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# Role of topological properties in object perception, representation, and categorization in children

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BOSTON UNIVERSITY  
GRADUATE SCHOOL OF ARTS AND SCIENCES

Dissertation

**ROLE OF TOPOLOGICAL PROPERTIES IN OBJECT PERCEPTION,  
REPRESENTATION, AND CATEGORIZATION IN CHILDREN**

by

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## **DEDICATION**

To my ancestors who fought for freedom from Caste

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**ABSTRACT**

Topological properties are considered structural properties of objects because these properties are sustained under continuous deformations of objects. Topological invariance provides stability to representations across changes to objects and viewpoints and are therefore central to object representation. I examined the role of topological properties in the cognitive development of object representations in perception, working memory, and categorization.

In Chapter 2, I examined the phenomenological perception of hole shape in 3-8-year-olds ( $N = 133$ ) by exploiting sound-shape correspondence (bouba/kiki effect). I hypothesized that if children directly perceived hole shape, they would show the sound-shape correspondence effect for holes. As predicted, the study findings were that children showed congruency between object hole shapes and the nonsense labels “bouba” and “kiki” suggesting that children from 3 years of age assign the inner contour of an object with a hole to the hole and not the material surrounding the hole.

In Chapter 3, I investigated whether topological properties are maintained similarly to surface features in working memory, and whether attention has a similar influence on the maintenance of these representations, in 24-30-month-old children (N = 43). I hypothesized that topological objects would be remembered better than surface features and that attention cues would support children's encoding of both feature types. Contrary to the predictions, I found that children maintained topological representations on par with surface features, and attention did support encoding in children's working memory.

In Chapter 4, I examined whether 3-8-year-old children (N = 151) use topological properties to make inferences about objects' categories using a name generalization task. I predicted that, if so, then topology should compete with or even supersede surface features (i.e., shape or color) as the target of children's extension of novel nouns to novel objects. As predicted, I found that topological properties competed with both shape and color, suggesting a similar but distinct role for objects' topological properties and objects' surface features in children's kind-based inferences.

Taken together, these findings show the critical role of considering topological properties in addition to surface features in achieving a comprehensive understanding of the development of perception, working memory, and object categorization.

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## CHAPTER 1

### GENERAL INTRODUCTION

How do our visual systems effortlessly construct real world objects? What properties of an object are privileged in veridical perception? What properties of an object take precedence in visual processing over other properties? Several prominent theories have been proposed in the last century of visual cognition research to address the question of how our visual system constructs objects (Koffka, 2013; Treisman & Gormican, 1988; Marr, 1982; Wagemans et al., 2012; Jäkel et al., 2016; Herzog, Thunell, & Ögmen, 2016). These theories can be broadly categorized into two approaches with opposing assumptions regarding what goes with what in visual processing.

One prominent approach that has overwhelmingly dominated the field of visual cognition is local-to-global perception. Simplistically, this approach is conceptualized like this: our visual system processes individual features of objects like lines with slopes, color, and texture first, and by combing these features it constructs an object. For the local-to-global approach, the assumption is that individual visual features are processed first by the visual system and the global object is constructed by combing these local features. Therefore, local features take precedence over the global features of an object in visual processing. There are two main approaches that subscribe to this local-to-global approach: one is Anne Treisman's theory of feature integration, and the other is David Marr's theory of visual cognition (Treisman & Gormican, 1988; Marr 1982).

According to Feature Integration theory, the construction of a multi-featured object occurs in two stages: one is pre-attentive, and another is an attentive stage

(Treisman & Gormican, 1988). In the pre-attentive stage, when we view a multifeatured visual object in the real world, our visual system deconstructs that object's features and creates featural maps automatically without the requirements of attention. This automatic encoding of featural maps occurs in parallel because they do not demand attention. In the attentive stage, deployment of focused attention occurs in the spatial locations retained by the master map. Focused attention at spatial positions allows the visual system to integrate the multiple features in the feature maps to construct representations of multifeatured objects.

For example, let's say there are two objects (a red circle, a blue square) in your visual field. In the pre-attentive stage, all features of these two objects red, circle, blue, and square are automatically processed in parallel and form feature maps (Wolfe & Utochkin, 2019). In the second stage, the master map that is functionally connected to the feature maps in the pre-attentive stage deploys attention serially to specific locations in the map to bind blue with square and red with circle making two objects red-circle and blue-square. However, if there is not enough time to deploy attention at all the locations in the master map, our visual system may combine two features to create an object that did not exist on the screen earlier. For example, in the above scenario, if the participant does not have enough time to pay attention to the objects, they might report red square and blue circle instead of red circle and blue square (i.e., they "create" objects that are not isomorphic to objects they were presented with). These errors are called illusionary conjunctions. Indeed, much of the evidence for the feature integration theory stems from

research on the conditions under which such illusory conjunctions arise (Humphreys, 2015).

Models that emphasize local-to-global perception were widely influenced by the neurophysiological findings of orientation maps in the primary visual cortex by Hubel and Wiesel (1959, 1962, 1963). Modern vision research that subscribes to local-to-global approach assumes that objects are constructed in bottom-up, feed-forward models, but with top-down influences of higher-order brain areas on lower-level visual areas in the form of attention (Lamme, 2006). Several newer models have built on these earlier models to address the complexity of the visual system's construction of objects from features, including the guided search model (Wolfe, Cave, & Franzel, 1989; Wolfe, 1994, 2001, 2021). These models made significant improvements in deciphering the mechanisms of construction of complex objects from simple features.

However, all the theories that subscribe to the local-to-global approach have similar shortcomings when it comes to two fundamental assumptions about visual processing. These include: an axiomatic approach to the assignment of veridical perception to certain features (like lines with slopes, spatial frequency) but not others, and isomorphism between the real-world objects and visually constructed objects (Chen, 2005; Jäkel et al., 2016; Herzog, Thunell, & Ögmen, 2016).

Let's take the example of Feature Integration Theory. As discussed above, local features like lines with slopes take precedence in visual processing over global features, and these local features do not demand attention for processing, such that they can be considered as processed automatically by the visual system. However, several studies

have shown that our visual system can encode grouping relations between objects in the pre-attentive stage (Humphreys, 2015; Enns & Rensink, 1990). For example, adults are faster at detecting a cube of a particular orientation among distractor cubes than they are at detecting a target among distractors that are constructed from the same lower-level features as the cubes but do not form 3D integrated objects (see, e.g., Enns & Rensink, 1991; Rensink & Enns, 1995), suggesting that grouped form features can be encoded at the pre-attentive stage. Furthermore, our perception is not necessarily isomorphic to the real world. Our visual system internally constructs the objects that we encounter in the real world and therefore forms relations between objects that do not necessarily exist in the real world. Take a simple example like perceptual interpolation, in which we perceive the triangle in the center of three carefully aligned pac-men (the Kanisza triangle) even though there is no actual triangle in real world (Kanisza, 1955). Or take an even more stringent case of apparent motion, called phi-motion by Max Wertheimer (1912), in which subjects perceive two stimuli that are presented side by side that disappear and appear in quick successions (200 ms) as a single object moving back and forth (see also Ramachandran, & Anstis, 1986; Herzog, Thunell, & Ögmen, 2016). These examples show that our visual system can construct objects internally from inputs that do not necessarily map on to real-world objects.

