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When Objects Disintegrate: Young Children Do Not Bind Features in Visual Working Memory

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Abstract

Remembering object identities requires ‘binding’ visual features together in working memory to form integrated object representations. Research with adults suggests that such feature binding is achieved through space: features at a given spatial location are ‘bound’ to create integrated objects that are anchored to a spatial map of the object layout. Critically, 4-year-old children do not form such spatial maps, whereas 5-year-old children do. This suggests that 4-year-olds might have difficulty binding features together in visual working memory. We tested 4- and 5-year-old children and adults in a change detection task, and found that 4-year-olds showed a binding-specific deficit. Thus, the ability to represent integrated objects in visual working memory is a relatively late developmental achievement. We suggest that before 5 years of age children’s object representations are primarily mediated through visual long-term memory.

Keywords: visual working memory; feature binding; spatial memory; cognitive development

Visual Working Memory

Human adults can quickly form a mental map of which objects are where in a local workspace. Adults form working memory representations of 3-4 objects in a few hundred milliseconds with enough detail to detect changes in those objects a second later, even when the objects are composed of multiple simple features such as color, orientation, and size (e.g., Luck & Vogel, 1997). Moreover, given just 20 seconds to scan the surrounds, adults can detect a subtle change in the features of an object in a scene as much as 24 hours later after viewing more than 400 objects (Hollingworth, 2005). There are, of course, limitations to humans’ visuo-spatial abilities (e.g., Pashler, 1992; Rensink, 2000), but these examples highlight the fast, flexible visual working memory (VWM) system that underlies adults’ interactions with objects.

The present report examines the developmental origin of this ability. Can young children quickly form representations of which objects are where with sufficient detail to detect changes in those objects a second later? This may not be the case. As we review below, research suggests that visual features such as shape and color are ‘bound’ in working memory by virtue of their shared spatial location within the configuration of objects in a scene (e.g., Hollingworth, 2007; J.S. Johnson, Spencer, & Schöner, 2008; Treisman & Gelade, 1980). Evidence further suggests

that 4-year-olds, but not 5-year-olds, have difficulty remembering object locations relative to object configurations (Nardini, Burgess, Breckinridge, & Atkinson, 2006). Here, we suggest that these results are linked and test whether 4-year-olds show a binding-specific deficit consistent with their inability to anchor features to object configurations. Thus, 4-year-olds might remember that a duck, ball, and car were present in a scene and, further, that the objects were red, blue, and yellow, but *not* remember that the duck was blue, the ball was red, and the car was yellow.

Feature Binding in Visual Working Memory

The past decade has seen considerable debate in the VWM literature over whether feature binding presents a problem in vision (for reviews, see Luck & Beach, 1998; Roskies, 1999; Treisman, 1996). Evidence suggests that object properties such as color, form, and size are coded in a distributed manner across different neural populations in the ventral pathway (Tootell, Dale, Sereno, & Malach, 1998). As information passes through this pathway, there is an increase in the complexity of the features coded (Desimone, Albright, Gross, & Bruce, 1984) and receptive field sizes, with a decrease in the spatial resolution of receptive fields for individual neurons (Gross, Rocha-Miranda, & Bender, 1972). Consequently, when multiple objects are present in a scene, it may be difficult to determine which features belong together as VWM representations. Consistent with this, adults sometimes report illusory conjunctions, correctly reporting that a target feature was present but mis-binding that feature with the color of a nearby distracter (Ashby, Prinzmetal, Ivry, & Maddox, 1996).¹

Although the debate over the binding “problem” is far from resolved (e.g., Garson, 2001), several behavioral studies with adults have shown that feature binding can present a challenge in working memory tasks (Allen et al., 2006; J.S. Johnson, Hollingworth, & Luck, 2008; Wheeler & Treisman, 2002). Several theories suggest that features may be bound by integrating spatial and non-spatial visual features (J.S. Johnson, Spencer, & Schöner, 2008). According to feature integration theory (Treisman & Gelade, 1980), for instance, object features are bound

¹ Although these studies did not use working memory paradigms, it is plausible that the perceptual mis-binding of features they show would affect working memory representations.

together by virtue of their shared spatial location as visual selective attention shifts sequentially about the scene. Such spatial information is represented in a second cortical pathway, the dorsal pathway (Ungerleider & Mishkin, 1982), which maintains multiple spatial reference frames including a frame anchored to the object configuration. This spatial frame is central to object representations; for example, adults show decrements detecting changes in object features when object configurations are broken (Hollingworth, 2007).

