 1440 × 900 pixels and a 60-Hz refresh rate. At an average viewing distance of 60 cm, the objects in the perceptual matching task were presented simultaneously and encompassed a rectangular shape with a size of 15.53 × 16.06° of visual angle at the center horizontal. The objects in the VWM tasks were presented at the vertical and horizontal meridian subtending 16.01 × 16.38° of visual angle. The objects were an outline resembling a penguin; the penguin's body was covered in gratings consisting of parallel lines embedded in the animal's frontal area with a size of 7.96 × 8.19° for Task 1 and 8.07 × 8.23° of visual angle for Tasks 2 to 4 (see Fig. 1). Gratings had a frequency of 2.48 cycles/degree alternating between gray and red, blue, or black.

To control for simultaneous and successive effects and minimize afterimages, the stimulus contrasts across colors were comparable (range of contrast: 0.7–0.9). In all four tasks, the phase of the comparison grating was offset horizontally by 5 pixels compared with the target's phase. Therefore, participants were prevented from using cues to an absolute spatial reference frame (i.e., the immedi-
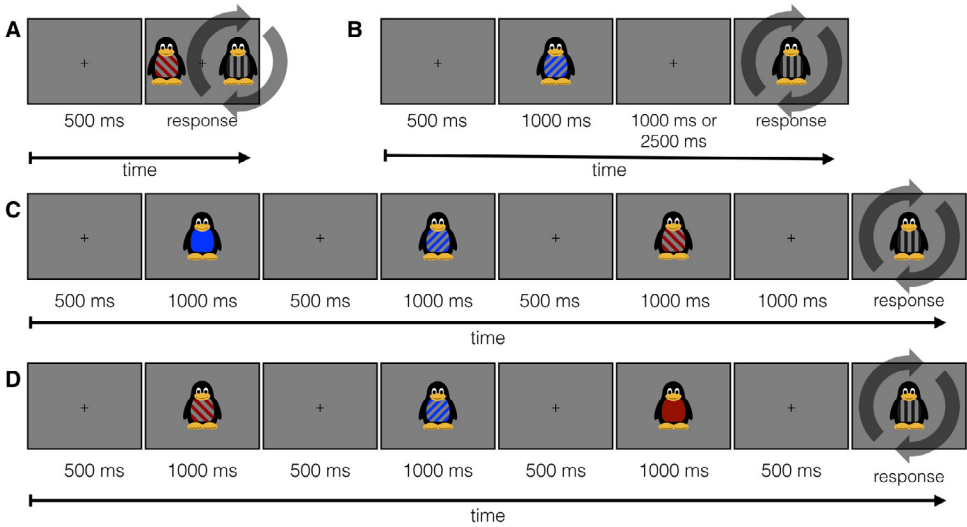
Fig. 1. Experimental paradigms for tasks: (A) Task 1: perceptual matching task; (B) Task 2: 1-item VWM task; (C) Task 3: 2-item pre-cue VWM task; (D) Task 4: 2-item retro-cue VWM task. Participants reported the orientation of the target object's line pattern by rotating the grating on the probe object until a match was obtained. (Line patterns are shown at a lower frequency for illustrative purposes.)

Table 1
Participant information.

Age group	n	Age range (years)	Mean age (SD) (years)
4- and 5-year-olds	13	4.05–5.99	4.50 (0.61)
6- and 7-year-olds	15	6.02–7.45	6.80 (0.48)
Adults	30	18.00–46.00	25.50 (5.26)

ate surround of the gratings) to solve the task. The grating orientation of the target and non-target objects varied parametrically between 0 and π radians, where the two extreme values were not included in order to avoid verbal naming and the specific effects that have been demonstrated for horizontal and vertical lines (Appelle, 1972).

The target and non-target objects in Tasks 3 and 4 differed in orientation by $\pi/6$ radians and by color. The probe object always had black line patterns and at the start of the response period appeared oriented at $\pi/2$ radians. The objects were presented on a gray background. MATLAB (Mathworks, Natick, MA, USA) with Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) was used for stimulus presentation, and responses were measured using a dial (PowerMate USB Multimedia Controller, Griffin Technology, Nashville, TN, USA) that participants turned to adjust the angle of the probe object and the button to finalize their response.

Procedure

A color-naming test was administered at the start of the testing session to determine whether each participant could correctly discriminate the three colors used in the task. A story was narrated to participants, where the main characters involved in the scenario matched in color to the objects used in testing. Participants were instructed to answer aloud the color of the main characters (red, blue, and black). All participants were successful at discriminating the colors.

Three practice trials to familiarize participants on the use of the dial were provided at the beginning of the four experimental tasks. Participants were instructed to rotate the dial and thereby manipulate the orientation of the gratings in real time until they matched a target angle, whereupon the black color of the grating changed to red, indicating that the current orientation corresponded to the target angle. There were 30 trials per task for a total of 120 trials. Before the start of each task, instructions and several practice trials were given to participants to make sure that they understood the instructions. If a participant failed to provide the correct answer, the experimenter would repeat the instructions and practice session. Similar to previous studies with young children (Burnett Heyes et al., 2012; Riggs et al., 2006; Simmering, 2012), the four tasks were presented in the same order because this made it easier for the young participants to follow the increasingly complex instructions.