In contrast to the local-to-global perception approach, Gestalt theorists subscribe to global-to-local perception approach. Gestalt theory was proposed by Max Wertheimer a little over a century ago (Gestalt in English crudely translates to configuration; Wertheimer, 1923). According to these theorists, the global properties of an object and its

relations with other objects precede visual processing over local features like orientations. Gestalt proposed several principles that our visual system utilizes in organizing the world (what goes with what) and some of them include proximity, connectedness, and common region (Wertheimer, 1923; Koffka, 2013; Palmer, 1998; Wagemans et al., 2012; Jäkel et al., 2016). Although Gestalt theory has successfully showed that phenomenological perception of global features occurs through various principles of organization and can remain consistent even with various changes to the local features, the mechanisms by which the visual system does so were left to subjectivity rather than computationally formalized (Jäkel et al., 2016) with the exceptions of some recent attempts (Gershman, Tenenbaum, & Jäkel, 2016; Blusseau et al., 2016; Jäkel et al., 2016).

Chen (2005) utilized a mathematical concept called topology to formalize the global-to-local perception perspective. According to this view, global topological properties are primitives to the visual system because they provide invariance to the object representations across continuous transformations. Therefore, topological properties can provide stability to object representations across various continuous transformations. Stability of representations is essential to the visual system to individuate objects and continue to identify the same object over space and time. For example, when we encounter an object, our representations of features of the object (like color, metric shape) might change based on our motion towards or away from the object, or the object's motions, or the nature of the light source, or the angle at which we view the object. To perceive the object as continuous across all these changes, one has to rely on properties of the object that do not change despite such environmental variation.

Topological properties of the object can provide such invariance to the object representations across these changes, therefore making them ideal candidates for primitives of visual perception. Properties that show invariance across a greater number of transformations are considered more global. In that regard, topology is considered as a global property that sits on the top of the hierarchy.

What makes objects' topological properties more robust to environmental changes? Topology is imagined as a "rubber-sheet geometry" in which the number of holes, connectivity, and inside/outside relationship of an object remain invariant through deformations like stretching, twisting, bending, and shrinking, except through gluing and tearing (Chen, 1982, 1985; Zhou et al., 2003; Zhou, Luo, Zhou, et al., 2010; He, Zhou, Zhou, et al., 2015; Chen, Zhang & Srinivasan, 2003). Two objects are topologically equivalent if they both have the same number of holes. For example, a cup with a handle and a doughnut are topologically equivalent because they both have one hole (the hole in the handle of the cup, the hole in the center of a donut). Two objects are topologically distinct if they have a different number of holes. For example, a donut and a ball are topologically different because the donut has one hole, and the ball has no holes. In addition to a number of holes in objects, topological properties include connectedness between objects, and inside/outside relationships between objects (Chen, 1990).

Topology can be more formally understood through the lens of Felix Klein's Erlangen theory of geometry (Torretti, 2019). According to Klein, geometry groups are organized in a hierarchy based on what properties of objects remain invariant and what properties of objects change during their corresponding transformations (Todd & Petrov,

2022). Therefore, a lower group in Klein's hierarchy is a subgroup of the group above it. The Euclidean (isometric) group is at the bottom of this hierarchy because transformations to this group only sustain the angles and lengths of an object. Right above the isometric group in the hierarchy is the similarity group (metric shape); transformations to this group result in invariance of ratios of distance, area, and volume of an object and reflective, rotational, or translational symmetries (Todd & Petrov, 2022). For example, a sphere and circle are variant in metric shape, and are therefore variant at the level of similarity group. The similarity group is a subgroup of the affine group; transformations to the affine group preserve collinearity and ratio of parallel lines. For example, transformations of a square into a rectangle or rhombus, or a circle into an ellipse are affine equivalent. The next step in the hierarchy of Erlangen theory of geometry is projective geometry: transformations in this group sustain cross-ratios for collinear points and coincidental relations but not parallelism. For example, two parallel lines that move away from the observer fall under projective geometry, since the cross-ratios between these lines do not change, and they do not exhibit parallelism because they (visually) intersect at infinity.

Finally, topology can be considered at the top of a hierarchy of Klein's Erlangen theory of geometry because topological properties -- like the number of holes in objects -- remain invariant during continuous transformations. One can conceptualize topology from the geometry perspective as a hierarchical variation of the metric shape that provides more general information about an object that sustains continuous transformations.

The Gestalt approach formalized by Chen (2005) suggests that topological properties of objects are processed earlier in vision and acts as primitive features in object perception. As mentioned above, Chen (2005) argues that topological properties provide stability to the representations across continuous transformations and therefore can be reliable candidates to be primitives in the visual system. In the next section, I outline evidence in favor of this theory.

### **Topology in visual perception**

In perception, the perceived surface features of a single object (like color, metric shape, texture, and size) can vary depending on many factors, including changes in the spectral quality of the light source, whether the object or observer is moving, or whether the object is being viewed from different angles. Therefore, these features of an object become unreliable for a perceptual system to rely on to represent an object with an identity that is consistent over time and space. For example, take a bird that flies from one tree branch to another tree branch. As the bird moves through space, the retinal projection of its metric shape and color at time 1 would be different than at time 2 (as the bird flaps its wings, or as the lighting changes as the bird moves into shadow). If we only relied on the retinal projections of surface features, the difference in these two retinal projections could lead to a representation of two different objects. By contrast, topological properties provide invariance to an object under such transformations, and therefore can act as reliable representations for our perceptual systems to represent an object's continuous identity when the surface features of an object change continuously. That is, although the perceived color, metric shape, texture, and size of a bird will vary as

it flies, its perceived topological properties (like connectedness) do not undergo such variation.

Evidence suggests that topological properties play a central role in different aspects of adult visual cognition (Chen, 1982, 1985; Zhuo, Zhou, Rao, et al., 2003; Zhou, Luo, Zhou, et al., 2010; He, Zhou, Zhou, et al., 2015; Chen, Zhang & Srinivasan, 2003; Watanabe et al., 2019; Lovett, & Franconeri, 2017; Xi, Wu, Wang, & Chen, 2020; Meng et al., 2018; Tsao & Tsao, 2022; Pomerantz, Sager, & Stoeber, 1977; Pomerantz, 2003; Wei et al., 2019; Wei et al., 2021). For example, Chen (1982) asked participants to report whether they detected a difference between two stimuli that varied in topology (e.g., solid circle and ring) or that varied in metric shape (e.g., solid circle and square). He found that participants discriminated topologically different objects (e.g., triangle with a hole and triangle without a hole) faster than they discriminated objects that differed in metric shape (e.g., a solid circle and a solid square) suggesting that topological properties are processed earlier in visual processing than metric shape.

Similarly, Chen (1985) tested which properties of objects can induce apparent motion. He presented two sets of stimuli sequentially. On each trial, participants first saw a single object which then vanished, and then two objects appeared slightly displaced from the location of the first object. Participants were asked to choose which of the two objects was the same individual as the first object (that is, which object appeared of the objects in the second set yielded a percept of *apparent motion* of the object presented first). To perceive apparent motion, one has to detect correspondence between the two objects as a function of time i.e., smooth transition of one object into another with time,

rather than perceiving as disappearance of one object and appearance of another object in discontinuous manner. He manipulated the properties that the second set of objects shared with first object. For example, if the first object was a solid square, the objects in the pair were a solid circle (same topology, different shape) and a solid square with a hole in it (same shape, different topology). He found that participants were more likely to choose the object that shared topologically with the first object as yielding apparent, smooth motion, even though these objects differed in metric shape. These results suggest that topological invariance between the objects plays a crucial role in the perception of apparent motion, and topological properties of objects act as a corresponding token for people to track individual objects across space and time.

