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Varieties of Visual Working Memory Representation in Infancy and Beyond

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Abstract
Research on the developmental origins of visual working memory in infants has largely progressed along two separate branches. One branch is rooted in the classic work on adult visual working memory, while the other is rooted in the classic work on the object concept in infancy. Both lines of research have yielded some converging results but also some surprisingly different patterns. In this review, I show that these different patterns are evidence for two distinct types of representations, which I term *feature-based* and *object-based*. I then show that there is evidence for both representation types beyond infancy.

Keywords
visual working memory, infancy, object cognition, development

The study of visual working memory (WM) has for decades focused primarily on adults. More recently, interest in the developmental origins of visual WM has led researchers to ask how infants encode and maintain visual information over brief intervals, leading to a flurry of new research. However, this research has largely progressed along two separate branches. One branch, rooted in the classic work on adult visual WM, has explored how perceptual information about items is bundled and stored over brief durations. The other branch, rooted in the classic work on the object concept in infancy, has explored whether perceptual information can be integrated into infants' rich conceptual expectations about objects' physical properties and how the resulting representations are stored during brief occlusions.

These separate branches have yielded two robust sets of data that are both informative and internally coherent but difficult to integrate with each other. While the branches have yielded some similar results, they have also yielded some surprisingly different patterns, making it difficult to paint an integrated picture of the developmental origins of visual WM. In this review, I will outline the similarities and differences between the branches and show that the evidence in fact suggests two distinct representational formats in infant visual WM, which I term *feature-based* and *object-based*. I will then show that these distinct representation types are not limited to infancy but are supported in visual WM into adulthood.

The Change-Detection Branch

Visual WM in adulthood is typically studied using the change-detection task (adapted from Luck & Vogel, 1997). In this task, participants view computer-generated displays of two or more items, which then vanish. One of the items then reappears, but on some trials the item has changed features (e.g., from blue to green). Participants report whether they detected the change. Visual WM capacity is estimated based on the number of items for which participants can reliably detect feature changes—typically around three to four items.

Following in this tradition, Oakes and colleagues cleverly adapted the change-detection task for infants. They showed infants two arrays side by side. Both arrays vanished and reappeared repeatedly, but one array underwent featural changes across reappearances, whereas the other array remained unchanged. Infants were judged to have remembered the items in the array if they looked longer at the changing versus the unchanging array. Using this method, Ross-Sheehy, Oakes, and Luck (2003; Fig. 1a) found that 6.5-month-olds could detect a featural change only in displays containing one item. These

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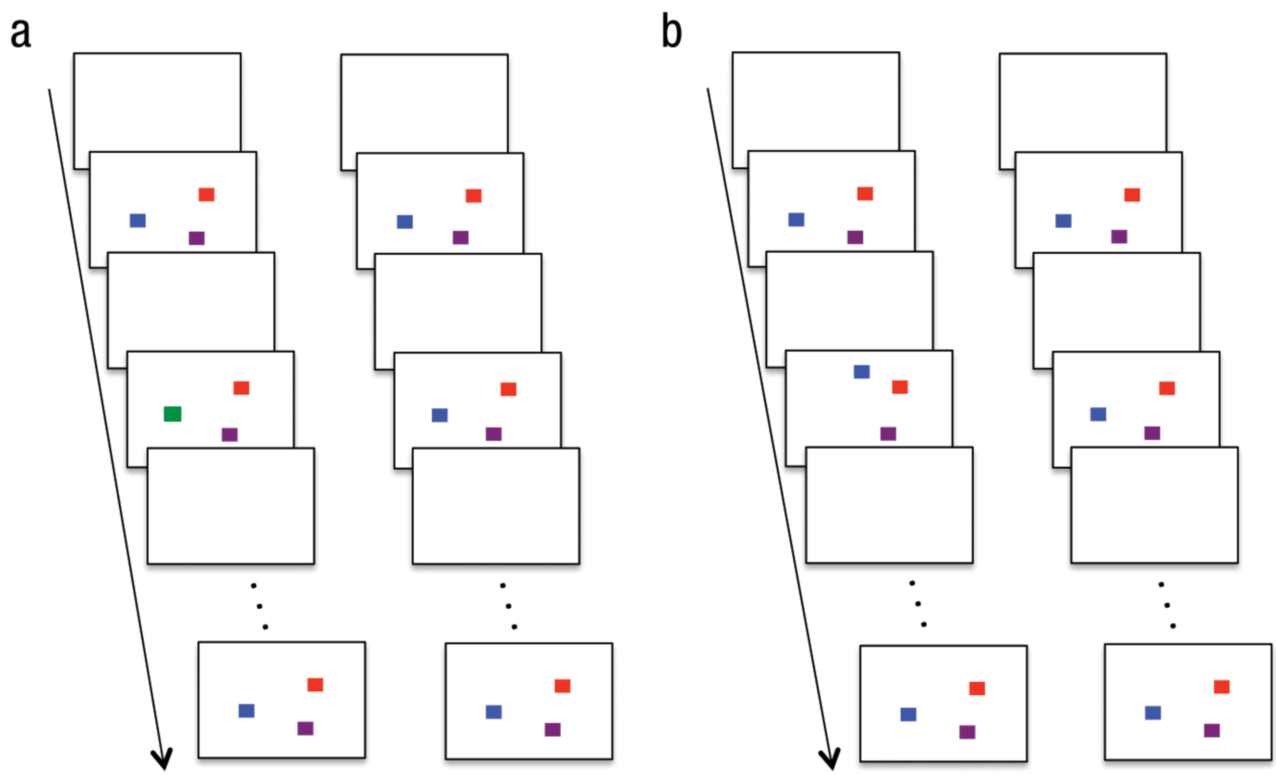

