Cognitive Development 38 (2016) 1–9

Contents lists available at ScienceDirect

Cognitive Development

The ring that does not bind: Topological class in infants' working memory for objects

Melissa M. Kibbe[a,*], Alan M. Leslie[b]

[a] Boston University, Department of Psychological and Brain Sciences, 64 Cummington Mall, Boston, MA 02215, United States
[b] Rutgers University, Department of Psychology and Center for Cognitive Science, 152 Frelinghuysen Rd, Piscataway, NJ 08854, United States

ARTICLE INFO

Article history:
Received 23 February 2015
Received in revised form 7 December 2015
Accepted 18 December 2015
Available online 11 January 2016

Keywords:
Object representations
Working memory
Topology
Infants

ABSTRACT

Infants and adults are highly sensitive to objects' topology (geometrical invariance under stretching). Indeed, topological class information may form the essential core of object representations. We tested this hypothesis by studying 6-month-old infants, who can remember the existence of multiple objects but are limited to remembering the featural identity (e.g., shape or color) of only one object. In two experiments, after hiding two topologically distinct objects separately, we revealed one of the objects to have either changed topology, remained the same, or vanished completely. Bayes Factor analysis showed that infants remembered the topology of only one of the two hidden objects ($n = 24$, Experiment 1), but failed to remember anything about the other object ($n = 36$, Experiment 2). These results contrast with the case of shape and suggest a different, more nuanced role for topological class in infants' object representation.

1. Introduction

Infants are greatly limited in their ability to represent the featural properties (e.g., color, shape, texture, etc.) of objects. Infants fail to individuate objects by shape until around five months of age, and it is not until 11.5 months that they successfully individuate objects by color or luminance (Wilcox, 1999; Woods & Wilcox, 2006). Infants' ability to bind featural information to object locations also undergoes protracted development (Mareschal & Johnson, 2003). At six months, infants can remember the featural identity (e.g., color or shape) of only a single object in a location (Káldy & Leslie, 2005; Ross-Sheehy, Oakes, & Luck, 2003). While these limits ease with development (Oakes, Ross-Sheehy, & Luck, 2006), infants' memory for object features remains fragile (Kibbe & Leslie, 2013), even well into the second year of life (Kibbe & Feigenson, 2016; Zosh & Feigenson, 2012; Tremoulet, Leslie, & Hall, 2000). Indeed, object identities may not to be attended to or processed even when the objects are visible: 4-month-old infants fail to use featural cues such as color or pattern to detect object boundaries or continuities in displays in which objects are partially in view (Kellman & Spelke, 1983; Needham, 1999).

While previous research has shown that infants' ability to represent object features shows a lengthy developmental time course, other research has emerged that at least one feature may hold a more privileged position in infants' object representations: topological class. An object's topological class is defined by those geometric properties that remain invariant under continuous deformations—like stretching or bending—that change the length, angles, or other metrical properties of

* Corresponding author.
E-mail addresses: kibbe@bu.edu (M.M. Kibbe), aleslie@ruccs.rutgers.edu (A.M. Leslie).

http://dx.doi.org/10.1016/j.cogdev.2015.12.001
0885-2014/

edges and surfaces. For example, objects that are *open* versus those that are *closed*, or objects with holes versus without holes, belong to different topological classes. Stretching or bending will not change a disk into a donut, though 'metrical' shape may well change (the disk may become, e.g., an oval). To illustrate, the findings reviewed in the paragraph above all concerned infants' sensitivities to changes in (metrical) shape, color, luminance, or pattern, while topological class remained unchanged.

Topological class information appears to be detected, discriminated, and maintained early in infancy. Newborn infants spontaneously categorize objects by topology; after repeated exposure to either open or closed forms, newborns showed increased looking to topologically distinct forms (Turati, Simion, & Zanon, 2003). Indeed, infants' sensitivity to topology appears to precede their sensitivity to geometric properties such as shape. In a recent study, Chien et al. (2012) found that infants at 1.5 months could discriminate objects by topology, but it was not until 3.5 months that they could discriminate objects by shape. Similar results on the primacy of topological class over shape information have been found in adults (Chen, 1982) and even in bees (Chen, Zhang, & Srinivasan, 2003).