Converging results were obtained by Zhou et al. (2010). In a multiple object tracking task, participants were asked to track sets of moving objects that either changed in their metric shape (e.g., solid square to solid circle, or letter K to letter S) or in their topology (e.g., circle to ring, or letter K to letter P) as they moved through space. Zhou et al. compared tracking performance within these conditions with a baseline condition in which objects did not undergo changes as they moved. They found that participants performance significantly decreased when the objects changed in their topological properties as they moved, but not when objects changes metric shape as they moved, when compared to the baseline condition. Similar results were found across different topological variations (e.g., S to O, S to 9, S to circle with two holes) and across different metric shape or color changes (e.g., S to solid circle, solid circle to S, black circle to pink circle). These results suggest that change in topological properties of an objects elicits a

representation of a *new object*, while changes to surface features of an object do not affect object individuation.

There also is evidence that objects' topological properties play a primary role in representations of objects that are no longer in view. For example, Wei et al (2019) tested visual working memory for sets of four different color objects while manipulating the metric shape or topological properties of objects in the to-be-remembered array. On each trial, participants viewed two sets of sequentially presented colors, and were asked to report the colors in the first array. In "repeated" trials, they presented the same four colors (e.g., red E, green E, blue E, yellow E) in both the first and second array. In "updated" trials, they presented a different set of colors in second array (e.g., the second array consisted of an orange E, violet E, pink E, and cyan E). Typically, participants in such tasks show higher performance when asked to recall the colors of the objects in the array for repeated trials compared to updated trials. However, Wei et al. also introduced different task-irrelevant changes to the two arrays. In the topological change condition, they changed the topological properties of the second array compared to first array in both repeated (e.g., red P, green P, blue P, yellow P) and updated trials (e.g., orange P, violet P, pink P, and cyan P). In the nontopological change condition, they changed the metric shape of the second array compared to the first array in both repeated and updated trials. They found that participants' color memory was higher in repeated trials compared to updated trials in the nontopological condition, suggesting task-irrelevant changes in shape did not interfere with participants' representations of the objects. However, when topological properties of the arrays changed between the first and second presentation of

the array, participants no longer showed the color repetition benefit, suggesting that changes in objects' topological properties resulted in the construction of new object representations in visual working memory. Converging results were obtained by Lovett and Franconeri (2017) who found that topological changes between sequentially presented arrays were more readily detected than changes to metric shape.

Finally, the primacy of topology is observed in other species: bees and pigeons discriminate patterns based on topology differences more readily than shape differences (Chen, Zhang, & Srinivasan, 2003; Watanabe et al., 2019). For example, Chen et al. (2003) trained bees in a Y-shaped maze with a small hole for bees to enter. At the entrance of each room, they placed a pattern (e.g., a ring or an S), and trained bees to distinguish patterns by providing a reward for one specific pattern. For example, they trained bees to choose a ring over an S to get a reward. During the test trials, they tested whether bees choose between two different patterns. They manipulated the patterns based on whether they shared a similar topology as the ring. For example, in one test trial, they tested bee's choices on a diamond with a hole and an S, and in another a circle with a hole and a disk. They found that bees chose the pattern that shared the same topological properties as the one they were trained on compared to the pattern that did not share the same topology as trained. Importantly, bees chose both patterns an equal number of times when they were tested with objects that both shared the same topology as the trained ring (e.g., a circle with a hole in it and a square with a hole in it).

Similar results were obtained by Watanabe et al. (2019), who tested whether pigeons were able to learn to discriminate between objects that differ on topology. They

trained one group of pigeons to classify objects that varied in topology (hole, no-hole), and another group of pigeons to classify objects that varied in arbitrary properties. Pigeons in the topology group were presented with two objects that varied in topology and they were rewarded when they pecked the object that had hole in it. Pigeons in the arbitrary group were rewarded randomly. They found that after 40 sessions, pigeons in the topology group learned to improve their performance significantly compared to arbitrary group pigeons, suggesting that these birds can discriminate between objects that differ on topology.

Overall, previous research has shown that topological properties of objects supersede objects' surface features to play a central role in different aspects of visual cognition including visual discrimination (Chen, 1982), apparent motion (Chen, 1985; Zhuo et al., 2003), visual crowding (Xi et al., 2020), attentional tracking (Zhou et al., 2010), and visual working memory (Wei et al., 2019; Wei et al., 2021).

### **Topology in Development**

No theory of visual cognition is complete without addressing the development of that phenomenon (Menon, 2013). Studying representations of global topological properties in infants and children can provide insights into whether, when, and how children use object topology to represent object identity across various transformations. In addition, any processes that develop earlier in development influence the processes that develop later in development. Prioritizing global topological properties in representations of objects would allow infants and young children not only to perceive objects as having continuous identities across various continuous transformations, but

these representations may also contribute to infants' and children's ability to reason about physical interactions with and between objects. Furthermore, understanding early representations of topological properties can provide insights into potential sources of children's notorious limitations in object tracking and object working memory, and what perceptual features provide support children's inferences about what objects can do and to what categories they belong.

Previous research has shown that topologically different objects are discriminated earlier in development compared to metric shapes (Quinn, Slater, Brown & Hayes, 2001; Turati, Simon & Zanon, 2003; Chien et al., 2012). For example, Quinn et al. (2001) tested both newborn infants' and 3-4-month-old infants' perceptual categorization in a novelty preference task. First, infants were familiarized on six different exemplars from the same category (e.g., triangles with holes in them), and then were presented with two test trials. In each test trial, infants were shown a novel exemplar from the familiarized category (e.g., a different variation of a triangle with a hole) and another object from a different category (e.g., a square with hole), and they measured infants novelty preference (looking times to the novel object). They found that 3-4-month-old infants showed a novelty preference for the new shape, but newborn infants did not. However, in an exploratory analysis, when they looked at the newborn infants who were familiarized with e.g., a cross and tested on a novel exemplar of that familiarized object (e.g., variation of a cross) and a novel object that differed from the familiarized object in topology (e.g., a triangle with a hole), newborns showed novelty preference towards the topologically different object.

Turati et al. (2003) tested newborn infants explicitly on whether they can form perceptual categories based on objects' topologies. They familiarized newborns with a stimulus that either did not contain a hole, and then showed infants a novel object from the familiarized category (e.g., containing a hole) and novel object from different category (e.g., not containing a hole). They found that newborns looked more at the object from the novel category, suggesting that they could form perceptual categories based on global object features - topology. Furthermore, Chien et al. (2012) showed that, when infants are habituated to metric shapes (triangle vs circle) and tested on topologically different objects (solid circle with hole vs without hole) or on objects that differed on metric shape (square vs triangle), infants dishabituated to the topologically different objects earlier in development (around 1 month) compared to the different metric shape objects (around 3 months) suggesting that topological properties of objects are extracted earlier in development than metric shape.

