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

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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

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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.

(2011) to examine 6-month-old infants' ability to maintain topological class information in object representations held in working memory. We showed infants two objects that contrasted in topological class: a disk and a ring. We reasoned that the topological distinction between these objects would be readily detectable by infants, since much younger infants have been shown to discriminate disks and rings in two-dimensional displays (e.g., Chien et al., 2012) and to use topological class to reason about how three-dimensional objects should interact (e.g., Hespos & Baillargeon, 2001a; Wang et al., 2005). We then hid the two objects behind two separate screens. This allowed us to test infants' memory for each location separately, by revealing either the object that was hidden *last* (for which infants can remember surface features such as metrical shape), or the object that was hidden *first* (for which infants previously have been shown to only remember the object's existence, but not features such as shape).

In Experiment 1, we first confirmed that infants could remember topological class by testing their memory for the topological class of last-hidden object. We revealed either the object that had been hidden originally (control) or that the object had changed topological class (swap). While previous research has shown that infants are sensitive to topological class and use it to reason about how objects should interact, no study to our knowledge has shown that infants can hold topological class information in working memory. We predicted that, since infants have been shown to robustly recall surface features of this object in previous studies (e.g., Káldy & Leslie, 2005), infants would successfully remember the topological class of the hidden object and look longer at the display when the topology of the object is revealed to have changed.

In Experiment 2, we then tested the hypothesis that topological class is essential to the structure of an object representation by testing infants' memory for the *critical first-hidden* object. We revealed either the object that had been hidden originally (*control*), that the object had changed topological class (*swap*), or that the object vanished completely (*vanish*). This method allowed us to test three contrasting hypotheses. If topological class essentially *is* the object representation (e.g., Zhou et al., 2010), then infants should remember both the topology and the existence of the object, and look longer at both the *swap* and *vanish* conditions versus the *control* condition. If topological class information is optional and requires binding to an otherwise featureless object representation, then infants should forget the topology of the object but remember its existence, consistent with previous results for metrical shape, and look longer at the *vanish* condition versus both the *swap* and *control* conditions. Finally, topological class may not be essential to the object representation, but instead may interact with object representation to make tracking multiple objects from contrasting topological classes more costly. In this case, we may observe infants looking equally at *swap*, *vanish, and control* outcomes.

In both Experiments 1 and 2, we used Bayes Factor analysis (Gallistel, 2009; Rouder et al., 2009) to provide statistical support for or against the null hypothesis that infants cannot remember the topological class (Experiments 1 and 2) or existence (Experiment 2) of an object. Bayes Factor analysis, unlike traditional null hypothesis significance testing, allows us to either accept or reject the null hypothesis by yielding the odds that two data sets were generated by the same or different processes. Bayes Factor analysis thus makes null results interpretable; obtaining odds for the null hypothesis allows us to accept the null hypothesis with confidence. For example, if we obtain significant odds for the null hypothesis in comparing the *control* and *swap* conditions of Experiment 2, we can confidently conclude that infants fail to remember the topological class of the probed object (see Kibbe & Leslie, 2011, 2013 and Kwon, Luck, & Oakes, 2014 for previous applications of Bayes Factor Analysis to infant looking time data).

2. Experiment 1

2.1. Participants

Twenty-four healthy, full-term infants participated at Johns Hopkins University (mean age: 5 months 29 days; range: 5 months 14 days to 6 months 16 days; 13 girls). An additional 2 infants were tested but excluded from analysis due to fussiness (1) or experimenter error (1). Participants were recruited from the Baltimore area through phone and mailing lists. All infants received a small gift for participating.

2.2. Materials

Stimuli consisted of a red wooden disk (10.15 cm in diameter, 0.8 cm thick) and a red wooden ring (10.15 cm in diameter with a 3.8 cm diameter hole in the center, 0.8 cm thick). During test trials, these objects could be hidden separately behind two gray foam-core occluding screens (17.75 × 17.75 cm). Stimuli were presented on a black wooden stage (130 × 43 × 50 cm). The stage was covered by a black curtain between trials. The experimenter wore long white gloves and wore jingle bells around her right wrist to help guide infants' attention to the actions on the stage. The presentation of stimuli was timed using a metronome.