Development of Feature Binding

Relatively little is known about how children bind object features together in VWM and the developmental course of this ability. The dorsal and ventral visual pathways appear to be functional in infancy but may not be tightly integrated (M.H. Johnson, Mareschal, & Csibra, 2001). Given that VWM and visual long-term memory work hand-in-hand, however, it is possible that young children can represent integrated objects when there is support from visual long-term memory. This possibility has not been adequately explored due to the challenges of isolating these two memory systems. For instance, studies using habituation or preferential looking paradigms suggest that infants can bind visual features (M.H. Johnson et al., 2001; Mareschal & Johnson, 2003; Oakes, Ross-Sheehy, & Luck, 2006). Nevertheless, because infants' visual preferences in such tasks emerge over 10 to 20 second trials, these paradigms likely recruit visual long-term memory and, therefore, do not specify whether features can be bound when VWM must work in isolation (Simmering & Spencer, 2009).

The quality of children's object representations in VWM might also be difficult to assess given the stability of the physical world—even though children might not remember the exact features of an object, they can typically look back to the location of the remembered object to refresh this information. To accomplish this, they need only 'bind' a single feature to the correct location. To refresh a memory of a blue circle, for example, one need only remember where the blue object was, look back to that location, and recover the relevant shape information. Critically, this would only refresh the currently fixated item; it would not help with the *integration* of information across visual samples. Interestingly, 4-year-olds have difficulty in tasks that require this type of integration, such as block construction and drawing tasks where they must scan back and forth between a complex design and a nearby workspace to duplicate the design (Georgopoulos, Georgopoulos, Kuz, & Landau, 2004). Thus, 4-year-olds have difficulty integrating information across visual samples, suggesting they might have limited VWM abilities.

Four-year-olds also have difficulty remembering object locations relative to an object configuration, whereas 5-year-olds are more proficient. Nardini and colleagues (2006) tested 3-, 4-, 5-, and 6-year-old children's location memory abilities when either the object array or the child moved during the delay. Critically, only 5- and 6-year-olds

performed at above-chance levels when the object array moved or both the child and the array moved during the delay. This suggests that 3- and 4-year-olds do not encode object locations relative to object configurations. If binding in VWM requires anchoring features to their spatial position in the object configuration as suggested by data with adults (Hollingworth, 2007), children younger than 5 years might have difficulty using space to bind features together in VWM.

Empirical Test of Predictions

In the present study, we tested whether 4-year-olds, 5-year-olds, and adults could detect changes in object features in a feature-binding versus multi-feature memory version of the change detection paradigm (cf. Wheeler & Treisman, 2002). In the feature-binding task, object features are swapped between two objects on change trials. In Figure 1, for instance, the cross and triangle swap positions in the 'shape change' example, thereby breaking the color-shape binding for these objects. This task was contrasted with a multi-feature memory task where a new color or shape is introduced on change trials. In Figure 1, for instance, the triangle changes to an hourglass in the 'shape change' example. The multi-feature memory task requires memory for the colors and shapes in the sample array; however, because a new feature is introduced at test, memory for color-shape bindings is not required.

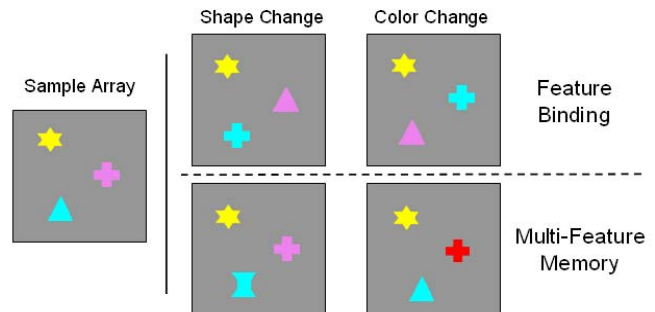


Figure 1. Examples of trial types in the change detection task.