Infants' physical reasoning about how objects should interact is supported by their perception of objects' topology; infants use topological features to reason about how objects should interact in physical events before they use other relevant surface featural properties like shape (Baillargeon et al., 2012). For example, by 3 months infants use the height and width of an occluded object in relation to an occluder to form expectations about whether the occluded object will be visible or not while passing behind the occluder (Hespos & Baillargeon, 2001a; Wang, Baillargeon, & Brueckner, 2004). However, the generalization of height to other physical events (e.g., containment) develops over the first two years and depends on the topological properties of objects

(Hespos & Baillargeon, 2001a; Hespos & Baillargeon, 2001b; Hespos & Baillargeon, 2006; Wang, Baillargeon & Paterson, 2005). For example, Hespos and Baillargeon (2001b) found that not until 7 and half months, infants consider object height hidden in an open-end container i.e., an expectation of object visibility if it is taller than the container. In addition, they expect the object hidden in the container to move along with the container. Not until the age of 14 months, did infants consider height when reasoning about an object hidden in a tube (open at both ends) (Wang, Baillargeon, & Paterson, 2005). These studies suggest that infants' expectations about how objects should interact depend upon the infants' representations of object features and their interactions with different topological properties.

After encoding the perceptual features of an object, infants have to retain these features in their visual working memory when they are perceptually unavailable to guide their behavior. In a visual working memory task, Kibbe and Leslie (2011) showed that 6-month-old infants can maintain metric shapes in their working memory when they are probed on last hidden object in a serial violation of expectation task, and the same age infants show surprise (look longer) when there was no object shown in first hidden location. These results suggests that 6-month-old infants can maintain object identity without maintain their features in their visual working memory. When Kibbe and Leslie (2016) tested 6-month-old infants on topologically different objects in the similar serial violation of expectation task as in Kibbe and Leslie (2011), they found that infants successfully maintained the topological property of the last hidden object but infants were unable to remember the presence of object or not in the first hidden location, suggesting

that maintaining topological properties might demand more attention compared to maintaining metric shapes.

Sensitivity to perceptual organization principles emerges early in infancy and continues to develop throughout childhood with an increase in efficiency in global processing (Bhatt, Hayden, & Quinn, 2007; Hayden et al., 2008; Quinn, Bhatt, & Hayden, 2008; Quinn, & Bhatt, 2005; Hayden, Bhatt, & Quinn, 2006). For example, 3-4-month-old infants can discriminate objects based on common region and connectedness which are two of the properties of topology and Gestalt grouping principles (Bhatt, Hayden, & Quinn, 2007; Hayden et al., 2008; Hayden, Bhatt, & Quinn, 2006). Infants at this similar age show sensitivity to proximity, continuation, and other gestalt principles (Quinn, Bhatt, & Hayden, 2008; Quinn, & Bhatt, 2005). There is limited research on how topological properties influence different aspects of perception or other cognitive processes in 2-10-year-old children. One of the studies conducted on 4-10-year-olds suggests that sensitivity to other topological properties like the hole in objects in peripheral vision develops until 10 years of age (Tang, Song, Hu, et al., 2003). Overall, evidence from infant studies suggest that global topological properties take precedence over local features like metric shape in infants' representation of objects. Furthermore, infants may develop the ability to represent the visual world through deploying various perceptual organization principles as they also develop the ability to differentiate between local features.

### **Present studies**

Overall, above mentioned research suggests that our visual system extracts topological properties from objects earlier in visual processing (Chen, 1982), earlier in development (Chien et al., 2012), and provides functional relevance in the phylogeny (Zhou et al., 2010) compared to surface features like color, texture, and metric shape. It also appears to play a significant role in the perception of apparent motion (Chen, 1985; Zhuo et al., 2003), crowding (Xi et al, 2020), and visual working memory (Kibbe & Leslie, 2016; Wei et al., 2019; Wei et al., 2021). However, there is a limited amount of research conducted on other than topological properties in perceptual processing and a very limited amount of research conducted on how topological properties are processed throughout the development, especially between 2-8-years of age, and how these properties appear to provide stability to visual representations and influence other processes at different levels of processing.

In my thesis, I aimed to investigate the role of topological properties at different levels of information processing (perceptual, working memory, and categorization) in children from 2-8-years-of-age. Our overarching goal was to systematically study how children perceive and represent global topological properties and use them to make inferences about object categories compared. These studies will inform us about whether global properties like topology take precedence over surface features during development and whether children's representations of topological or surface features varies with development and depending on the task.

In Chapter 2, I investigated whether 3-8-year-old children show the phenomenological perception of the shape of holes and whether this ability develops

between 3-8-years of age. In figure/ground organization, the contours that are assigned to the object are perceived as figure (Palmer, 1999; Kim, 2020). However, holes, unlike any other surface features, create a paradox in figure/ground organization and shape perception (Palmer,1999): Holes constitute a negative mass, but we nevertheless report the shape of the hole. Previous research on adults showed that the shape of holes is retained similarly to the shape of objects in visual working memory (Palmer et al., 2008) and adults can phenomenologically perceive the shape of a hole (Kim, 2020) suggesting that, adults can assign the inner contour of the object with a hole towards the hole and therefore perceive the shape of the hole. Several studies in infants have shown that newborn infants can categorize objects based on whether objects have a hole in them or not (Turati et al., 2003), and by 2-months they can differentiate objects based on whether they have a hole in them or not (Chien et al., 2012), and by 6-months represent an object with a hole in visual working memory (Kibbe & Leslie, 2016). Previous research also showed that infants develop a rudimentary ability to distinguish the figure from the ground, and they can assign edges to the objects, and this efficiency of contour processing and integration develops around 12 years of age (Kovács, 1996; Hipp et al., 2014; Nayar et al., 2015). Finally, Giralt and Bloom (2003) showed that 3-year-olds can detect, count, and track holes on par with objects when children are explicitly referred to as holes. Although infant studies show that they can distinguish objects that differ in the presence or absence of holes they assume that infants automatically perceive the shape of holes in objects. Furthermore, while 3-year-old children detect, count, and track holes, this ability was tested only when holes are explicitly mentioned in the task, therefore possibly leading children to reverse assignment of the inner

contour of the object with hole to the hole and allowing them to perceive the shape of the hole.

To study whether children can perceive hole shape directly i.e., by assigning the inner contour of the hole object to the hole, we should avoid explicitly mentioning holes in the task (to avoid figure/ground reversal). In Chapter 2, I used a similar methodology as Kim (2020) to study 3-8-year-old children's phenomenological perception of hole shape. Kim (2020) exploited the bouba/kiki effect to study adults' phenomenological perception of hole shape. In his study, he presented two objects that had the same outer contour and varied the shape of the holes of the two objects. One object had a flower shaped hole and the other object had a spikier hole. He asked participants to choose which of the objects was called "bouba" (or "kiki", counterbalanced across participants). In his task, holes were not explicitly mentioned, such that the participants responses should reflect direct perception of hole shape. He found that adults associate flower-shaped holes with bouba and spikier-shaped holes with kiki suggesting that adults automatically assign an inner contour to the hole of an object.

In Chapter 2, I conducted two experiments to test children's direct perception of hole shape. In the first experiment, I presented two objects that varied in the hole: one had a flower-shaped hole, and another with a spikier-shaped hole. I asked the children which one of these was bouba/kiki. This allowed us to test children's direct perception of hole shape without mentioning holes explicitly. In the second experiment, I tested whether children's representation of hole shape changes if we provide functional meaning to the objects, to do that I added eyes to the material surround of hole objects.