2.3. Procedure

Infants were seated in a caregiver's lap about 70 cm from the stage. At the beginning of the experiment, the experimenter raised the curtain revealing the empty stage. She then drew infants' attention to the bottom and top corners and the center of the stage by jingling the bells around her wrist, so that an observer who was watching the infant on a monitor could get a sense of the infant's eye positions relative the stage. The experimenter then lowered the curtain in front of the stage.

2.3.1. Familiarization

At the beginning of each familiarization trial, the experimenter raised the curtain revealing the empty stage. She then placed the objects one at a time on the center of the stage about 7 cm apart, removing her hand from the stage area after the placement of the second object. After 4 s, the experimenter moved the objects one at a time to the back of the stage in the same order they were presented (e.g., if disk was placed first, disk was moved first), again removing her hand after the placement of the second object. The objects in their final positions were approximately 55 cm apart. Infants were then allowed to freely view the objects for an 8 s period. After 8 s, the trial ended and the experimenter lowered a curtain over the stage.

The experimenter repeated this procedure three additional times, for a total of four familiarization trials. Across familiarization trials, the order in which the objects were presented and their relative locations on the stage were counterbalanced. This meant that infants could not form any long-term associations between the features of an object and its temporal order or spatial location, since this varied across trials. There was no occlusion during familiarization trials. Fig. 1, top panel, shows a sample familiarization trial.

2.3.2. Test

At the beginning of each test trial, the experimenter raised the curtain revealing the empty stage. She then placed the two occluders on the empty stage, and then placed the two objects in front of the occluders, one at a time, removing her hand from the stage area after the placement of the second object. After 4 s, the experimenter reached in and moved the objects to the back of the stage one at a time in the order in which they were initially presented, just as she had done during familiarization trials, this time hiding the objects one at a time behind each occluder (taking about 3 s to hide each object). After each object was hidden, the experimenter showed infants her empty hand, palm out (about 2 s). Unlike in the familiarization trials, the experimenter then immediately drew infants' attention to the screen occluding the last-hidden object by jingling bells she wore around her wrist for about 2 s. She then lifted the screen to reveal one of two possible outcomes. Half of the infants saw the object that had been hidden in that location originally (e.g., the disk was hidden and the disk was revealed, *control condition*). For the other half of infants, the object was surreptitiously swapped for the other object through a hidden trap door in the back of the stage (e.g., the disk was hidden and the ring was revealed; *swap condition*). Because our task requires infants to track the locations of objects across trials, we chose a between-subjects design to mitigate interference effects of observing different kinds of outcomes across trials. Crucially, the durations of hiding and revealing the objects were kept constant across conditions. While objects were only swapped during the *swap* condition, the experimenter opened and closed the trap doors during the *control* condition as well to equate sound and timing. A period of 4 s elapsed between when the probed object was hidden and when it was revealed.

An observer who was unaware of the condition timed infants' looking duration after the screen was lifted. When infants looked away for two consecutive seconds, the observer signaled the experimenter to end the trial. The experimenter then lifted the curtain to hide the stage from view.

Infants then saw three more test trials, for a total of four. Just as in the familiarization trials, the order of placement and relative locations of the objects were counterbalanced across trials. Thus, to succeed at the task, infants had to hold in working memory the identities of the objects in each location on any given trial, since they could not form any long-term associations between particular objects and locations. Fig. 1 shows a sample test trial (middle panel) and the two experimental outcomes (bottom left panel) in Experiment 1.

An additional observer later rescored a random 50% of infants' looking times frame-by-frame using Preferential Looking Coder (Libertus, 2011). Inter-observer agreement averaged $r = 0.96$.