Task 1: Perceptual matching

In the perceptual matching task, participants were presented simultaneously with a target object and a probe object. The target object appeared to the left of central fixation, and the probe object appeared on the right (Fig. 1A). Using the response dial, participants adjusted the orientation of the grating on the probe object until they were satisfied that it matched the orientation of the target object. Participants indicated the completion of a trial with a button press, advancing to the next screen that reported their progress in the current task, that is, the number of trials completed and remaining. There were no time constraints to produce a response; however, to encourage participants to finish within 15 s, the program signaled the passing of time with an auditory statement: "Let's finish up." An experimenter was present assure participants that if they had not yet matched the object, they should take their time until they were ready to terminate the current problem. Participants initiated the next trial with a button press.

This task had minimal memory demands on participants. Reproduction errors on this task, therefore, would be a product of perceptual variability, motor control, or trans-saccadic memory (Melcher & Colby, 2008) and would be used to correct for these individual differences in the subsequent memory tasks. Performance biases from reference frames (visual information in the immediate surroundings of the stimuli that could be used to anchor comparisons) have been reported to influence discrimination performance, especially on spatial tasks (Palmer, 1986). Here, we aimed to minimize the potential effects of spatial reference frames by introducing a 5-pixel horizontal grating offset between the target and probe objects.

Task 2: 1-item visual working memory

Following the perceptual matching task, participants completed the 1-item VWM task. This task was identical to the perceptual matching task except that the stimuli were presented sequentially, with the probe object following the target object after either a short (1000 ms) or long (2500 ms) delay (Fig. 1B). The trial began with a center fixation cross displayed for 500 ms. The target object followed and was displayed for 1000 ms. Adult studies show 1000 ms to be sufficient time to encode simple stimuli, such as colored squares, with no additional gains in performance with extended encoding times (Brady, Störmer, & Alvarez, 2016). The two delay intervals were selected to match the timing of the object presentation featured in the 2-item pre-cue VWM task.

Task 3: 2-item pre-cue visual working memory

The 2-item pre-cue VWM task used the same method as the 1-item VWM task except that for each trial there were two objects presented sequentially and a color pre-cue was used to indicate which object was the target at the beginning of the trial (Fig. 1C). On each trial, participants did not know whether the first or second object would be the cued item. For half of the trials, the first object in the sequence was the target. Trials began with a 500-ms fixation cross, followed by a colored cue displayed for 1000 ms. Then, after 500 ms, the target and non-target objects were presented sequentially, counterbalanced within the task. Each object was displayed for 1000 ms with a 500-ms delay between the two objects. The equivalent delay time between the 1-item VWM task and the 2-item pre-cue task allowed for a direct comparison of performance where the 1-item VWM task accounts for memory decay independent of non-target interference. The non-target's orientation was greater than the target's value on half of the trials and was less than the target's value on the other half.

Task 4: 2-item retro-cue visual working memory

All aspects of the retro-cue task were identical to those of the pre-cue task with the critical difference that the cue was shown after the presentation of the memory array (Fig. 1D). A trial began with a central fixation cross was displayed for 500 ms. The two objects were presented sequentially for 1000 ms with a 500-ms fixation cross in between. After 500 ms, the retro-cue was displayed for 1000 ms before the response period with the probe. Retro-cues differ from post-cues, with the former providing time to orient attention and the latter serving as the probe requiring an immediate response (Astle, Summerfield, Griffin, & Nobre, 2012). Post-cues have been used in many delayed estimation tasks that measure the quality of the memory representation (Burnett Heyes et al., 2012; Ma et al., 2014), and comparisons with retro-cues show a memory advantage with the use of retro-cues (Pertzov, Bays, Joseph, & Husain, 2013; Sligte, Scholte, & Lamme, 2008).

Analysis

Participants' behavioral performance was quantified in terms of their reproduction error. The reproduction error was calculated as the difference between a participant's reported orientation and the target object's orientation on each trial. The variance, using Fisher's (1995) definition of variance (σ^2) for circular data, was computed per participant across all trials and served as a measure of VWM fidelity (Fig. 2A). Data analysis was performed in MATLAB using custom functions and the Circular Statistics Toolbox (Berens, 2009).

Hypotheses concerning the effect of experimental parameters (non-target and attentional biases) on the variability and central tendency of responses were tested with analysis of variance (ANOVA) and t tests. To evaluate age effects, the response variability of the errors was compared across tasks. Repeated-measures ANOVA with Bonferroni-corrected t tests were performed to compare VWM error variability within age groups and across tasks using variance correction described below.