In Chapter 3 of my dissertation, I will discuss how topological properties are maintained in visual working memory compared to surface features (color) in 24-40-month-old children. I planned to test working memory performance in 24-40-month-old children because of two reasons: one is that there are several studies that tested working memory performance with infants and children in late childhood but only couple of studies that tested working memory performance in toddlers (Kibbe & Applin, 2022; Chen et al., 2020) leaving a gap in our understanding between infancy and late childhood. Second is that, only one study that tested working memory for topological objects was conducted on infants with 6-months of age (Kibbe & Leslie, 2016). Our first research question was to study toddlers' working memory performance for objects that varied in topology and surface features like color. The results of the study provide insights into whether toddlers' performance on a working memory task depends on the content of the representations that they maintain in their working memory. This also provide evidence for the development of working memory for topological objects with age and allowed us to compare our results on color condition with previous studies that tested toddlers working memory performance. Our second goal was to test whether toddlers benefit from attention cues when representing information in working memory, and whether their performance would vary based on when they represent topology or color objects. Our study results for this research question provide insights into whether children use object based endogenous cues to selectively encode relevant items into working memory, and whether the ability to selectively encode relevant items and ignore irrelevant items varies based on whether toddlers are asked to represent topological properties or colors in their working memory.

In Chapter 4, I investigated whether children use topological properties or metric shape or color to infer object categories. Previous research has shown that children overwhelmingly use the metric shape of the objects to extend labels to novel objects (Landau et al., 1988; Diesendruck & Bloom, 2003). This phenomenon is called shape bias. Shape bias is often observed when a metric shape is pitted against other surface features like color or texture, and it is often shown when children extend count nouns to artifacts. However, there is a significant gap in our understanding of whether global features of objects contribute and compete with the metric shape when children extend count nouns to novel objects. Studying this would inform us whether certain perceptual features of an object can guide children to learn words and infer object categories. Therefore, in this chapter, I conducted three experiments that tested whether 3-8-year-old children prefer topological properties of objects or metric shape or color when they extend count nouns to novel objects. The results of these experiments will inform us whether global topological properties compete with metric shape when children extend novel labels.

Finally, in Chapter 5, I will discuss the implications, limitations, and future directions of the findings of these studies.

## **CHAPTER 2**

### **CHILDREN'S PERCEPTION OF HOLE SHAPE**

#### **Introduction**

In figure/ground organization, objects that own the edge borders are perceived as figures and the surround as the background (Palmer, 1999). Figures appear closer in depth compared to the surround. For material objects, the edge contour is owned by the figural object, the contours are assigned to the figural objects, and therefore we perceive the shape of the figural object. However, unlike any material objects, holes create a paradox in figure/ground organization and visual shape perception because holes constitute negative mass and therefore do not “own” the contour they share with the material object (because the contour is defined by the material object), but nevertheless we perceive holes as having a shape.

Two views have emerged from the previous research on perception of the shapes of holes (Kim, 2020; Nelson et al., 2014; Nelson et al., 2009; Palmer et al., 2008; Nelson et al., 2001; Bertamini, Casati, 2015; Bertamini, & Farrant, 2006; Bertamini & Lawson, 2006; Bertamini & Mosca, 2004). One view argues that we directly perceive the shapes of holes by assigning the interior contour of an object with a hole to the hole rather than to the material side of the object (Kim, 2020; Nelson et al., 2014; Nelson et al., 2009; Palmer et al., 2008; Nelson et al., 2001). For example, Nelson and Palmer (2001) found that participants report holes better if the hole is in the center of an object and when inner and outer counter orientation are aligned. Palmer et al. (2008) has shown that memory for the shape of holes was similar to memory for shape of objects only when the holes are

connected to a single surface but not when they are formed via the interaction of multiple objects (accidental) (Nelson et al., 2009). In a perceptual shape matching task, participants were faster at detecting the shape of a hole compared to detecting the shape of the material side of the hole object, but participants' reaction times were similar when they detected the shape of holes and shape of objects (Nelson et al., 2014). These results suggest that inner contour of an object with a hole is assigned to the hole resulting in perception of hole shape.

The other view suggests that holes do not own shape but rather shape of a hole is inferred indirectly by reversing the figure/ground relations after assigning inner contour of an object with hole to the surrounding material (Bertamini, Casati, 2015; Bertamini, & Farrant, 2006; Bertamini & Lawson, 2006; Bertamini & Mosca, 2004). For example, in a visual search task, Hulleman and Humphreys (2005) found that participants were faster at detecting the objects among holes than findings holes among objects, suggesting that holes are inferred indirectly after assigning edges to the material side of hole object. Furthermore, participants show a convexity advantage for material objects but not for holes (Bertamini & Croucher, 2003). In a shape interference task, when participants are asked to report the shape of the hole or object that had same shape (congruent) or different shape (incongruent) as surrounding objects, participants were faster in reporting the congruent shapes (for holes and objects) compared to incongruent shapes. However, the difference between congruent and incongruent was higher when reporting the shapes of holes compared to objects suggesting that holes are perceived differently compared to objects (Bertamini & Helmy, 2012).

Both the views mentioned above provide indirect evidence for the perception of hole shapes. Kim (2020) for the first time tested the phenomenological (direct) perception of hole shape by utilizing sound-shape correspondence, called Bouba/Kiki effect. The effect arises due to the arbitrary correspondence between abstract shapes and phonetic sounds (Ramachandran & Hubbard, 2001). People across different cultures and writing systems associate the word “Bouba” with round shapes and the word “Kiki” with spikier shapes (Ćwiek et al., 2021; Bremner et al., 2013). Kim (2020) presented two-hole objects that had same outer contour but different shape holes: one with a flower shaped hole that had round bulges and sharp convexities and another one with spikier shaped holes that had sharp concavities and round indents, and asked participants which one is Bouba/Kiki. Kim (2020) reasoned that, if we have phenomenological perception of hole shapes i.e., assigning the inner contour of a hole object to the hole, participants will report that the flower-shaped hole with sharp concavities and round bulges (Figure 1a) is “Bouba” (hole-shape congruent, object shape incongruent) and the spikier shaped hole with sharp convexities and round indentations (Figure 1b) is “Kiki” (hole-shape congruent, object shape incongruent). Alternatively, if participants assign the inner contour of the hole object to the outside material, they will report figure 1a as “Kiki” (hole-shape incongruent, object shape congruent) and figure 1b as “Bouba” (hole-shape incongruent, object shape congruent). Therefore, this paradigm directly tests whether participants assign the inner contour of a hole in an object to the hole (interior) or to the surrounding material (exterior). Kim (2020) found that 80% of participants reported the flower shaped hole (Figure 1a) as “Bouba” and the spikier shaped hole (Figure 1b) as “Kiki”, suggesting

that adult participants indeed automatically assign the inner contour to the hole. This study for the first time showed that adults show a phenomenological perception of hole shapes.

