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Developmental changes in infants' visual short-term memory for location

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ABSTRACT

To examine the development of visual short-term memory (VSTM) for location, we presented 6- to 12-month-old infants ($N = 199$) with two side-by-side stimulus streams. In each stream, arrays of colored circles continually appeared, disappeared, and reappeared. In the *changing* stream, the location of one or more items changed in each cycle; in the *non-changing* streams the locations did not change. Eight- and 12.5-month-old infants showed evidence of memory for multiple locations, whereas 6.5-month-old infants showed evidence of memory only for a single location, and only when that location was easily identified by salient landmarks. In the absence of such landmarks, 6.5-month-old infants showed evidence of memory for the overall configuration or shape. This developmental trajectory for spatial VSTM is similar to that previously observed for color VSTM. These results additionally show that infants' ability to detect changes in location is dependent on their developing sensitivity to spatial reference frames.

1. Introduction

The input to the visual system consists of brief static snapshots during periods of fixation, separated by sudden shifts of gaze during which vision is effectively suppressed (Henderson, 2008). The ability to store information from one fixation and compare it to a subsequent fixation is essential to recognize the correspondence between particular objects in the first and second fixation periods, to determine whether the saccade actually landed on the intended target, and to integrate information acquired from the individual fixations into a coherent representation of the entire scene. Therefore, adults—and infants—need a memory system that can rapidly store information gained from one period of fixation and maintain that information long enough so that it can be integrated with information from the next period of fixation. The adult visual short-term memory (VSTM) system has these properties and is used every time we blink, make a saccadic eye movement, compare two objects that cannot be simultaneously fixated, or observe objects that are momentarily occluded (Hollingworth & Henderson, 2002; Irwin, 1991; Pomplun, Reingold, & Shen, 2001; Pomplun et al., 2001; Scott-Brown, Baker, & Orbach, 2000). VSTM, therefore, is critically important for infants who encounter an enormous number of new objects and scenes. Because information about objects and scenes is experienced over temporal gaps due to blinks, eye movements, and occlusion, infants would have difficulty learning about those object, events, and scenes, if they could not use VSTM to integrate visual information over time.

Research has revealed significant development in VSTM for object identity over the first postnatal year. Given its importance for moment-to-moment visual processing, it is not surprising that VSTM emerges at least by 4 months (Ross-Sheehy, Oakes, & Luck, 2003). However, VSTM at this age is quite limited: 4- to 6-month-old infants can store the features of a single item in VSTM (e.g., the item's color), but they have difficulty storing information about items in multiple-item arrays (i.e., arrays that contain two or more simple items). There appears to be a rapid developmental shift between 6 and 8 months, when infants become able to store the features of multiple items (Ross-Sheehy

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et al., 2003) and bind these features to their spatial locations (Oakes, Messenger, Ross-Sheehy, & Luck, 2009; Oakes, Ross-Sheehy, & Luck, 2006). Remarkably, Kaldy and Leslie (2003, 2005) observed a transition at this same point in development for infants' memory for object identity and the binding of identity to location using tasks in which objects and events could be encoded over several seconds and must be remembered over tens of seconds. Although our focus here is on VSTM (in which encoding and retention occur over periods of tens or hundreds of milliseconds), the similarity in the developmental trajectory in these two task contexts suggests some similarity in the underlying processes.

The present investigation extends the existing literature by examining infants' VSTM for location information. This extension is important because tasks such as object comparison and eye-movement targeting depend on representing not only *what* items were in the array, but also *where* the items were located. For example, making accurate eye movements requires encoding and maintaining a representation of where items were located in a visual array. Separate dorsal-stream and ventral-stream areas appear to be involved in representing location information and object identity, respectively (Goldman-Rakic, 1996; Jonides et al., 1997; Postle & D'Esposito, 1999; Ungerleider, Courtney, & Haxby, 1998). Moreover, these dorsal and ventral pathways appear to undergo different developmental trajectories (e.g., Distler, Bachevalier, Kennedy, & Mishkin, 1996; Kovacs, 2000; Mash, Quinn, Dobson, & Narter, 1998). Thus, our understanding of infants' developing VSTM for item identity may or may not translate to the development of VSTM for location.