Fig. 1. Illustrations of example trial sequences in change-detection tasks used with infants. Panel (a) shows a trial in which infants view two streams of arrays that vanish and reappear continuously in a repeated alternating pattern, with one array undergoing featural changes and the other remaining unchanged (after Ross-Sheehy, Oakes, & Luck, 2003). Infants' attention to the changing versus unchanging display is measured as an index of infants' visual working memory. Panel (b) shows a similar method used to test memory for location (after Oakes, Hurley, Ross-Sheehy, & Luck, 2011).

infants also could detect a change in the location of only a single item (Oakes, Hurley, Ross-Sheehy, & Luck, 2011; Fig. 1b), further suggesting a capacity of one item. Indeed, 6.5-month-old infants failed to remember anything (locations or features) about items in larger displays. This severe limit eases with development—by 12 months, infants could reliably detect featural changes in arrays of up to four items (see also Kwon, Luck, & Oakes, 2014; Oakes, Baumgartner, Barrett, Messenger, & Luck, 2013).

Together, these patterns in infants' performance on the change-detection task suggest a structure for visual WM representations: Infants' visual WM can support a single item at 6.5 months, but this capacity increases with development. These representations appear to consist of integrated bundles of features, such that if all of the features of an item are forgotten, the item is not represented in visual WM.

The Objects-and-Occlusion Branch

The foundational work on the object concept explored the kinds of expectations infants have about how physical objects should behave. In these studies, real physical objects were occluded and then were revealed to have undergone changes that were either physically possible or physically impossible, and infants' attention to the displays was measured. While the words "working memory" were not used in these early studies, they provided initial evidence for the structure of infants' representations of objects during brief occlusion: Infants expected occluded objects to persist in physical space and to not suddenly vanish (Baillargeon, Spelke, & Wasserman, 1985), break apart (Spelke & Van de Walle, 1993), or lose cohesion or rigidity (Spelke, Breinlinger, Macomber, & Jacobson, 1992). In fact, infants could hold up to three (but not four) of these representations in visual WM at once (Feigenson & Carey, 2003).

Following in this tradition, later research explored what infants remembered about the features of objects. In these studies, objects were occluded and then disoccluded to reveal that they had undergone featural changes (e.g., to their color or shape). Using this method, Káldy and Leslie (2005) found that 6.5-month-old infants could remember the features of only a single object (see also Kibbe & Leslie, 2015), similar to the results found by Oakes and colleagues using the classic change-detection task. These findings suggested that featural information could be integrated into infants' conceptually rich representations of physical objects.

However, a more nuanced picture emerged when researchers asked what happens to these representations when featural information is forgotten. Kibbe and Leslie (2011; Fig. 2a) found that 6-month-olds who failed to notice when one of two hidden objects was revealed to have changed shape were nevertheless surprised when the object was revealed to have vanished completely, suggesting that infants could maintain a persisting object representation that did not contain information about the objects' features. Similarly, Zosh and Feigenson (2012; Fig. 2b) found that 18-month-olds who forgot the features of objects nevertheless expected the objects to conform to physical principles consistent with the object concept—infants failed to search in a box for missing objects after three objects were hidden and three featurally distinct (but physically cohesive) objects were retrieved, but continued to search when one of the retrieved objects was a non-object substance (e.g. a non-rigid, non-cohesive blob).