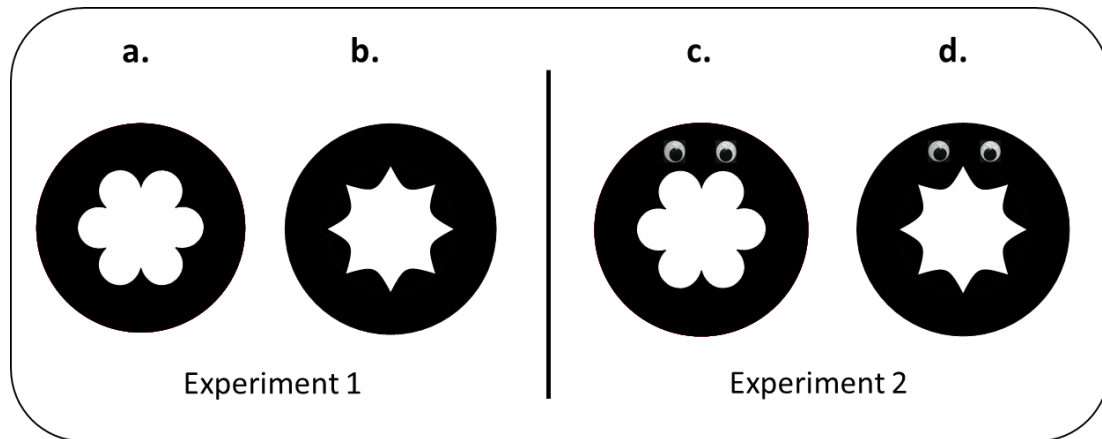


Figure 1. Left and right panels depict the stimuli used in the Experiment 1 and 2 respectively.

Overall, the above-mentioned research suggests that adults' visual systems can automatically assign the inner contour of an object with a hole towards the hole and therefore perceive the shape of the holes. Although the ability to parse figure and ground for solid objects emerges in infancy and becomes more efficient with age, little is known about whether children can perceive the shape of holes, whether they can perceive the shape of holes automatically like adults, and whether there is an improvement in the ability to assign inner contour to the hole in an object with a hole. Research on the development of visual perception shows that infants segment surfaces using myriad of processes like edge detection, common motion, background texture, proximity, depth cues, contour ownership (Forbes & Plunkett, 2021; Atkinson & Braddick, 2020; White et al., 2018; Quinn & Bhatt, 2018; Taylor et al., 2014; Braddick & Atkinson, 2007;

Johnson, 2001, 2004; Johnson et al., 2012; Kellman & Spelke, 1983). For example, when 2- and 4-month-old infants were habituated with an aligned rod that moved back and forth behind a narrow box in the center (such that the motion of the visible parts of the rod corresponded), and were then shown either a broken rod (which would be expected if infants failed to perceptually complete the rod behind the occluder) or a completed rod (which would be expected if infants correctly assigned figure and background to perceptually complete the rod behind the occluder, both 2- and 4-month-old infants looked longer at the broken rod, suggesting that they could correctly assign depth to perceptually complete the object when it was occluded by narrow box. However, when 2- and 4-month-old infants were habituated on aligned rod moving behind a much wider occluder (such that less of the rod was visible), only 4-month-old infants showed preference to the broken rod suggesting that perception of edge connectedness with wider proximity increases with age (Johnson, 2004).

These local and global processes that are observed in infancy become efficient with age with some developing through adolescence (Taylor et al, 2014; Hadad & Kimichi, 2006). For example, Kovács (1996) has shown that children's ability to detect contours in visual noise increases between 5 and 14 years of age. Similarly, children's ability to construct objects through perceptual interpolation reaches adult-like levels around age 12 (Hadad et al., 2010). Furthermore, children's ability to integrate contours across space in visual noise becomes more efficient with age, reaching adult-like levels by age 12 (Kovács et al., 1999). These development patterns in the ability to extract local

features from global visual information are likely due to the development of long-range connections in the visual cortex (Marsh et al., 2008).

To perceive the shape of an object, one must parse the figure object from the ground by detecting the contour of an object, integrating the contour across space, and assign that contour to the object. Because contour detection and integration which are fundamental to shape processing does not reach adult-like levels until around 12 years of age, children's ability to perceive the shape of 3 dimensional objects increases with age (Rentschler et al., 2004). Although studies show that children develop the ability to integrate visual information across space and segregate figure from ground to perceive material objects, there are no studies to our knowledge that tested whether children assign the inner contour to the negative mass of objects (holes) in an object with hole, rather than to surrounding material to perceive the shape of hole. Importantly, there are no studies that addressed whether the assignment of inner contour to the hole changes over the course of development. Giralt and Bloom (2000) showed that 3-year-old children can identify, count, and track the number of holes as accurately as they can identify, count, and track material objects, potentially suggesting that children by this age perceive holes as having form. However, in Giralt and Bloom's (2000) task, the experimenters explicitly referred to the holes (e.g., "Can you count the holes?") thereby guiding children's attention to the holes. Therefore, their findings do not inform us whether children automatically assign the inner contour of a hole object to the hole or to the surrounding material, thereby leaving us with an open question that whether children perceive the shape of holes directly or they infer hole shapes indirectly by reversing figure/ground

relations. Perception of shape of the shape of a hole in an object requires similar perceptual processes as in perception of the shape of material objects, and because of the developmental pattern of contour detection and integration and segregation of figure and ground (Kovács, 1996; Kovács et al., 1999; Gunn et al., 2002; Hipp et al., 2014; Nayar et al., 2015), children's ability to perceive the shape of a hole may increase with age.

To measure whether children show phenomenological perception of hole shapes, we should use a task that does not explicitly guide children's attention to the holes and allows us to test how do children assign the inner contour of the hole to the exterior surrounding material object or to the interior hole. In our study, similar to Kim (2020), we used the Bouba/Kiki effect to test whether 3-8-year-old children show developmental change in phenomenological perception of hole shape. Previous research has shown that children by age 3 show sound-shape correspondence (i.e., they associate “|Bouba” with rounded shapes and “Kiki” with spikier shapes) (Maurer, Pathman, & Mondloch, 2006; Spector & Maurer, 2013), and sensitivity to the sound-shape correspondence increases with age (Tzeng et al., 2017; Fort et al., 2018; Chow & Ciaramitaro, 2019). In our study we presented two cardboard objects with two different shape holes (Figure 1a & 1b) and asked children which one is “Bouba/Kiki”. If children assign the inner contour of the material object in Figure 1a to the hole, they should perceive inner contour curvature as sharp concavities and rounded bulges and therefore report it as “Bouba”. However, if they assign the inner contour to the surrounding material object, they should perceive the inner contour curvature as sharp convexities and round indentations and therefore associate Figure 1a with the word “Kiki”. Similarly, if children assign the inner contour

in Figure 1b to the hole, they should perceive the inner contour curvature as having sharp convexities and round indentations and therefore associate Figure 1b with the word “Kiki”. Conversely, if they assign the contour to surrounding material, they should report it as “Bouba”. This task allows us present children with stimuli that provide directly contrasting shapes depending on whether children assign the inner contour of the object with hole to the interior or exterior, and therefore provides a clear test examine whether children show phenomenological perception of hole shapes and whether perception of hole shapes changes over the course of development.

Although previous research suggests that children by age 3 can identify, count, and track holes (Giralt & Bloom, 2000), there is a lack of research on children’s direct perception of hole shapes in an implicit task, therefore we do not have a unidirectional prediction in our study. However, we have few possible predictions. One is that children would show congruency between the shape of holes and their corresponding phonetic sounds (Bouba/Kiki) suggesting that children by age 3, like adults, perceive shape of holes. Another prediction is that children show developmental change in perceiving shape of holes, with older children in our sample choosing congruent responses whereas younger children choose randomly. Developmental change in our experiment can occur due to two reasons. One is that there is an improvement of contour assignment to the hole in a hole object because of the improvements of contour detection, integration, and assignment. Another is that children do assign the inner contour of the object to the hole in a hole object but because of the developmental improvement in shape-sound

correspondence, older children will show higher congruency compared to younger children in our sample.