2.4. Results

Analyses were based on 96 total test trials. Because looking time data is not normally distributed, all data were log transformed to correct for right skew (Hays, 1994); this is a common procedure when analyzing infant looking-time data (e.g., Kibbe & Leslie, 2011; Leslie & Chen, 2007; Spelke, Kestenbaum, Simons, & Wein, 1995). We conducted a repeated-measures ANOVA with Trial (4: *1st*, *2nd*, *3rd*, or *4th*) as a within-subjects factor and Condition (2: *control* or *swap*) as a between-subjects factor. We observed no main effect of Trial ($F_{3,66} < 1$, $p = 0.80$, $\eta_p^2 = 0.014$) and no Trial X Condition interaction ($F_{3,66} = 1.19$, $p = 0.31$, $\eta_p^2 = 0.052$). We observed a significant main effect of Condition ($F_{1,22} = 4.92$, $p = 0.037$, $\eta_p^2 = 0.183$); infants who saw the *swap* outcome looked longer than infants who saw the *control* outcome.

In addition to conventional statistical methods, we also conducted a Bayes Factor analysis to obtain the odds for or against the null hypothesis that infants cannot remember the topology of the last-hidden object. Bayes Factor analysis revealed odds of 3.18:1 *against* the null hypothesis, greater than the 3:1 odds that may be considered roughly equivalent to the $p = 0.05$ level in conventional statistics (Gallistel, 2009). Fig. 2 shows mean raw looking times and mean log-scaled looking times for both conditions in Experiment 1.