Results show that adults perform comparably well in both tasks (e.g., J.S. Johnson, Hollingworth, & Luck, 2008; Wheeler & Treisman, 2002), providing an ideal starting point for a developmental examination of feature binding: we know adults do not show a binding deficit in this task; the question is, do children?² Because 4-year-olds have difficulty in tasks that require remembering object locations relative to the object configuration and integrating

²One study used a variant of the change detection task to examine whether children bind visual features to locations. Results showed that 8- to 11-year-olds had difficulty binding colors to locations (Cowan, Naveh-Benjamin, Kilb, & Saults, 2006). Critically, college-aged adults also had difficulty in this condition, which is not consistent with other results (e.g., J.S. Johnson, Hollingworth, & Luck, 2008). This might reflect the use of a non-standard task that required the detection of feature repetitions.

information across visual samples, we expected 4-year-olds to show binding-specific deficits in VWM. Such a deficit would suggest that integrated object representations in VWM are a developmental achievement that occurs surprisingly late in childhood.

Method

Participants Participants were 28 four-year-olds (M age = 4.19 years, SD = 1.89 months; 15 females), 28 five-year-olds (M age = 5.08 years, SD = 1.75 months; 11 females), and 28 adults (M age = 19.69 years, SD = 11.84 months; 9 females) who were randomly assigned across conditions. Nine additional participants were excluded for the following reasons: failure to understand the task (2 four-year-olds); equipment failure (1 four-year-old, 2 five-year-olds); experimenter error (1 four-year-old, 3 five-year-olds). Children were recruited from a university database and given small prizes for participating; adults volunteered or were recruited through a psychology course for research exposure credit. Informed consent was obtained from adult participants and parents of child participants. All participants reported normal or corrected-to-normal vision and no colorblindness.

Apparatus and Procedure Complete details of the apparatus and procedure are described by Simmering & Spencer (2009). The task was presented on an 18" CRT monitor with a black background at a viewing distance of approximately 60 cm. Stimuli were comprised of one of eight possible shapes with one of eight possible colors (cf. Wheeler & Treisman, 2002); note that no color or shape was repeated within a given array. Trials included 1, 2, or 3 item arrays (set sizes [SS] 1-3) because 4- to 5-year-old children have a VWM capacity of approximately 2-3 items in change detection (Simmering & Spencer, 2009); testing array sizes within children's memory capacity ensured that their performance was not generally impaired by task difficulty.

Each trial began with the memory array, presented for 2 s (extended from the typically duration of 500 ms to be appropriate for children), followed by a 900 ms delay. Next, the test array was displayed until the participant responded *same* or *different* (the terms *match* and *no match* were used for children). Children responded verbally, and an experimenter entered the response on a keyboard; adult participants entered their responses directly on the keyboard. To keep child participants motivated, a chime played for each correct response; note that this feedback was also provided to adult participants.³ For adults, a verbal load was added to prevent verbal recoding and/or rehearsal: a 3-digit number appeared on the computer screen before each block, and adults repeated this number throughout the trials. This was included only for adults because children younger

than 7 years do not spontaneously verbally recode or rehearse visual stimuli (Pickering, 2001).

Each session began with a block of eight practice trials, four each (two *change*, two *no change*) in SS2 and SS3, presented in random order; excluding SS1 trials from the practice block facilitated the experimenter's evaluation of whether children understood the task. After the practice block, the test trials were blocked by SS and presented in the following order: SS2-SS1-SS3. Based on pilot data and previous studies (Simmering & Spencer, 2009), this order elicited the best performance from children, avoiding boredom and frustration. Children were offered breaks between blocks to prevent fatigue. Each test block included six *change* and six *no change* trials, presented in random order. For all *no change* trials, the sample and test arrays were identical. For SS1 *change* trials, binding changes were not possible; instead, for both conditions, the item changed in either color or shape (half of the trials each). For SS2-3 *change* trials in the Multi-Feature Memory condition, this same type of change occurred for one item in the test array. In the Feature Binding condition, however, two items would swap color-shape pairings. On half of the *change* trials, two colors swapped locations; on the other half, two shapes swapped locations (see Figure 1).

Results

Responses were tabulated separately for *change* and *no change* test trials to arrive at percent correct scores for each participant, trial type, and SS. Mean percent correct data, shown in Table 1, were analyzed separately by trial type and set size (SS1 separately from SS2-3) because *no change* and all SS1 trials were identical across conditions (recall that binding changes are not possible with one item). Thus, we expected differences across conditions only on multi-item (SS2-3) *change* trials.