## **Experiment 1**

### *Methods*

#### *Participants*

Participants were 67 3-8-year-olds (mean age = 60.64 months, age range = 26.76 - 98.93 months). Parents reported that 36 children were male, 30 were female and 1 child's sex was not reported. An additional two participants were tested but were not included in analyses due to failure to respond to task prompts. Participants were recruited from the greater Boston area through phone lists and recruitment events. Data were collected in the laboratory at Boston University. Study procedures were approved by the Boston University Charles River Campus Institutional Review Board. All caregivers gave written consent for their children to participate in the study, and children received a small gift for their participation.

Sample size was determined prior to data collection. We estimated the sample size for Experiment 1 based on an adult study that used a similar methodology (Kim, 2020,  $n = 40$ ). We opted to include a relatively larger sample size compared to the previous research that has found the age-related change in children's sound-shape correspondence for the outer contours of objects (Chow & Ciaramitaro, 2019,  $n = 47$  for 6-17-year-olds). We opted to include a larger sample size to explore possible developmental differences in children's perception of hole shapes. We aimed to test  $n=64$  children total. The final sample of  $n=67$  was the result of overscheduling.

### *Materials*

Stimuli were modeled after the stimuli used in Kim (2020). Children were presented with two cardboard cut-outs (Figure 1a & 1b) with differently shaped holes in the center. The outer contour for both stimuli was circular in shape and the inner contour shape varied between the two stimuli. The stimuli were designed so that assignment of inner contour to the hole or to the material figure should elicit opposite convexities and concavities. For example, the assignment of the inner contour towards the hole in figure 1a should result in a perception of the inner contour curvature as sharp concavities and round bulges, and therefore should elicit an overall impression of flower shaped hole and show correspondence with the sound “Bouba”. However, if the inner contour is assigned to the material side of the object in figure 1a, it should result in a perception of an inner contour with sharp convexities and round indentations, and therefore should elicit an overall impression of spiker shaped hole and should result in the association of figure 1a with sound “Kiki”. The contrast in a perception of convexities and concavities based on the assignment of contour towards the hole or material of the object and its associated response of ‘Bouba’ or ‘Kiki’ is the same for figure 1b stimuli.

### *Procedure*

After children sat opposite to the experimenter, they were told that they are going to play a game. The experimenter told children, “I am going to show you two objects and I will ask you a question, your job is to pick one of the objects as soon as possible and there are no right or wrong answers.” Following that, the experimenter presented the two stimuli in figure 1a & 1b and asked, “Which one is bouba?” or “Which one is kiki?”.

Children's responses were recorded after they choose one of the two objects for the question asked. Each participant received only one trial. Thirty-four children were asked, "Which one is bouba?" and 33 children were asked, "Which one is kiki?". The presentation locations of stimuli were randomized between participants.

### *Results*

Children's responses were coded as *congruent* when children selected the stimulus whose hole shape matched the typical sound-shape correspondence for "Bouba" or "Kiki" (i.e., they selected to the object in Figure 1a when asked which is "Bouba", and the object in Figure 1b when asked which is "Kiki"). Children's responses were coded as *incongruent* when they selected the *material figure* shape that matched with typical sound-shape correspondence (i.e., they selected Figure 1a when asked which is "Kiki", and Figure 1b when asked which is "Bouba").

We first tested whether children selected the congruent responses at rates above guessing (chance = 50%). These results are shown in Figure 2. We found that 44/67 (65.67%) children made congruent responses, greater than would be expected if children were guessing (binomial test,  $p = .014$ ) (see Figure 2). Children's congruent responses did not differ significantly depending on whether they were asked to choose "Bouba" or "Kiki" (Fisher's exact test,  $p = .204$ ).

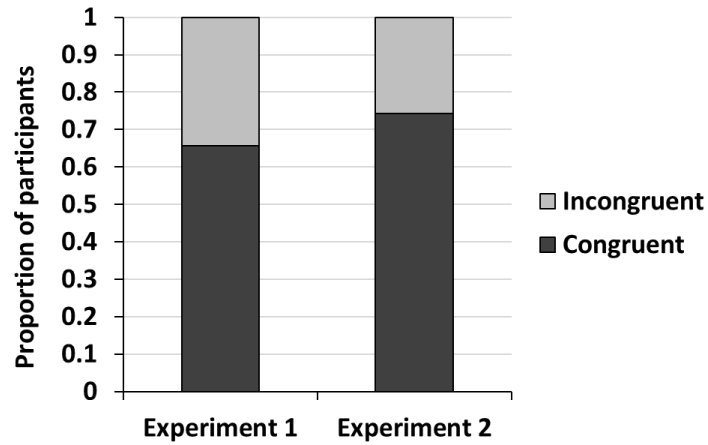


Figure 2. Proportion of children that chose congruent and incongruent responses for Experiments 1 and 2.

We further examined whether children's congruent responses correlated with their age in months. We found that children's age in months was significantly correlated with their selection of congruent responses (Spearman's  $r = .353$ ,  $p = .003$ ) suggesting an increase in age in months was associated with an increase in children's perception of hole shapes (Figure 3).

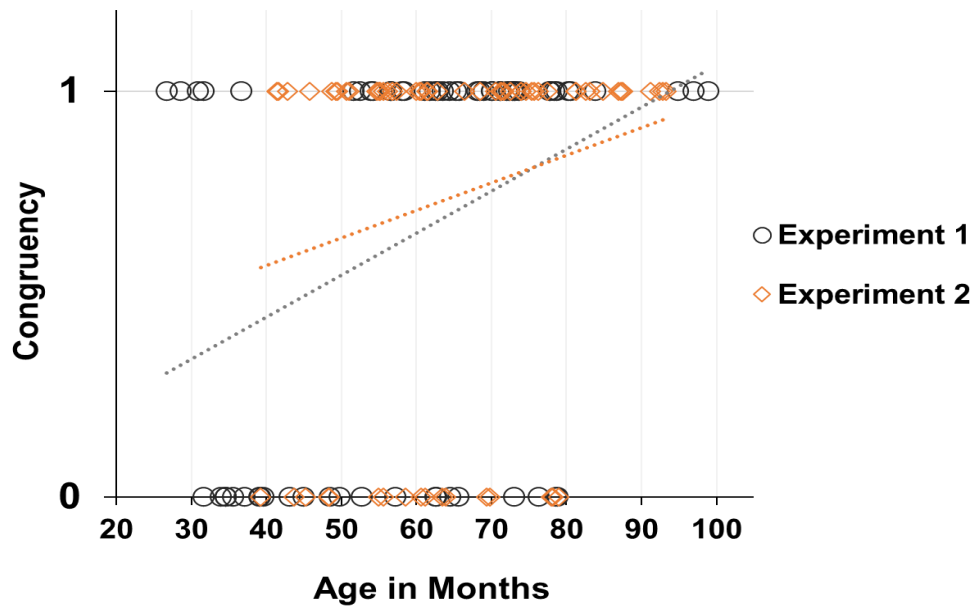


Figure 3. Congruent responses as a function of age in months for Experiments 1 and 2. Individual markers represent individual children's responses.