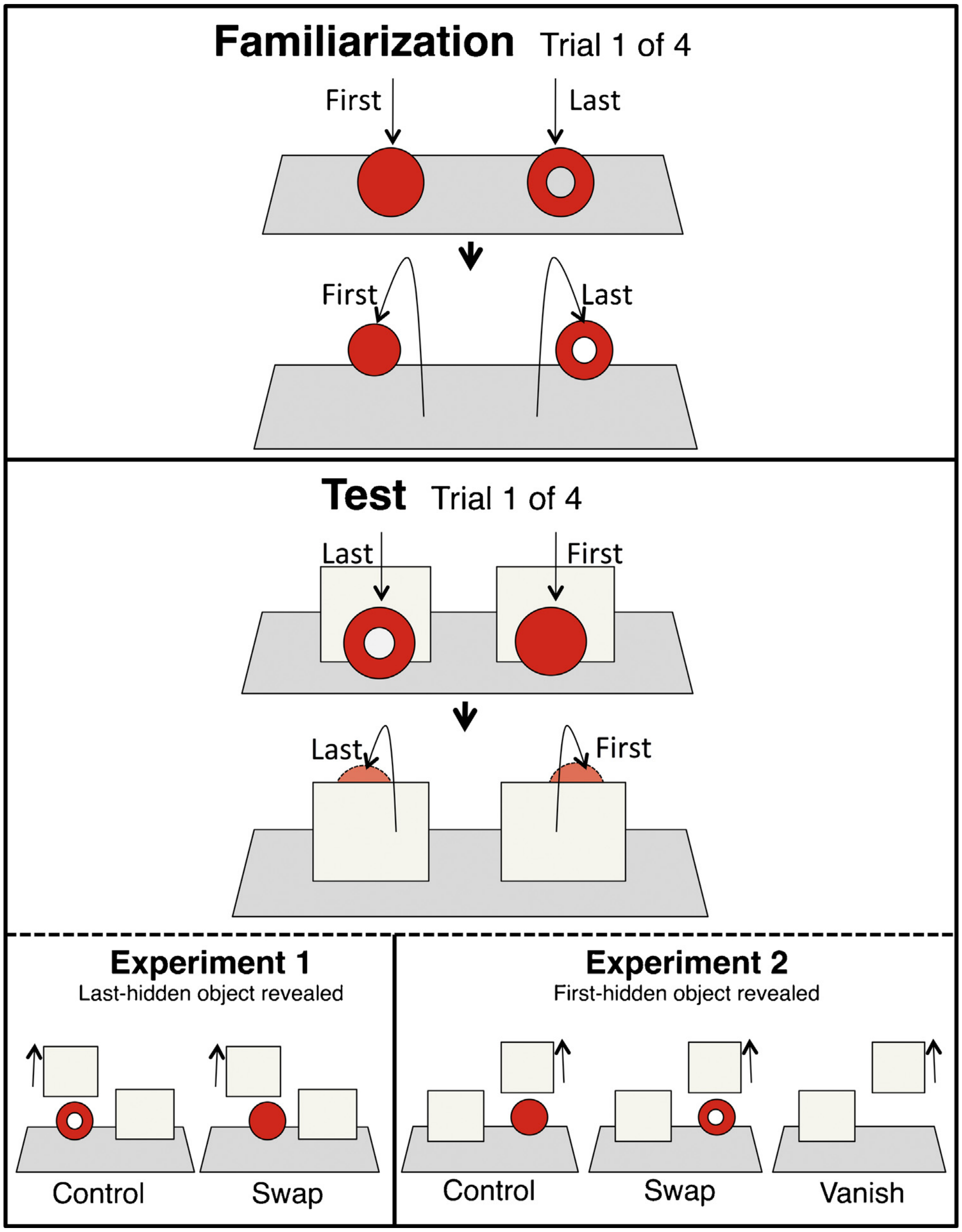

Fig. 1. Top panel shows a sample familiarization trial from Experiments 1 and 2. Middle panel shows a sample test trial sequence, in which the two objects are hidden sequentially, each behind their own screen. Bottom panels show test trial outcomes from Experiment 1 (left panel), in which the last-hidden, harder-to-recall object is revealed, and Experiment 2 (right panel) in which the first-hidden, harder-to-recall object is revealed.

2.5. Discussion

In Experiment 1, infants successfully remembered the topological class of the last-hidden object, consistent with previous results showing that 6-month-old infants successfully recall surface features of one object (e.g., Káldy & Leslie, 2005; Ross-Sheehy,et al., 2003). To our knowledge, this result is the first to demonstrate that infants can hold information about topological class in working memory. Moreover, it shows that the difference between the stimuli is indeed detectable and recallable by 6-month-olds.

Previous work demonstrated that infants fail to remember surface features (e.g., shape) of the first-hidden of two hidden objects, but nevertheless remember its existence (Kibbe & Leslie, 2011). Therefore, in Experiment 2, we asked whether 6-month-olds also could remember the topological class of this object. If topology is an essential part of the structure of an object representation, then infants in Experiment 2 should look longer when the topology of the first-hidden object changes, just as they were surprised when the object vanished completely in Kibbe and Leslie (2011). However, if topological class,

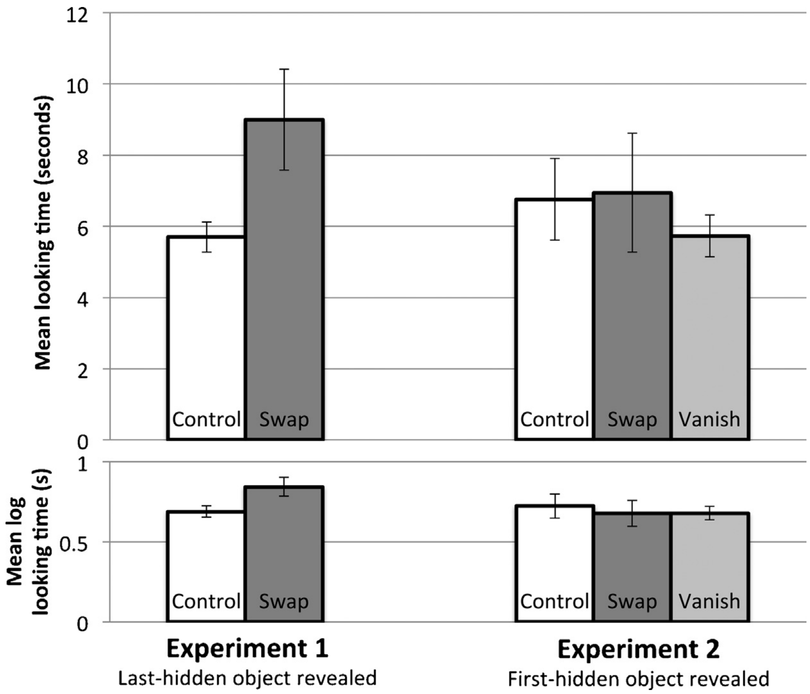

Fig. 2. Mean raw looking times (top panel) and mean log-scaled looking times (bottom panel) in the control and swap conditions in Experiments 1 and 2. Error bars show +/ −1 SEM.

like surface features, must be bound to an otherwise featureless object representation, infants should fail to notice when the topology of the first-hidden object has changed, just as they failed to notice a change in the shape of the object in previous studies, but should notice when the object vanishes completely.