Results for SS2-3 *change* trials are shown in Figure 2A. A three-way ANOVA with Set Size (2, 3) as a within-subjects factor and Age (4 years, 5 years, adults) and Condition (Multi-Feature Memory, Feature Binding) as between-subjects factors revealed significant main effects of Set Size ($F_{1, 78} = 7.47, p < .01$), Age ($F_{2, 78} = 22.18, p < .001$), and Condition ($F_{1, 78} = 8.13, p < .01$), as well as a significant Age x Condition interaction ($F_{2, 78} = 5.23, p < .01$).

The Set Size main effect was driven by better performance in SS2 ($M = 74.84\%$) than in SS3 ($M = 66.96\%$), which is consistent with previous findings that performance decreases as set size increases (e.g., Luck & Vogel, 1997). Follow-up Tukey HSD tests ($p < .05$) on the Age main effect showed that adults ($M = 85.48\%$) performed better than both 4-year-olds ($M = 61.16\%$) and 5-year-olds ($M = 66.07\%$), but the two groups of children did not differ significantly. The Condition main effect was driven by overall lower performance in the Feature Binding condition ($M = 66.41\%$; Multi-Feature Memory $M = 75.40\%$), but this effect was qualified by the significant interaction. Analyses of each Age group separately showed that 4-year-olds performed significantly worse in the

³ Although this positive feedback seemed to improve children's motivation, the design of the current study precluded us from testing whether children's performance improved as a result of this feedback. Specifically, the number of trials within each block was too small for reasonable analysis within blocks, and set size was confounded with order (see details in the following paragraph).

Table 1: Mean percent correct across conditions, trial types, set sizes, and age groups.

	Set Size 1			Set Size 2			Set Size 3		
	4 years	5 years	Adults	4 years	5 years	Adults	4 years	5 years	Adults
M-F Memory									
<i>Change</i>	96.43 (9.65)	91.67 (10.84)	100.00 (0.00)	73.81 (21.40)	72.62 (23.21)	91.67 (12.66)	71.43 (18.98)	58.33 (18.20)	84.52 (17.86)
<i>No Change</i>	94.05 (10.56)	91.67 (10.84)	100.00 (0.00)	79.76 (24.62)	83.33 (16.10)	97.62 (6.05)	73.81 (22.37)	82.14 (15.28)	98.81 (4.46)
Feature Binding									
<i>Change</i>	90.48 (12.60)	96.43 (9.65)	100.00 (0.00)	53.57 (17.52)	70.24 (23.73)	87.14 (14.25)	45.83 (26.30)	63.09 (18.69)	78.57 (17.82)
<i>No Change</i>	84.52 (21.15)	97.62 (8.91)	100.00 (0.00)	90.43 (14.19)	89.29 (14.03)	91.66 (15.70)	81.31 (21.92)	84.52 (15.28)	98.81 (4.46)

Note. Standard deviations are shown in parentheses below means. $N = 14$ for each age group.

Feature Binding condition ($F_{1, 26} = 14.48, p < .001$), with no significant differences across conditions for 5-year-olds or adults ($F_{1, 26} < 1.5, p > .2$). In summary, on multi-item *change* trials, adults performed well in both conditions, consistent with previous studies. Although 5-year-olds performed worse than adults overall, they had no specific difficulty with the feature-binding task. By contrast, 4-year-olds showed significantly worse performance when binding was required.

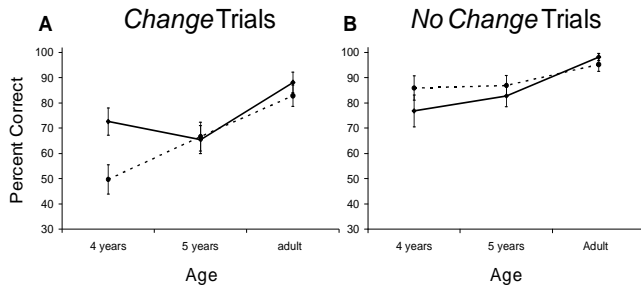


Figure 2. Mean percent correct on multi-item *change* (A) and *no change* (B) trials for each age group and condition. Solid lines show the Multi-Feature Memory condition; dashed lines show the Feature Binding condition. Error bars show one standard error.