Kibbe and Leslie (2013) later showed that infants' ability to remember the features of individual objects is limited by the demands of tracking multiple objects in occlusion: Nine-month-olds could remember the features of two objects hidden behind two separate occluders but failed to remember these features when the same two objects were part of a set of three hidden objects. By 12 months, infants succeeded where 9-month-olds failed, suggesting that these limits ease with development.

Together, infants' pattern of performance on objects-and-occlusion tasks suggests a structure for visual WM representations: Infants' visual WM can support a small number of object representations, which can optionally have featural information bound to them if the attentional resources to do so are available. While these representations need not contain information about an object's featural identity, they appear to contain information about the object's *objecthood*; that is, they contain information about how physical objects in the world ought to behave. Infants' ability to maintain bindings between objects and their identifying features requires sustained attention and undergoes development between 6 and 12 months.

Continuity and Divergence Across the Branches

Evidence from both branches suggests that, by 12 months, infants' visual WM capacity is around three to four items and that infants' ability to remember features develops significantly between 6 and 12 months. Despite these similarities, however, there are critical differences that make further comparison challenging.

For example, 6.5-month-olds in Ross-Sheehy et al. (2003) could detect feature or location changes only in arrays containing a single item. By contrast, 6-month-olds in Kibbe and Leslie (2011) could remember multiple objects (at least two) in multiple locations, even when they forgot some of the objects' features. Each branch has also shown different trajectories in the development of visual WM for features. Oakes, Ross-Sheehy, and Luck (2006) found that 7.5-month-olds could reliably detect feature changes in three-item arrays, which was not due to other factors such as the development of attention, suggesting rapid visual WM development between 6.5 and 7.5 months,. By contrast, Kibbe and Leslie (2013) found that infants' ability to remember features in objects-and-occlusion tasks developed much more slowly and was dependent upon the attentional demands of the task. Indeed, infants in objects-and-occlusion tasks continue to show much more limited memory for features than for objects well into the 2nd year (Zosh & Feigenson, 2012).

Finally, when infants in objects-and-occlusion tasks fail to remember features, they continue to have robust expectations about how physical objects should behave (e.g., that they cannot vanish or lose cohesion), suggesting that information about conceptual objecthood is part of the object representation even when features are not. Indeed, infants' representations of objects can be disrupted if objects suddenly break apart as they move (Cheries, Mitroff, Wynn, & Scholl, 2008). By contrast, infants in change-detection tasks do not appear to have such constraints; items can be tracked even as they vanish and reappear, allowing infants to detect feature and location changes to items across physically implausible disappearances.

Evidence for Two Representational Formats

What drives the characteristic differences in infants' performance across the branches? Some methodological variables, such as encoding and/or maintenance duration or the complexity of feature changes, are less likely to be the source, since within each branch these also vary but yield similar patterns. Instead, differences in the physical properties of the stimuli themselves are the likely source. Items in the change-detection task are stationary, two-dimensional, and vanish and reappear in a way that is physically implausible. Items in objects-and-occlusion tasks move independently in three dimensions and physically persist in space even when occluded.

Indeed, infants' differential pattern of performance across the branches suggests two distinct representational formats in visual WM that reflect the physical plausibility of items in the to-be-remembered array:

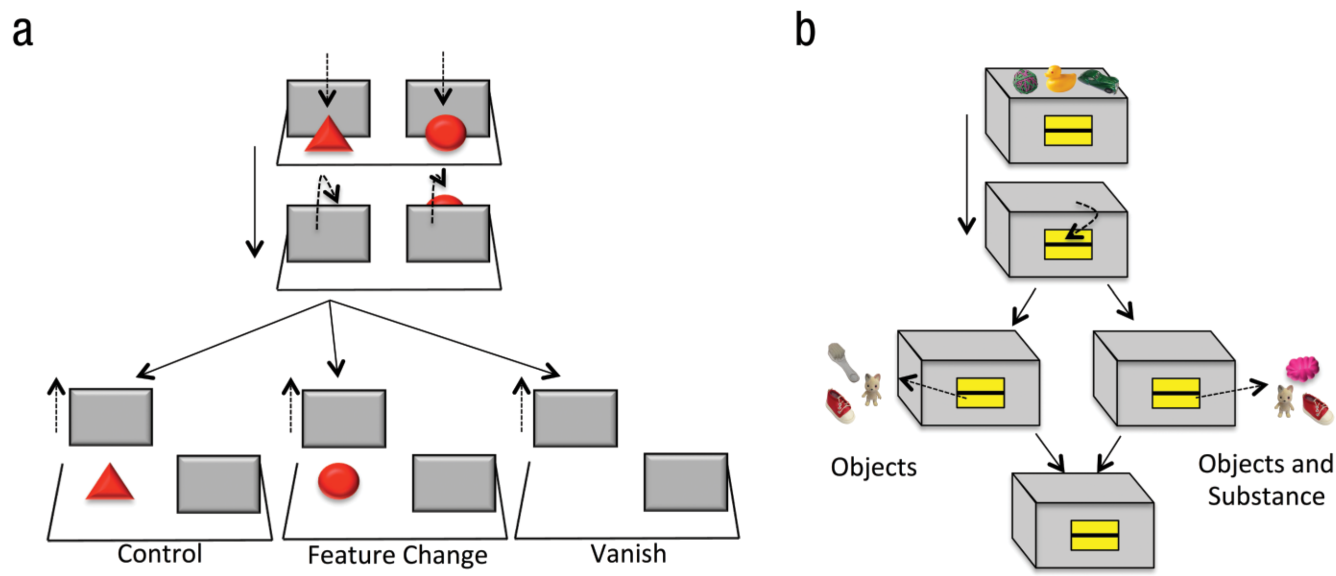

Fig. 2. Illustrations of example trial sequences in objects-and-occlusion tasks. Panel (a) depicts a scenario in which two objects are hidden sequentially behind screens in separate locations. One of the screens is then lifted to reveal either the control (unchanged) object, the object with its feature changed, or no object, and infants' looking time is measured as an index of infants' visual working memory for the hidden object (Kibbe & Leslie, 2011). Panel (b) depicts a scenario in which three objects are hidden inside of a box, and then infants are allowed to retrieve either three featurally distinct objects or two objects and a non-object substance (e.g., a non-rigid, non-cohesive blob). Infants' continued search of the box following retrieval is measured as an index of infants' visual working memory for the hidden objects (Zosh & Feigenson, 2012). Panel (a) is adapted from "What Do Infants Remember When They Forget? Location and Identity in 6-Month-Olds' Memory for Objects," by M. M. Kibbe and A. M. Leslie, 2011, *Psychological Science, 22*, p. 1501. Copyright 2011 by the Association for Psychological Science. Adapted with permission.

feature-based representations and *object-based* representations (Table 1). These terms refer to the most fundamental component of each representation type. Feature-based representations are characterized as integrated bundles of features. If all features are forgotten, items are not represented. Feature-based representations persist even when items violate physical laws (e.g., by vanishing and reappearing). By contrast, object-based representations are characterized by robust structures that contain information about the physical properties of three-dimensional objects, which may optionally have featural information bound to them. If features are forgotten, the core object representation remains. Unlike feature-based representations, object-based representations can be disrupted when objects violate physical laws. EEG evidence from infants supports this distinction: Different brain areas underlie representations of items that vanish versus objects that persist in occlusion (Kaufman, Csibra, & Johnson, 2005).

Crucially, both representational formats can contain information about items' features (or only a subset of the items' features; e.g. Cowan, Blume, & Saults, 2013; Hespos & Baillargeon, 2001), enabling identification of items. However, the way features are integrated into the representation, and what (if anything) remains of the representation when features are forgotten, differs across the two representational formats (see Table 1).

Representational Continuity Across Development

Both feature-based and object-based representations are supported in visual WM beyond infancy. Evidence for feature-based representations across development comes from young children's and adults' performance on the classic change-detection task (see Simmering & Perone, 2012), which shows the signatures of feature-based representations summarized in Table 1. Recently, a variety of models have been proposed to characterize visual WM representations based on change-detection performance (e.g., the slots + averaging model: Zhang & Luck, 2008; the resource model: Bays & Husain, 2008; the hierarchical-structure model: Brady & Tenenbaum, 2013), all of which could explain infants' pattern of performance on the change-detection task and suggest representations that are consistent with feature-based representations. However, while these and other models have progressed the field toward understanding the structure of feature-based representations, none of the models can explain infants' pattern of performance on objects-and-occlusion tasks, and thus they cannot account for object-based representations (see Kibbe & Leslie, 2013, for a detailed discussion).