Performance on the perceptual matching task was compared by age to measure developmental differences and to correct for these differences in subsequent tasks. Assuming that perceptual and memory errors contribute independently to the response variability, the variability contributed by the perceptual matching task was subtracted from the working memory tasks using the following equation (see Burnett Heyes et al., 2012; Howell, 2012), where the covariance term equals zero based on the independence assumption: $\sigma_{corrected} = \sigma^2_{VWM\,task} - \sigma^2_{perceptual\,task} + 2 \cdot Cov(VWM \times Perceptual)$.[2] In the 2-item VWM tasks, the central tendency of the distribution of each participant's responses (the median) was represented as a signed transformed reproduction error (TRE; see Huang & Sekuler, 2010). The relationship among the target, non-target, and participants' reported orientation was determined such that when the reported orientation was in the direction of the non-target, the reproduction error corresponded to a positive value, and when it was in the opposite direction, the reproduction error corresponded to a negative value (Fig. 2B). Because in half of the trials the non-target's orientation was greater than the target's, any calculation of central tendency without the algebraic transformation would have a net effect of zero if a systematic shift were present. The median shift on each task represented the central tendency of the distribution for each participant.

Results

The results are organized as follows. First, we compared the fidelity of the memory representation between the age groups to characterize developmental changes in response variability (σ^2) across VWM tasks. Second, we investigated the effect of a non-target on the response variability of VWM by comparing performance on the 1-item VWM task with that on the 2-item pre-cue task and the effect of memory load by comparing the 1-item VWM task with the 2-item retro-cue task. Third, we analyzed the effects of attention by comparing the 2-item tasks with each other. Finally, we quan-

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[2] Burnett Heyes and colleagues (2012) presented and discussed their findings in terms of precision ($1/\sqrt{\sigma}$). Because $1/x$ distributions do not have the necessary mathematical properties for our statistical analyses, here we analyze σ^2 throughout.
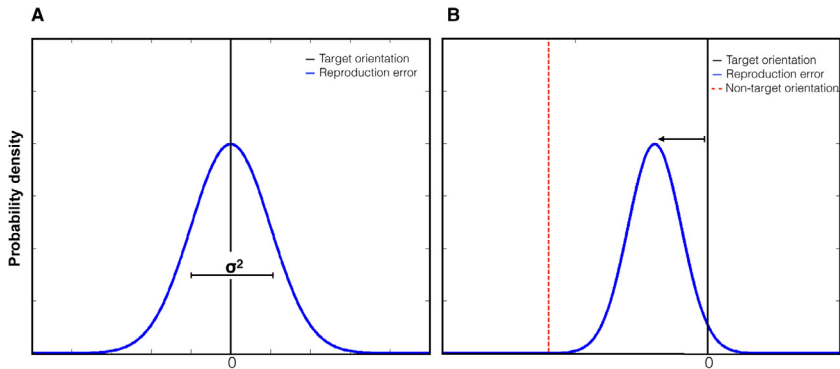
Fig. 2. An illustration of the dependent measures. (A) VWM fidelity is represented as the variance (σ^2, the population's variance; SD^2, the sample's variance) of the distribution of reproduction errors (blue) for the target orientation (black line), where the variance is used as a measure of VWM fidelity. (B) The median shift in the response distribution of the reproduction error of the target (blue) orientation is shown as a bias in the direction of the non-target orientation (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

tified a non-target bias as shifts in the central tendency (signed transformed median reproduction errors).

VWM fidelity: Improvements in recall variability over development

Age effects in the perceptual matching task showed a decrease in the dispersion of errors from childhood to adulthood: one-way ANOVA by age group, $F(2, 55) = 36.16$, $p < .001$, $\eta_p^2 = .57$. Adults (0.004 ± 0.0025 rad^2 [mean ± SD]) had less variability in their reproduction errors than 4- and 5-year-olds (0.082 ± 0.054) and 6- and 7-year-olds (0.037 ± 0.020), post hoc test Bonferroni-corrected $p < .01$. In addition, there was a significant difference in perceptual performance between the two groups of children, $p < .001$. This effect could be driven by factors such as the development of fine-motor control abilities, the thresholds in tolerating errors, and reference frame biases (Simmering & Spencer, 2008). To control for these perceptual differences among age groups, in subsequent analyses we subtracted the variance measured in the perceptual matching task from the VWM tasks.