If 4-year-olds know that they need to look for changes but have difficulty binding features together, then they should have roughly equal difficulty when shapes versus colors are swapped between objects (see Figure 1). By contrast, the detection of new features at test in the Multi-Feature Memory condition might be driven more by the salience of the new feature, which could differ on shape-change versus color-change trials (see Figure 1). For instance, previous research using a single-feature memory task showed that shape changes are more difficult to detect than color changes (Simmering & Spencer, 2009).

To examine this issue, we computed the proportion of misses for shape- versus color-change trials across conditions for SS2-3 (Figure 3). When a new feature was introduced in the Multi-Feature Memory condition, participants missed the changes more frequently on shape-

change trials (Figure 3A), consistent with our previous results. When features were swapped between objects in the Feature Binding condition, however, participants showed a comparable proportion of misses for both types of feature changes (Figure 3B). This resulted in a more than three-fold increase in color-change errors for 4-year-olds in the Feature Binding condition. This dramatic increase in errors, specific to the task and type of change presented, is consistent with ANOVA results suggesting that 4-year-olds have a binding-specific deficit in VWM.

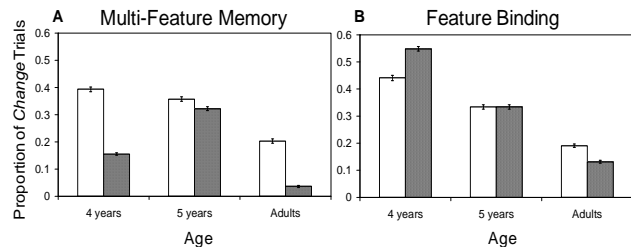


Figure 3. Proportion of miss errors ('same' response on *change* trials) for each age group on trials with shape changes (open bars) or color changes (filled bars) for the Multi-Feature Memory (A) and Feature Binding (B) conditions. Error bars show one standard error.

Nevertheless, it is possible that 4-year-olds in the Feature Binding condition did not understand the task. To evaluate this, we analyzed performance on SS2-3 *no change* trials, which were identical across conditions and randomly intermixed with *change* trials; results are shown in Figure 2B. A three-way ANOVA with Set Size (2, 3) as a within-subjects factor and Age and Condition as between-subjects factors revealed only a significant main effect of Age ($F_{2, 78} = 1.59, p < .001$). Follow-up Tukey HSD tests ($p < .05$) showed that adults ($M = 96.72\%$) performed better than both 4-year-olds ($M = 81.34\%$) and 5-year-olds ($M = 84.82\%$), but the two groups of children did not differ significantly. Thus, all children could detect matching arrays that were intermixed with *change* trials.

We also analyzed data from the SS1 trials, which were identical across conditions, separately by trial type. We first

analyzed the SS1 *change* trials in a two-way ANOVA with Age and Condition as between-subjects factors. Once again, the ANOVA revealed only a significant main effect of Age ($F_{2, 78} = 4.76, p < .05$). Follow-up Tukey HSD tests ($p < .05$) showed that adults performed better than both 4- and 5-year-olds, but that the two groups of children did not differ significantly (see Table 1 for means).

Next, we analyzed the SS1 *no change* trials with a two-way ANOVA. This analysis revealed a significant main effect of Age ($F_{2, 78} = 6.38, p < .01$) and a significant Age x Condition interaction ($F_{2, 78} = 3.39, p < .05$). Tests of simple effects revealed significant main effects of Age in both the Multi-Feature Memory ($F_{2, 39} = 3.38, p < .05$) and Feature Binding conditions ($F_{2, 39} = 5.54, p < .01$). Follow-up Tukey HSD tests ($p < .05$) showed different patterns across conditions: in the Multi-Feature Memory condition, adults performed significantly better than only 5-year-olds, whereas adults performed significantly better than only 4-year-olds in the Feature Binding condition (see Table 1 for means). No other comparisons were significant. Critically, additional tests of simple effects revealed no significant Condition main effects for any of the age groups ($p > 0.125$), showing that, although 4-year-olds tended to be less accurate than 5-year-olds and adults on SS1 *no change* trials, there were no significant condition-related differences in performance within age groups.