3. Experiment 2

3.1. Participants

A separate group of 36 healthy, full-term infants (mean age: 5 months 29 days, SD: 15 days) participated. Twenty-one infants were tested at Johns Hopkins University, 12 were tested at Boston University, and 3 were tested at Rutgers University. An additional 9 infants were tested but excluded from analysis due to fussiness (6) or experimenter error (3). Infants were recruited through phoning or mailing lists and received a small gift for participating.

3.2. Materials and procedure

Materials and familiarization trials (Fig. 1, top panel) were identical to Experiment 1.

During each of the four test trials, as in Experiment 1, the screens were placed on the empty stage, the objects were placed one at a time on the stage, and then the objects were moved behind their respective screens. This time, unlike Experiment 1, the screen occluding the *first-hidden* object was removed. Infants saw one of three possible outcomes: a third of the infants saw the object that had been hidden there originally (e.g., the ring was hidden and the ring was revealed; *control condition*), a third of the infants saw the unexpected other object (e.g., the ring was hidden and the disk was revealed; *swap condition*), and a third of the infants saw the object had vanished completely (*vanish condition*) (between-subjects design). The object was hidden for about 7 s before it was revealed. Fig. 1 shows a sample test trial (middle panel) and experimental outcomes (bottom right panel) for Experiment 2.

An observer who was naive to condition (*control*, *swap*, or *vanish*) measured infants' looking time during the test trials. An additional observer later rescored a random 50% of infants' looking times. Inter-observer agreement averaged $r = 0.95$.

3.3. Results

Analyses were conducted on 143 total test trials. One trial was excluded due to infant fussiness on the fourth trial. As in Experiment 1, because of right skew, all data were log-transformed. We conducted a repeated-measures ANOVA with Trial (4: *1st, 2nd, 3rd,* or *4th*) as a within-subjects factor and Condition (3: *control, swap,* or *vanish*) as a between-subjects factor. We observed no main effect of Trial ($F_{3,96} < 1$, $p = 0.59$, $\eta_p{}^2 = 0.019$) and no Trial X Condition interaction ($F_{6,96} = 1.11$, $p = 0.36$, $\eta_p{}^2 = 0.065$). We also observed no main effect of Condition ($F_{2,32} < 1$, $p = 0.87$, $\eta_p{}^2 = 0.008$); infants looked equally at *all* outcomes.

We found no significant effect of Condition using conventional statistics, which allow us only to *fail to reject* the null hypothesis that infants are unable to recall the topological class of the object hidden first. However, Bayes Factor analysis provides the means of obtaining the odds that the null hypothesis should be *accepted*. We used Bayes Factor analysis to compare mean looking time for the *control* condition to mean looking times during both the *swap* and *vanish* conditions. Bayes Factor analysis of the *control* and *swap* conditions revealed odds of 3.45:1 in *favor* of the null hypothesis, suggesting that infants in Experiment 2 indeed failed to recall the topological class of the first-hidden object. Bayes Factor analysis of the control and vanish conditions revealed odds of 3.75:1 in *favor* of the null hypothesis, suggesting that infants also failed to remember even the existence of the object. Fig. 2 shows mean looking times to *control, swap,* and *vanish* conditions in Experiment 2.