To determine age-related changes in memory performance, a repeated-measures ANOVA of task (1-item pre-cue, 2-item pre-cue, or 2-item post-cue) × serial position/delay (first/long or second/short) with age (4- and 5-year-olds, 6- and 7-year-olds, or adults) as a between-participant factor was performed. Age group had a significant effect on recall variability, $F(2, 55) = 9.09$, $p < .001$, $\eta_p^2 = .25$. Adults (0.017 ± 0.005) were less variable in their responses compared with both groups of children, $p < .01$, and 6- and 7-year-olds (0.052 ± 0.008) were not significantly different from 4- and 5-year-olds (0.047 ± 0.008), $p = 1.00$. These results support that the precision of memory representations improves from childhood to adulthood but that these differences are not as pronounced during early childhood. There was a significant main effect of task (Greenhouse–Geisser corrected), $F(1.65, 90.92) = 10.93$, $p < .001$, $\eta_p^2 = .16$, where the 2-item retro-cue VWM task (0.05 ± 0.005) had greater variability than the 1-item VWM task (0.027 ± 0.004). The serial position of the target occurring first/long delay (serial position 1 [SP$_1$]: 0.046 ± 0.005) had greater variability of the errors compared with appearing second/short delay (serial position 2 [SP$_2$]: 0.032 ± 0.004), $F(1, 55) = 15.14$, $p < .001$, $\eta_p^2 = .22$. There was no significant Task × Age interaction, $F(3.3, 90.9) = 1.10$, $p = .36$, $\eta_p^2 = .038$, or Position × Age interaction. $F(2, 55) = 1.77$, $p = .18$, $\eta_p^2 = .061$. A significant Task × Position × Age Group interaction, $F(4, 110) = 2.58$, $p = .042$, $\eta_p^2 = .086$, indicated that the age groups were differentially affected by task and position; therefore, to investigate the influence of the non-target and attention, each age group was analyzed separately.

VWM fidelity: Changes in recall variability as a function of memory load

The 1-item VWM task requires maintaining the representation of a single gratings orientation with two delay periods, whereas the 2-item retro-cue task increases the cognitive load on VWM with the requirement that participants remember the orientation of two gratings where the target object was presented first (SP_1) or second (SP_2) in the series. To explore the influence of a second item on memory fidelity, the mean variability between the 1-item and 2-item retro-cue tasks was analyzed for each age group.

Adults showed greater variability on the 2-item retro-cue task (0.021 ± 0.002) than on the 1-item VWM task (0.011 ± 0.001), $F(1, 29) = 18.05$, $p < .001$, $\eta_p^2 = .38$. There were no significant main effects of serial position/delay, $F(1, 29) = 2.58$, $p = .12$, $\eta_p^2 = .082$, or an interaction effect, $F(1, 29) = 3.83$, $p = .06$, $\eta_p^2 = .12$. The addition of holding onto an additional item in VWM reduced recall performance in adults.

The 6- and 7-year-old children demonstrated similar patterns in performance as adults, with greater variability in the 2-item retro-cue task (0.066 ± 0.010) compared with the 1-item VWM task (0.040 ± 0.007), $F(1, 14) = 6.97$, $p = .019$, $\eta_p^2 = .332$. There was no main effect of serial position/delay, $F(1, 14) = 1.42$, $p = .25$, $\eta_p^2 = .092$, or an interaction effect, $F(1, 14) = 0.110$, $p = .75$, $\eta_p^2 = .008$.

With the 4- and 5-year old children, there were no significant main effects of task, $F(1, 10) = 3.61$, $p = .086$, $\eta_p^2 = .27$, or serial position/delay, $F(1, 10) = 1.10$, $p = .32$, $\eta_p^2 = .099$. There was a significant interaction effect, $F(1, 10) = 20.29$, $p = .001$, $\eta_p^2 = .67$, where performance on SP_1 trials in the retro-cue task had greater variability of recall errors (0.027 ± 0.01) compared with the 1-item long delay trials (0.10 ± 0.016, $p = .007$) and the SP_2 retro-cue trials (0.050 ± 0.014, $p = .020$), indicating limited resources with increasing VWM load.

VWM fidelity: Measuring the non-target's influence

In the 1-item VWM task, the variability of reproductions for a single item using two delay periods measured the potential effect of temporal decay. The 2-item pre-cue VWM task manipulated the deployment of attention with the addition of a non-target object presented either following (SP_1) or preceding (SP_2) the target object. To investigate the effects of the non-target item on the fidelity of VWM, an analysis of mean variability between the 1-item VWM task and the 2-item pre-cue VWM task with serial position/delay was conducted for the age groups separately.

Adults were less precise on the 2-item pre-cue VWM task (0.017 ± 0.002) compared with the 1-item VWM task (0.011 ± 0.001), $F(1, 29) = 6.95$, $p = .013$, $\eta_p^2 = .19$ (Fig. 3), and had overall lower dispersion of errors when the target object was second (SP_2)/short delay compared with first (SP_1)/long delay, main effect of serial position/delay: $F(1, 29) = 6.84$, $p = .014$, $\eta_p^2 = .19$. A significant Task × Serial Position/Delay interaction, $F(1, 29) = 7.09$, $p = .013$, $\eta_p^2 = .20$, implicates the non-target object's impact on the fidelity of the target because delay differences alone did not significantly influence the variability of reproduction errors in the 1-item VWM task, post hoc test Bonferroni-corrected $p = .76$.