Even though follow-up tests showed no significant condition effects for the 4-year-olds on SS1 trials, we conducted one final analysis to assess whether 4-year-olds in the Feature Binding condition might have had a general response bias that could explain their binding deficit. We computed response criterion bias on SS1 trials⁴ as follows (Cowan et al., 2006):

$$\beta = -0.5 * [z(\text{proportion hits}) + z(\text{proportion false alarms})].^5$$

Response criterion bias is commonly used in signal detection analyses to determine how likely participants were to indicate a change when they are unsure whether a change actually occurred, that is, whether they had a general bias to respond *change* (Cowan et al., 2006). Scores range from -2.33 to 2.33, with zero reflecting no bias (i.e., equal numbers of *change* and *no change* responses), negative scores indicating more *change* responses, and positive scores indicating more *no change* responses. Mean bias scores and standard deviations are shown in Table 2.

If young children in the Feature Binding condition had a general bias to respond *no change*, this could explain their lower performance on *change* trials with multi-item arrays. If this were the case, response criteria adjustments that participants made as a consequence of the type of changes

⁴We computed these scores for SS1 only because it is inappropriate to compare bias across conditions that affect *change* and *no change* trials differentially (i.e., multi-item trials in this study; see Figure 2).

⁵“Hits” are correct responses on *change* trials, and “false alarms” are incorrect responses on *no change* trials. Because z-scores cannot be computed on values of 0 or 1, these values were replaced with 0.01 and 0.99, respectively.

Table 2: Mean response criterion bias (β) scores in set size 1 across conditions and age groups

	Multi-Feature Memory	Feature Binding
4 years	-0.12 (0.45)	-0.11 (0.49)
5 years	0.00 (0.46)	0.05 (0.41)
Adults	0.00 (0.00)	0.00 (0.00)

Note. Standard deviations are shown in parentheses.

they saw in the first block of trials (i.e., new features in the Multi-Feature Memory condition versus binding swaps in the Feature Binding condition) should carry over to the SS1 trials (since these trials occurred in the middle of the session; see Method). Such an effect would yield a difference in response bias across conditions. A two-way ANOVA with Age and Condition as between-subjects factors revealed no significant effects ($ps > .38$). Thus, there is no evidence that the deficit 4-year-olds show in the Feature Binding condition was due to a general difference in response criteria compared to the Multi-Feature Memory condition. Rather, our analyses are consistent with the conclusion that *4-year-olds show a binding-specific deficit in VWM*.

Conclusions

Evidence suggests that adults quickly bind visual features into integrated object representations in VWM anchored to the configuration of objects in the scene. Recent results show that 4-year-olds have only a rudimentary ability to remember locations anchored to an object configuration (Nardini et al., 2006). Here, we suggested these results were linked and hypothesized that 4-year-olds might show a binding-specific deficit in VWM. This was indeed the case—feature binding in VWM emerges between 4 and 5 years. These data contradict the commonly-held view that feature binding in VWM is achieved in infancy (e.g., Oakes et al., 2006). As discussed previously, the tasks used with infants likely recruit long-term visual memory, which was precluded here (Simmering & Spencer, 2009). Rather, our data suggest that the ability to represent integrated objects in VWM, without support from visual long-term memory, is a relatively late developmental achievement.

What are the consequences for young children of representing *disintegrated objects in VWM*, that is, failing to recognize exactly which object features were where in the visual scene? This failure should present challenges in tasks that rely heavily on object-centered spatial frames, and 4-year-olds have difficulty in such tasks including block construction and drawing, visuo-motor alignment tasks, and tasks that assess spatial relations across multiple objects (Landau & Hoffman, 2007). Nevertheless, in supportive situations, children may compensate by using long-term visual memory, as described above (see also, Simmering & Spencer, 2009). Indeed, there might be adaptive reasons to *not* bind visual features together in a fast, flexible manner in early development—this would help minimize errors in binding until enough evidence accumulates in long-term

visual memory to support a fully integrated representation of objects.

Note that our data do not address whether young children's difficulty in the feature binding task arises during the encoding, maintenance, or comparison of items that is required for the change detection task. Moreover, we cannot determine whether the feature-binding deficit at 4 years reflects a problem binding multiple features to one location or binding features together. For instance, several researchers have proposed that feature binding is achieved via phase-locked neural oscillations rather than through spatial means (Crick & Koch, 1995). Although this is computationally viable, it is not clear from this perspective why 4-year-olds, but not 5-year-olds, have difficulty binding features in VWM. By contrast, the developmental parallel between our findings and research on spatial cognitive development (e.g., Nardini et al., 2006) implicates some role for binding through space, although conclusive evidence will require studies that compare spatial memory and feature-binding performance within individual subjects.

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