Evidence for object-based representations in adulthood comes instead from multiple-object-tracking (MOT) tasks. In MOT tasks, participants must track a set of target objects

Table 1. Summary of the Characteristics of Feature-Based and Object-Based Representations

Feature-Based Representations	Object-Based Representations
Common Attributes	
Can be stored in visual WM	
Can contain featural information, enabling identification of items	
Supported in visual WM across the life span	
Essential Differences	
Features are integrated into the representation	Can be featureless
Arise from physically implausible arrays	Arise from physically plausible arrays
Not limited by physical laws; persist when to-be-remembered items violate physical laws (e.g. vanishing)	Contain information about an object's physical *objecthood;* can be disrupted when to-be-remembered items violate physical laws
Incidental Differences	
Studied using the classic change-detection task	Studied using objects-and-occlusion or multiple object-tracking tasks

Note: Both representational types share some common attributes. The essential differences identified in the table reflect structural dissimilarities that distinguish the two representational formats. Incidental differences reflect variation across the branches—removing these differences (e.g., by exploring how occlusion impacts performance on the classic change-detection task; Kibbe, 2015) can yield new insights into the characteristics of these different representational formats.

as they move independently among moving distractors, sometimes in and out of occlusion. Adults in MOT tasks show performance signatures similar to those of infants in objects-and-occlusion tasks: They can track approximately four items through occlusion but are unable to track items that do not conform to principles of physical persistence (e.g., if the items vanish or deform as they move; Scholl & Pylyshyn, 1999; Zhou, Luo, Zhou, Zhuo, & Chen, 2010). Further, they can track items without necessarily tracking their features (Pylyshyn, 2004), similar to infants (Kibbe & Leslie, 2011). Indeed, when object-based representations are stored in visual WM, adults show signature constraints similar to those of infants in analogous tasks (Kibbe, 2015; Li, Zhou, Shui, & Shen, 2015; Saiki, 2003).

Note that the evidence I have described supports varieties of representational formats across the life span, not varieties of working memories. Common processes in visual WM likely operate over multiple representational formats (e.g., processes that support encoding, maintenance, and retrieval of information; Kibbe & Feigenson, 2014; Shipstead & Engle, 2013). Both representational formats might be supported by binding processes (e.g., Kahneman, Treisman, & Gibbs, 1992; Leslie, Xu, Tremoulet, & Scholl, 1998), which incorporate information about locations and features into cohesive feature-based representations (e.g., Xu & Chun, 2006) or bind locations and features to core object representations to form cohesive object-based representations. Visual WM itself can be characterized as a dynamic process that flexibly works with other cognitive processes to allow performance of the task at hand (see Kibbe & Kowler, 2011; Simmering & Perone, 2012). In fact, the demands of visual WM tasks themselves likely inject some variability into estimates of visual WM capacity. For example, young children in change-detection tasks can remember fewer items than infants in similar tasks, likely as a result of task demands unrelated to representational format (Cowan, AuBuchon, Gilchrist, Ricker, & Saults, 2011; Simmering, 2012).

Conclusions

The goal of this article was to shed light on two patterns of results from divergent branches of the study of the development of visual WM. The evidence suggests that visual WM supports two different representational formats early in infancy, feature-based representations and object-based representations, and that both show continuity into adulthood. That infants can maintain context-appropriate representations, using the same representational formats that adults do, suggests that visual WM is flexible and robust early in development.

This new framework opens a variety of avenues for future research. One exciting avenue involves the further exploration of object-based representations in adulthood. The notion that visual WM supports object-based representations extends the "core knowledge" framework proposed by infant researchers (e.g., Baillargeon et al., 2012; Spelke et al., 1992) into a new domain and suggests that visual WM representations can contain rich conceptual information about objects. Further study is needed to explore how these representations are encoded, maintained, and manipulated in adult visual WM (see Strickland & Scholl, 2015, and Kibbe, 2015, for some steps toward this goal).

Recommended Reading

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Simmering, V. R., & Perone, S. (2012). (See References). An extensive theoretical analysis of a large number of child and adult visual working memory studies, taking a dynamic-systems approach.

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Declaration of Conflicting Interests

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