Infants' reasoning about how objects should interact appears to be constrained by topological class. Infants distinguish among solid objects, containers, tubes, and rings early in infancy, long before they use featural information such as size or shape to reason about how objects should interact (Baillargeon et al., 2012). For example, two-and-a-half month-old infants expect that objects with a deep concavity can contain other objects and expect another solid object can enter the concavity only through the open end but not through one of the sides (Hespos & Baillargeon, 2001a; Wang, Baillargeon, & Paterson, 2005; see also Caron, Caron, & Antell, 1988). But it is not until 7.5 months that infants use the objects' relative heights to reason about whether a given container can completely hide an object entering that concavity (Hespos & Baillargeon, 2001b; Hespos & Baillargeon, 2006), and it is not until 14 months that infants use object height to reason about whether a tube can completely hide an object (Wang, Baillargeon, & Paterson, 2005). The critical difference, geometrically speaking, between the container (cylinder with a deep concavity but no hole) and the tube (identical cylinder with a hole) is in topological class. Topology can be highly behaviorally relevant and can provide a powerful cue to how objects should interact with each other, and how agents can act upon objects.[1]

Evidence for the primacy of topological information in infants', adults', and non-human animals' representations of objects has led researchers in both the infant (e.g. Baillargeon et al., 2012) and adult (e.g., Chen, 2005) literatures to propose that topological class may be an essential part of an object representation. Baillargeon et al. (2012) suggest that whether an object is open or closed is represented in the "structure" of an object representation, while other features such as shape, color, and texture may be optionally bound to the object representation. In adults, changing the topology (but not shape, color, or luminosity) of objects in motion disrupts multiple object tracking (Zhou, Luo, Zhou, Zhuo, Chen, 2010), leading these authors to argue that the "core intuitive notion of an object [is] characterized precisely as topological invariance." Under this proposal, if topological class information is not represented, then the *object* is not represented. However, an alternative possibility is that topological class may interact with object representation in a more nuanced way, such that contrast in topological class may make multiple object tracking more costly. Under this proposal, topological class information is not essentially represented, but may play a different role in object representation than surface features such as metrical shape. Nevertheless, to our knowledge no research has directly tested the hypothesis that topological class information is a necessary part of an object representation.

We tested the above hypothesis by taking advantage of a robust signature limit in 6-month-olds' memory for objects. By 6 months of age, infants can remember the existence of multiple individual hidden objects (e.g., Wynn, 1992; Simon, Hespos, & Rochat, 1995; Wilcox, 1999). However, 6-month-olds are much more limited when it comes to remembering the featural identities (e.g., shape, color) of those objects. While infants consistently can remember the featural properties of a single object, they consistently *fail* to remember the featural properties of *more* than a single object (Káldy & Leslie, 2005; Kibbe & Leslie, 2011; Ross-Sheehy et al., 2003). For example, Káldy and Leslie (2005) showed infants two shapes hidden sequentially behind two different screens. When they then lifted the screen occluding the last-hidden object and showed infants that it had changed shape, infants looked longer than when the expected shape was revealed, suggesting that they successfully remembered the shape of the object. But when infants were tested in the same way for the object that was hidden *first,* infants failed. However, when infants forget the features of an object, not all is lost. Using a similar method, Kibbe and Leslie (2011) found that infants who forgot the shape of an object nevertheless remembered its existence and were surprised when it vanished completely, suggesting that they had retained a representation of the object even though they failed to remember what the object looked like.

This signature pattern in 6-month-olds' working memory for objects—that they can remember multiple individuated objects, but can remember the features of only one object—makes them an ideal age group to test the hypothesis that topological class is essential to the structure of an object representation. We used the two-screen task of Kibbe and Leslie

[1] The topological class of the (real world) containers in the studies cited here is somewhat moot. If the container is considered as formed by depressing one end of a solid cylinder to form a dimple then stretching the end surface further in until a deep concavity is formed, then the resulting object is of the same class as the original cylinder. If, however, it is considered as starting out as a hollow cylinder (like a can) that then has one end removed (as by a can-opener), then it is of a different class from the unopened cylinder. If the opened can has the other end removed too (making a tube) then it has a double-holed topology. The underlying question concerns how the infant represents the geometry of these various real world objects, a question that, as far as we know, is unstudied.