In addition, a full understanding of the origins and development of short-term memory requires examining infants' VSTM for spatial information. In Baddeley's influential working memory model, modality-specific *slave systems* are used for storing information, and a *central executive* is used to read, write, and manipulate this information (Baddeley, 1986, 1992; Baddeley & Hitch, 1974; Baddeley & Logie, 1999). Short-term storage of visual information is accomplished by a *visual cache* that is used to store visual object identities, and a separate *visuo-spatial sketchpad* that is used to store spatial information (Baddeley & Logie, 1999). Thus, this model proposes a dissociation between memory for object properties like color and shape, and memory for spatial properties like location. It should be pointed out that Baddeley's work asked whether the memory system that is used in typical STM tasks is a "working memory" (i.e., a memory system that is used for the temporary storage and manipulation of information in the service of complex tasks). Because it is difficult to determine whether the memory system isolated in experimental paradigms used with infants is a working memory (see Reznick, 2007), we use the more conservative term *short-term memory* to refer to the memory system we are studying. However, the task we use to study VSTM in infancy (Oakes et al., 2006, 2009; Ross-Sheehy et al., 2003) is closely related to a task commonly used in adults to study a short-term memory system that has shown to function as a working memory (see Luck, 2008), and it is therefore very likely that the infant version of this task taps into the developmental origins of the adult working memory system. A few studies have examined some aspects of infants' working or short-term memory for location information (Gilmore & Johnson, 1995; Reznick, Morrow, Goldman, & Snyder, 2004), but infants' developing VSTM for object identity information has been studied more extensively (Oakes et al., 2006, 2009; Ross-Sheehy et al., 2003). Thus, an important step in our understanding of this aspect of infants' memory is to document the developmental trajectory of VSTM for location.

Understanding infants' VSTM for location is also important because there are many different reference frames that can be used to encode location, and the salience of those reference frames may vary by context or over development. Locations are coded in a retina-centered reference frame from the retina through the early stages of cortical processing, but this frame is unstable because it shifts every time the eyes move. Consequently, later stages of processing recode information with respect to more stable reference frames. For example, the location of an object can be encoded relative to the highly stable environmental reference frame provided by the ceiling or walls of a room, which do not vary with the viewpoint of the observer or with changes in locations of other objects in the room. Locations can also be coded with respect to reference frames provided by the observer's body or by other objects in the environment, which are less stable than the overall environmental reference frame but are more stable than the retina-centered reference frame.

The adult primate brain uses all of these reference frames (Cohen & Andersen, 2002), depending in which is most useful for a given task (e.g., programming eye movements, reaching for objects, navigating an environment). Infants also use these different types of reference frames in tasks that engage long-term memory (LTM) systems (i.e., when visual arrays are available for inspection over many tens of seconds, or hiding events occur over many seconds or minutes). In such tasks, infants represent object locations relative to other objects in scenes (Acredolo & Evans, 1980; Quinn, 1994), relative to structural features of the environment, such as the edge of a sandbox (Newcombe, Huttenlocher, & Learmonth, 1999), and relative to their own body (Acredolo & Evans, 1980). However, infants' reliance on one encoding strategy over another may be driven by the demands of the task, by development, or both.

In multiple-item arrays, location can be encoded in terms of the overall *configuration*. Here, we use the term "configuration" to mean some kind of shape-based representation, in which the locations define key elements of the shape (e.g., vertices) and in which the locations are defined with respect to the shape. In the two sets of three O's shown below, for example, the location of each O can be remembered: (1) relative to one's eye position, (2) relative to the edges of the page, or (3) in terms of its position within the triangle made by the set of three O's (i.e., in terms of the *configuration*). That is, a set of *N* locations can be represented by an *N*-sided polygon in which the locations define the vertices of the polygon.

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