In the 6- and 7-year-old children, there was no significant main effect of task, $F(1, 14) = 0.75$, $p = .40$, $\eta_p^2 = .05$, with similar performance on the 2-item pre-cue VWM task (0.051 ± 0.012) and the 1-item VWM task (0.040 ± 0.007). Variability was higher when the target was presented first (SP_1)/long delay compared with when it was presented second (SP_2)/short delay: $F(1, 14) = 7.09$, $p = .019$, $\eta_p^2 = .34$. There was a significant Task × Serial Position/Delay interaction, $F(1, 14) = 8.60$, $p = .011$, $\eta_p^2 = .38$ (Fig. 3). Post hoc analysis confirmed that the interaction is due to a difference in the 2-item pre-cue task, but not the 1-item task, because performance on the SP_1 of the 2-item pre-cue task showed greater imprecision compared with the advantage of SP_2 and its similarity to the 1-item VWM task with the lack of an intervening item, $p = .003$.

Performance of the 4- and 5-year-old children on the 2-item pre-cue VWM task (0.047 ± 0.019) and the 1-item VWM task (0.031 ± 0.16) was not significantly different, $F(1, 12) = 0.64$, $p = .44$, $\eta_p^2 = .051$. There was no significant main effect of serial position/delay, $F(1, 12) = 0.43$, $p = .52$, $\eta_p^2 = .04$, or Task × Serial/Delay interaction, $F(1, 12) = 1.45$, $p = .25$, $\eta_p^2 = .11$. The younger children performed similarly on the VWM task regardless of the presence of a non-target item. It is possible that the 4- and 5-year-olds' performance was at ceiling with these particular task demands of remembering a single
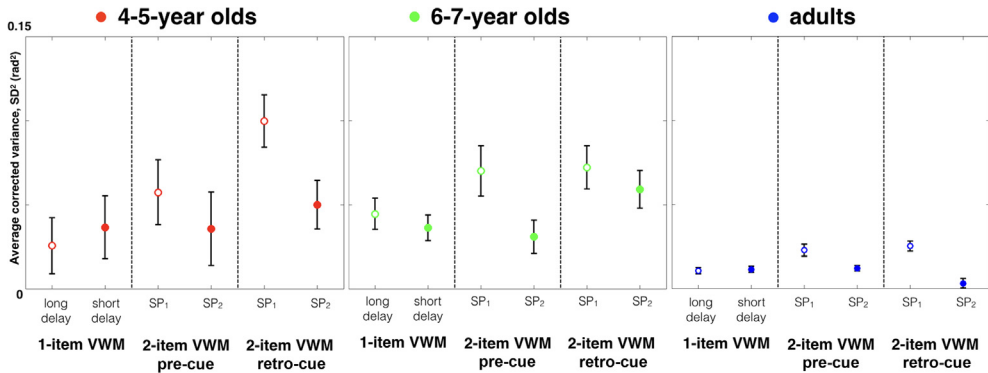
Fig. 3. Mean variance (SD^2) across groups in Task 2 (1-item VWM task), Task 3 (2-item pre-cue VWM task), and Task 4 (2-item retro-cue VWM task). Conditions where the target was presented first [(SP_1)/long delay] are represented as open circles, and those where the target was presented second [(SP_2)/short delay] are shown as filled circles. The adult group (blue) showed less variability across all tasks compared with the 6- and 7-year-old group (green) and the 4- and 5-year-old group (red). Error bars are standard errors of the mean. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

item in memory and that guessing the target object's orientation had a substantial contribution to the variance. Sarigiannidis et al. (2016) found decreases in the guess rate with age.

An analysis of the pre-cue task versus the retro-cue task with serial position was performed to measure attentional control mechanisms. The retro-cue task tested the observer's ability to flexibly shift attention to items maintained in VWM.

For adults, their memory recall on the 2-item retro-cue task (0.021 ± 0.002) was not significantly different compared with that on the 2-item pre-cue task (0.017 ± 0.002), $F(1, 29) = 3.33$, $p = .08$, $\eta_p^2 = .10$ (Fig. 3). The position of the target in the sequence affected performance, where recall for SP_1 had greater variability compared with that for SP_2, $F(1, 29) = 16.53$, $p < .001$, $\eta_p^2 = .36$. There was no significant Task × Serial Position interaction, $F(1, 29) = 0.47$, $p = .50$, $\eta_p^2 = .016$. These findings indicate that shifting attention while maintaining two items intentionally in memory (retro-cue) is similar to directing attention to facilitate encoding of a single item (pre-cue) with a memory advantage to the last item.

The 6- and 7-year-old children showed similar patterns of performance in comparison with adults. Memory recall during the 2-item retro-cue task (0.066 ± 0.010) was not significantly different from that during the 2-item pre-cue task (0.051 ± 0.12), $F(1, 14) = 2.03$, $p = .18$, $\eta_p^2 = .13$ (Fig. 3), and there was a main effect of serial position, where SP_1 was recalled with more variability compared with SP_2, $F(1, 14) = 5.97$, $p = .028$, $\eta_p^2 = .30$. There was a significant Task × Serial Position interaction, $F(1, 14) = 6.54$, $p = .023$, $\eta_p^2 = .32$, and a post hoc test showed that variability was lowest during the pre-cue task when the target was presented second (SP_2) compared with serial positions when the target occurred first (SP_1) in the pre-cue task, $p < .003$, and in the retro-cue task, $p = .011$. The 6- and 7-year-olds showed reductions in recall variability using pre-cues when the target object followed the non-target object compared with retro-cues, whereas adults had similar recall performance using the two types of cues to direct attentional resources.