3.4. Discussion

Infants in Experiment 2 looked equally at all three conditions, suggesting that they did not have strong expectations about either the topological class or the existence of the first-hidden object. Infants' failure in Experiment 2 could not have been due to an inability to discriminate the topological differences between the objects or to a general inability to remember topological class, since infants in Experiment 1 successfully remembered the topology of the last-hidden object. Further, infants' failure in Experiment 2 is not likely to be due to a general inability to maintain representations of more than a single object, since previous research using similar hiding scenarios and similar timings has shown that 6-month-olds can remember the existence of multiple objects (e.g., Wynn, 1992; Simon, Hespos, & Rochat, 1995; Kibbe & Leslie, 2011; Wilcox, 1999) even when they fail to remember the objects' specific identities (Kibbe & Leslie, 2011). Finally, infants' performance is unlikely to be due simply to a longer delay between hiding and revealing the object versus Experiment 1, since previous research has shown that infants can retain robust representations of multiple objects over similar or longer delays (e.g., Káldy & Leslie, 2005; Kibbe & Leslie, 2011; Mareschal & Johnson, 2003; Wilcox, 1999; Wynn, 1992).

Instead, infants' performance suggests a subtle interaction between representation of topological class and representation of the object. When objects are distinct in topological class, infants appear to privilege one object over the other, such that they forget or are uncertain about the other object. Potential mechanisms are discussed in the next section.

4. General discussion

Previous research has suggested that topological class is privileged information in the object representation, and indeed may be essential to representing an object in infants (Baillargeon et al., 2012) and in adults (Chen, 2005; Zhou et al., 2010). We tested this hypothesis by studying 6-month-old infants, who remember multiple individuated objects simultaneously, yet are limited to remembering the surface features of only a single object. We first confirmed that 6-month-olds could remember the topological class of the last-hidden of two objects, consistent with previous results on surface features such as metrical shape. We found that infants successfully remembered the topology of this object, providing, to our knowledge, the first direct demonstration that topological class information can be stored in infants' working memory.

Next, we asked what infants remembered about the critical first-hidden object. Previous work showed that 6-month-old infants did not remember the surface features of such an object (Káldy & Leslie, 2005; Kibbe & Leslie, 2011) but did remember its existence (Kibbe & Leslie, 2011). We reasoned that, if topological class is fundamental to the structure of an object representation, then it should be remembered by 6-month-olds even when surface features are forgotten. Alternatively, if topological class is not fundamental, infants should remember the existence of an object even when topological class is forgotten. Contrary to both of these hypotheses, we found that infants failed to recall both the topology *and* the existence of the other object.

This surprising result offers a more nuanced picture of the role of topological class in infants' object representations. Topology is processed earlier in the brain (Chen, 1982), recognized earlier in development (e.g., Chien et al., 2012), and is more behaviorally relevant (e.g., Hespos & Baillargeon, 2001a) than surface-featural properties such as shape. Nevertheless, infants did not have strong expectations about the topology or even the existence of the critical first-hidden object. Why did infants fail to remember such a highly relevant/salient property?

One possibility is that topological class may be more costly to maintain than surface features such as color or shape, so that infants are more limited in the number of topologically distinct objects they can concurrently individuate and maintain in working memory. When infants in Experiment 2 saw two hiding events involving objects of contrasting topological classes, they may have allocated limited resources to representing only one of those objects, leading to uncertainty about the other hidden object. By contrast, infants in Kibbe and Leslie (2011), who observed two topologically closed objects, would not have shown this limit.

Another possibility is that working memory for topological class may interact with object indexing. Recall that topological class seems to play a role in determining object individuation. For example, in a series of studies of multiple object tracking in adults, Zhou et al. (2010) found that simultaneously tracking four visual objects among four featurally identical distractors was made harder if the objects changed topological class from open (containing a hole) to closed (no hole) or from closed to open. By contrast, objects could undergo large changes in color and 'metrical shape' (e.g., from square to rectangle, from S-shape to disk, from disk to barbell) without affecting tracking. Zhou et al. (2010) argue that these results support the idea that topology is essential to object representation. However, it was not the case in their studies that topological changes abolished object tracking altogether. Whereas their adult participants tracked objects at about 97% accuracy through changes in metrical shape and color, accuracy dropped to about 90% if the objects changed topological class. The effect is highly reliable but it represents a drop from around $m = 3.8$ objects tracked to around $m = 3.2$ objects tracked (calculated using the index m of objects simultaneously tracked provided by Scholl, Pylyshyn, & Feldman, 2001: Appendix A). By contrast, some kinds of change abolish multiple object tracking (MOT) altogether, leaving only focal attention. For example, van Marle & Scholl (2003) found that, under the conditions of a typical MOT experiment, when the objects move with the expanding and contracting motion of a non-rigid object that is characteristic of *pouring* a substance from one location to another, adults can track only a single object, presumably using focal attention.

Taken together, these studies suggest a different conclusion than the one made by Zhou et al. (2010). We suggest that, unlike changes to metrical shape and color, which have no measurable effect on MOT, changes to topological class increase attentional load in adults, reducing the number of objects that can be individuated simultaneously by about one object. This means that topological class interacts with object individuation in a way that surface features do not, without that also meaning that topological class must be represented whenever an object is.

What is the relation between MOT tasks in adults and our multiple hiding tasks (MHT) in infants? The essential feature of the MOT task is that it calls for simultaneous attention to and tracking of more than a single object all moving along random trajectories (Brownian motion) against a background of featurally indistinguishable distractor objects also moving with Brownian motion. We consider the infant MHT to be a test of object working memory (WM), but there are reasons for supposing that there are some close relations between adult MOT and infant MHT (for a discussion, see Kibbe, 2015). Theoretically, the "working" part of working memory in MHT reflects the need for sustained attention if the memory system is to retain information. Although in MOT the visibility of objects diminishes the need for memory (though objects can be tracked through occlusion in MOT tasks, Scholl & Pylyshyn, 1999), there is evidence (Káldy & Leslie, 2003, 2005; Káldy & Leslie, 2005; Kibbe & Leslie, 2013) that what impacts memory for the first hidden object in infant MHT is the attentional demands of the second hiding rather than just the passage of time or lack of visibility.

Putting these ideas together we offer the following speculative account. Changes to the topological class of objects in adult MOT leads to increased attentional load on simultaneous individuation and reduces the upper limit by about one object. There are parallels between the mechanisms engaged by MOT in adults and MHT in infants. Whereas topological class is not "essentially" bound to the object index in either case, changes in topological class in MOT and contrasting topological classes in MHT have similar effects, each reducing the upper limit of simultaneous individuation by about one object. We already know that, with surface feature information bound to one object, the upper limit on simultaneous individuation in 6-month-olds is about two objects (Káldy & Leslie, 2005; Kibbe & Leslie, 2011). Therefore, with bound topology information reducing this upper limit, the young infant is left with only focal attention—on the last hidden object.

We advance the above account in the spirit of a speculative working hypothesis. To date, there have been very few studies of object topology in infant cognition. Our account has the advantage that it explains why topological class only has an effect when there is a topological contrast between objects. Note that, if topological class were essentially represented, then it would *always* be represented—whether or not the objects contrast. Yet previous MHT studies (e.g. Kibbe & Leslie, 2011; Wynn, 1992) found no effect like the one observed in Experiment 2–infants consistently track at least two objects when the objects are from the same topological class. This account also points the way toward new studies of the links between the MHT and MOT literatures, for example, whether contrast in MHT has similar effects as change in MOT.

Further work is needed to explore the role of topological class in infants' (and adults') object representations. While topological class features appear to impair object individuation, cueing infants to the physical or behavioral relevance of such features may improve infants' ability to maintain this feature in working memory. For example, research has suggested that properties of an object that grant it "affordances" (i.e., the ability to act upon it; Gibson, 1979) are processed and stored differently than other properties such as those critical for identifying the object (Mareschal & Johnson, 2003; Kaufman, Mareschal, & Johnson, 2003). Leslie (1994) has discussed how infants might represent the way object geometries affect the transmission of contact-mechanical forces. Baillargeon et al. (2012) have elaborated an account of the relation between topology, individuation, and physical reasoning. Finally, cueing infants to the relevance of topological class may improve infants' ability to attend to and track objects in the face of topological contrast (e.g. Wilcox, Woods, Chapa, & McCurry, 2007; Wilcox & Chapa, 2004).

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