Younger children (4- and 5-year-olds) had no significant difference in response variability in the 2-item pre-cue task (0.052 ± 0.19) compared with the 2-item retro-cue task (0.073 ± 0.13), $F(1, 10) = 4.72$, $p = .055$, $\eta_p^2 = .32$ (Fig. 3). There was a main effect of serial position, $F(1, 10) = 11.89$, $p = .006$, $\eta_p^2 = .54$, where variability of errors was lower on SP_2 trials compared with SP_1 trials. There was no significant interaction effect, $F(1, 10) = 0.52$, $p = .47$, $\eta_p^2 = .050$. Thus, just like the other age groups, younger children had greater memory fidelity when the target was the last object presented, suggesting difficulties in maintaining the memory representation when intervening information was shown.

Median shift: Biases in pre-cue and retro-cue tasks

To examine whether a shift in the central tendency of the reproduction error distribution occurred due to the presence of a non-target item and whether the magnitude of the shift was attenuated with age, pre- and post-cue 2-item tasks were compared across age groups. There was no significant main effect of task, $F(1, 53) = 1.42$, $p = .24$, $\eta_p^2 = .026$. Serial position had a significant effect on the magnitude of the shift in central tendency [main effect of serial position: $F(1, 53) = 9.89$, $p = .003$, $\eta_p^2 = .16$], with SP_1 (0.042 ± 0.010 rad [mean ± SD]) exhibiting a greater shift in the central tendency toward the non-target compared with SP_2 (0.002 ± 0.008). This shift was mediated by task [Task × Serial Position interaction: $F(1, 53) = 64.16$, $p < .001$, $\eta_p^2 = .55$]. There was a main effect of group, $F(2, 53) = 3.31$, $p = .044$, $\eta_p^2 = .11$, and the groups were affected differentially by the non-target [Group × Task × Serial Position interaction: $F(2, 45) = 17.38$, $p < .001$, $\eta_p^2 = .40$] and are analyzed separately in the following section, where serial positions in both tasks are compared with a test value of zero, that is, a zero shift in the central tendency.

A one-sample t test showed that the adult group in the pre-cue task was shifted in the direction toward the non-target when presented in SP_1 (0.036 ± 0.061), $t(29) = 3.25$, $p = .003$, and a shift away from the target in the SP_2 (-0.027 ± 0.045) condition, $t(29) = -3.27$, $p = .003$ (Fig. 4C). When participants were given a retro-cue, there were no statistically significant shifts of the median observed [SP_1: $t(29) = 1.27$, $p = .21$; SP_2: $t(29) = 0.25$, $p = .80$].

The 6- and 7-year-old children in the pre-cue task showed a shift toward the non-target when the target was presented first (SP_1: 0.17 ± 0.11), $t(14) = 5.70$, $p < .001$) and a shift away from the non-target when the target was presented second (SP_2: -0.13 ± 0.15), $t(14) = -3.40$, $p = .004$. Interestingly, 6- and 7-year-olds showed the opposite effects in the retro-cue task, where SP_1 (-0.12 ± 0.13) resulted in a shift away from the non-target, $t(14) = -3.43$, $p = .004$, and SP_2 (0.12 ± 0.11) resulted in a shift toward the non-target, $t(14) = 4.16$, $p = .001$ (Fig. 4B). In the pre-cue task, the shifts are similar to those for adults. However, in the retro-cue task, when maintaining both items in memory, there is a bias for the first object such that when the non-target is first (SP_2), the memory representation is attracted toward the non-target and the target is weighted more (SP_1) when presented first in the sequence.

Younger children showed a significant shift in SP_1 toward the non-target object when the non-target was the intervening object in the pre-cue task (SP_1: 0.20 ± 0.13), $t(12) = 5.24$, $p < .001$, but not in SP_2 (-0.029 ± 0.17), $t(12) = -0.62$, $p = .55$ (Fig. 4A). There were no statistically significant shifts of the median observed in the retro-cue task [SP_1: $t(10) = -0.84$, $p = .42$; SP_2: $t(10) = 1.54$, $p = .16$]. The lack of a non-target shift along with the increase of imprecision measurements in the retro-cue task
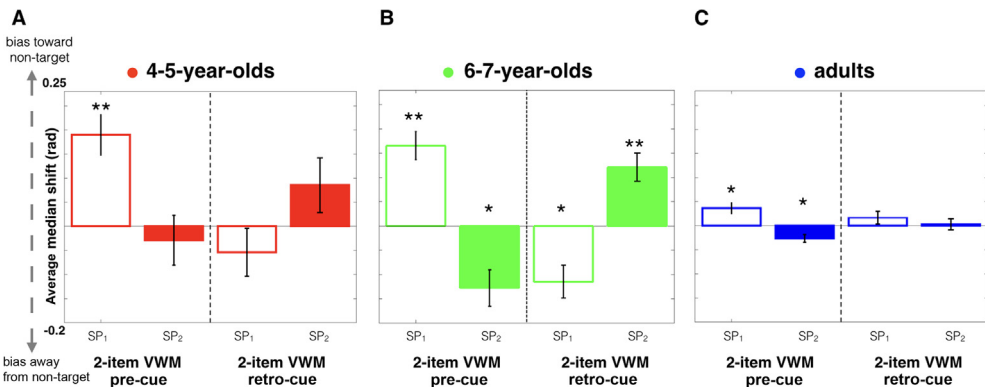

Fig. 4. Signed TRE from Tasks 3 and 4 by age group (A: 4- and 5-year-olds [red]; B: 6- and 7-year-olds [green]; C: adults [blue]). Shift in central tendency: the zero horizontal represents no bias in recall; above: a bias toward the non-target object; below: a bias away from the non-target object. SP_1 (open bars) and SP_2 (filled bars) are the conditions where the target was presented first and second, respectively. Error bars are standard errors of the mean. $^*p < .01$; $^{**}p < .001$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

would suggest that the 4- and 5-year-olds had difficulty in holding onto two objects in memory. In the pre-cue task, the recency effect in the SP_2 condition led to a lack of contamination from the non-target, but with only a significant effect seen in SP_1, the non-target was likely reported more than the target (a mis-binding error).

To summarize, younger children showed a greater non-target shift in their responses compared with adults; there was a shift toward the non-target when it was presented after the target (all groups) and a shift away when the target was second (6- and 7-year-olds and adults) in the pre-cue task; and, by comparison, the retro-cue effects were attenuated or in the opposite direction of the pre-cue task.

Discussion

The aim of this series of tasks was to understand attentional control mechanisms and influences of non-target information on the fidelity of VWM across development. Adults were superior in their performance compared with the groups of children, whereas the two age groups did not differ in their performance from one another. These results reflect improvements in the resolution of the memory representation from childhood to adulthood. Although overall changes in VWM fidelity during this period of childhood were not as distinguishable, it is important to note differences in performance with respect to a non-target object.

Notably, the presence of the non-target object influenced recall. The variability of recall errors with 1 item compared with 2 items in the retro-cue task was lower in all age groups. These results demonstrate that VWM fidelity depends on load in both children and adults. Addressing our third aim, serial position differences were found in the pre-cue VWM task but not in the 1-item VWM task, with comparable delay periods for adults and 6- and 7-year-old children. Retro-cueing also revealed differences in the serial position of the target item for adults and both groups of children. Losses in accuracy for earlier items retained in memory have been reported as a recall advantage for the last item in the sequence (Burnett Heyes et al., 2012; Gorgoraptis et al., 2011; Huang & Sekuler, 2010). These results suggest that it might be easier to suppress and ignore non-target information prior to encoding a target object compared with protecting the memory representation from interference during maintenance. Marshall and Bays (2013) demonstrated that encoding may be a more involuntary process and that maintenance may be a more voluntary one. In addition, prior research has found that intervening objects act as a memory mask and that when stimuli share a particular feature (e.g., orientations), discrimination thresholds on the stored representation are increased (Magnussen & Greenlee, 1999).

As predicted, attentional cues were more beneficial to the 6- and 7-year-old children when they were presented as a pre-cue, whereas adults performed similarly when deploying their attentional resources. It has been proposed that directing attention retrospectively to items in memory and prospectively to incoming information may have different developmental trajectories (Astle et al., 2012; Shimi et al., 2014; reviewed in Astle & Scerif, 2011). Astle, Scerif, Kuo, and Nobre (2009) discussed processing differences as searching memory for items (retro-cues) and pre-cues that operate during encoding by selecting particular features, that is, temporal order and color. It is also plausible that differences in the encoding/maintenance process exist among the age groups. For instance, adults might be attempting an intermediate level of encoding in addition to encoding serial position, which results in no shifts in the representations, whereas older children might be emphasizing the encoding of the first item but not the second one, leading to the smaller difference in variability during the retro-cue condition and to a shift away from non-target in SP_1. These results show that the ability to flexibly allocate attentional resources retroactively seems to emerge between 6 and 7 years of age.

Our fourth goal was to quantify biases (shifts in the central tendency of responses) when a non-target is present. We found that, relative to adults, children's biases were greater. Moreover, when the target was presented first in the sequence, a measurable shift in the central tendency of the response distribution was greater. This distortion of the memory representation toward the non-target again could be attributed to the involuntary process of encoding the non-target during the maintenance period of the target object. Non-target or task-irrelevant stimuli have been previously

found to influence spatial memory representations (Huang & Sekuler, 2010). Van der Stigchel, Merten, Meeter, and Theeuwes (2007) reported that a visual stimulus presented after a target can capture attention and interfere with the maintenance of a memory location, resulting in a shift toward the task-irrelevant stimuli. They hypothesized that the close proximity in time between the relevant and irrelevant stimuli causes an overlap in activated neuron populations that code both stimuli. Such occurrences would explain attraction effects toward the non-target. Similarly, in spatial attention tasks, systematic reference frame-related shifts in errors have been observed when the focus of attention is diverted during a retention period, with greater biases associated with larger shifts in attention (Johnson & Spencer, 2016).

In the pre-cue VWM condition, both adults and older children exhibited a shift away from the non-target in SP_2 trials and toward the target in SP_1 trials. Thus, whereas the SP_1 trial type saw the disruption of the information stored in memory, the SP_2 trial type might have interference acting at the level of encoding. Scocchia, Cicchini, and Triesch (2013) found that non-target stimuli can affect how information is perceived in adults and described a repulsion effect similar to that experienced after adaptation. This phenomenon is caused because the populations of neurons from the initially presented non-target are dampened, influencing the population coding of the target as away from the non-target (Dragoi, Sharma, & Sur, 2000). Similar results have been reported with motion, where the content of VWM has influenced perception (Kang, Hong, Blake, & Woodman, 2011). In the SP_1 condition, it is also possible that the maintenance of the target might deplete attentional resources, preventing them from dampening non-target orientation representation and actually allowing those neurons to be activated. In the retro-cue VWM task, where both stimuli were relevant and equally likely to be selected as the target, adults and 4- and 5-year-olds had reduced bias effects that were nonsignificant. For adults, the voluntary encoding of both items in the retro-cue task resulted in less inter-item interference, whereas the incidental encoding of the non-target in the pre-cue condition resulted in a greater shift. The lack of a significant bias in the retro-cue condition in adults is similar to results reported by Rademaker et al. (2015) that further illustrate the many interactions between items stored in memory. The authors speculated that a decisional component might be exerting an influence. Interestingly, 6- and 7-year-olds showed the opposite effects compared with their performance in the pre-cue condition. We speculate that this effect is not a feature of mere mis-binding errors because if that were the case we would expect a bias toward the non-target for both SP_1 and SP_2. We suspect that with 6- and 7-year-olds, the first item encoded into memory biases the memory representations of the second object. The bias could be an artifact of post-perceptual processes associated with encoding the first object in the sequence impairing the processing of the second object, similar to an attentional blink effect (Raymond, Shapiro, & Arnell, 1992).

Although these results demonstrate improvements of VWM in (a) the fidelity of the representation, (b) the flexibility of attention in directing resources to facilitate encoding and shifting focus during maintenance, and (c) reducing the bias that a non-target object has on a memory representation, the study is limited in describing the decisional strategies that affect how memory representations are stored. The repulsion effect seen in older children (and adults) may reflect a strategy of comparing the two objects, where the non-target is used as a guide in determining whether the target is judged as greater or less than the non-target. Further empirical research is needed to determine changes in encoding strategies. Although perceptual differences were controlled for across age groups, developmental changes in perceptual processing and the use of reference frames could conceivably modulate the non-target bias effects (Schutte et al., 2017; Simmering & Spencer, 2008). Older children have improved performance on a mirror image discrimination task compared with younger children (4-year-olds), with younger children making greater errors attributed to left–right reversal images than 6-year-olds (Uehara, 2013). In this study, younger children would be more susceptible in reproducing a mirror image of the target object and increasing error variability.

Most of the developmental research on VWM, much like the classic adult literature, had focused primarily on capacity changes (Cowan et al., 2005; Riggs, Simpson, & Potts, 2011; Riggs et al., 2006). Recently, researchers have sought to measure changes in VWM fidelity using more sensitive metrics (Sarigiannidis et al., 2016; Simmering & Patterson, 2012). A prominent model based on dynamic field theory can account for the development of both VWM capacity and resolution (Johnson, Simmering, & Buss, 2014; Simmering & Miller, 2016). Tests of this computational model

and comparisons with children's performance demonstrated that an experience-driven strengthening of connections between neural fields and stronger activation levels can lead to VWM capacity improvement. Moreover, the strengthening in connectivity also accounted for more robust representations in the model that were less prone to interference. This model provides a comprehensive mechanistic explanation for the processes underlying VWM development.

Other related psychophysical studies have investigated improvements in the fidelity of VWM representations for features (e.g., orientation) during middle childhood using the delayed estimation task (Burnett Heyes et al., 2012, 2016). Here, we extended this inquiry by exploring how changes in attentional control affect the current and future content of memory, and quantified how non-target information can systematically interfere and distort the to-be-remembered representation, in 4- to 7-year-old children, the youngest age range ever tested with this method. Investigating attentional contributions to the development of VWM can provide new insights to the interactions of these systems and how these networks become more integrated during development.

Acknowledgments

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