### *Discussion*

In our Experiment 1, we found that children in our sample overall show sound-shape correspondence between hole shapes and associated phonetic sounds (“Bouba/Kiki”), suggesting that children show the phenomenological perception of hole shapes.

However, we observed that children's congruency responses increased with age in our sample. There could be two possible explanations for this. One is that as previous studies on contour processing showed that children's ability to detect and integrate contours and assign them to the objects develops with age (Kovács, 1996; Kovács et al., 1999; Gunn et al., 2002; Hipp et al., 2014; Nayar et al., 2015). Younger children in our

sample might have had difficulty in integrating inner contour convexities and concavities to assign that contour to the hole. However, previous studies that found improvement in contour detection and integration manipulated visual noise and therefore made it difficult to detect and integrate contours (Kovács, 1996; Kovács et al., 1999; Gunn et al., 2002; Hipp et al., 2014; Nayar et al., 2015). While our stimuli were not noisy (the contours could be readily detected), it is nevertheless possible that the same processes that support contour detection and integration in noise may also be deployed to assigning figure and ground, and therefore in assigning a contour to a hole, and developmental change in this ability could drive developmental change in our study. Another possibility has to do with the development of sound-shape correspondence. Previous research has shown that sensitivity to shape-sound correspondence increases with age (Tzeng et al., 2017; Fort et al., 2018; Chow & Ciaramitaro, 2019). Although even 3-year-olds show sensitivity to sound-shape correspondence (Maurer et al., 2006), it could be that children in Experiment 1 might have assigned the inner contour to the hole but because older children are more sensitive to sound-shape correspondence we might have observed developmental differences in our experiment.

The results of Experiment 1 suggest that children can perceive the shape of holes inside material objects. In Experiment 2, we asked whether children's default is to perceive the shape of holes whenever holes are in objects, or whether the perception of the shape of the contour can be "flipped" to the material object rather than hole. In Experiment 2 we added eyes on top of the holes in the Experiment 1 objects, giving the impression that the hole was a "mouth" (see Kim (2020) Experiment 2 for a similar

approach). For Experiment 2, we reasoned that turning the objects into faces with mouths might drive children's attention to the material shape of the object rather than to the shape of the hole (i.e., because the contours now represent teeth). The "pointy" parts in the flower-shaped hole in Figure 1c become pointy teeth in the material surround, and the round petals in the star-shaped hole in Figure 1d become rounded teeth. If inducing the perception of a mouth "flips" shape assignment to the material figure rather than the hole, we should observe that the object in Figure 1c is more likely to be associated with "kiki", while the object in Figure 1d should be more likely to be associated with "bouba" (opposite of what we observed in Experiment 1).

Previous work with adults (Kim, 2020) showed that adults consistently perceive the shape of the inner contour of the material object (i.e., the shape of the hole) under such conditions, suggesting that, for adults, direct perception of hole shape may be the default and is not influenced by context. However, children, whose perceptual systems are still developing, may be more likely to flexibly assign shape to material objects or holes depending on context. If this is the case, we should observe differences between Experiments 1 and 2 with respect to children's sound-hole shape correspondence judgments. We also should observe a different developmental trend: younger children should be more likely assign novel sounds to the material object, and older children should be more likely to assign novel sounds to the hole, resulting in a significantly steeper developmental trend.

## Experiment 2

### *Methods*

#### *Participants*

Participants were 66 3-8-year-olds (Mean age = 65.37, age range = 39.22 – 93.24 months). Parents reported their children were male (36), female (27), or declined to report (3). One additional child participated but was not included in analysis because their caregiver did not report the child's birthdate, so we were unable to determine the child's exact age. Data for this experiment were collected in the Natural Mysteries exhibit at the Museum of Science, Boston. All study procedures were approved by the Boston University Charles River Campus and Museum of Science Institutional Review Boards. Caregivers gave written consent for their children to participate in the study. Sample size was chosen prior to data collection to be similar to Experiment 1.

#### *Materials*

Materials in Experiment 2 were the same as in Experiment 1 except that “googly eyes” were glued to the stimuli above the holes to introduce a perception of the inner contour of an object as an open mouth (see Figure 1c & 1d, see also Kim, 2020, Experiment 2).

#### *Procedure*

The procedure was same as in Experiment 1.

### *Results*

Children's responses were coded as congruent and incongruent, as in Experiment 1. We found that children's congruent responses were significantly above chance (49/66 (74.24%) binomial test,  $p < 0.001$ ; see Figure 2). Children's responses were not significantly different depending on the prompt (i.e., which one is "Bouba" or "Kiki") (Fisher's exact test,  $p = .574$ ). Children's congruent responses were not significantly correlated with their age in months (Spearman's  $r = .208$ ,  $p = .093$ ) (See Figure 3).

#### *Comparison between Experiments 1 and 2*

We used a binomial logistic regression to examine whether the likelihood of children's responses differed between the experiments or as a function of age. Children's responses were not different between Experiment 1 and 2 ( $\chi^2(1) = .33$ ,  $p = .56$ ) and their responses did not change with age ( $\chi^2(1) = 2.46$ ,  $p = .117$ ). We also did not observe a significant interaction between age and experiment ( $\chi^2(1) = .22$ ,  $p = .64$ ).

## **General Discussion**

In this study, we set out to answer the fundamental question that whether 3-8-year-old children can directly perceive hole shape. Previous research in the development of visual perception has shown that a rudimentary form of figure-ground segregation is observed in infancy and the efficiency to detect and integrate contours across space in a visual noise increases with age and becomes adult-like around 12 years of age. By age 6, children show adult-like segregation of figure from the ground in form coherence stimuli (White et al., 2018; Quinn & Bhatt, 2018; Kovács, et al., 1999; Taylor et al, 2014; Hadad

& Kimichi, 2006). Previous research also showed that 3-year-old children can identify, count, and track holes similar to material objects (Giralt & Bloom, 200). However, there is a significant gap in our understanding of whether children show a phenomenological perception of hole shapes like adults (Kim, 2020) when there are no explicit instructions about the holes.

In two experiments, we asked whether 3-8-year age can show a direct perception of hole shape, i.e., can they assign the inner contour of the hole object to the hole in an implicit shape-name matching task. We used the method of Kim (2020), exploiting sound-shape correspondence that to test whether 3-8-year-old children assign the inner contour of an object with a hole in it to the hole or to the surrounding material. We presented two objects with the same outer contour and varied the inner contour in a manner that would elicit opposite hole shape perception based on which side of the inner contour children assign (interior or exterior). If children assign the inner contour of figure 1a towards the hole, they should perceive it as having a flower-shaped hole and associate it with “Bouba”, whereas if they assign the inner contour to surround material in figure 1a, they should perceive a spikier-shaped hole and associate it “Kiki”. This opposite perception of hole shapes through contour assignment allowed us to test whether children directly perceive hole shapes or not.

In both experiments, we found that overall, children in our sample showed congruency between the shape of holes and their associated sounds (i.e., flower-shaped hole with “Bouba” and spikier-shaped hole with “Kiki”) suggesting that, similar to adults (Kim, 2020), children assign inner contour of an object with a hole in it to the hole rather

than to the surrounding material – evidence that they therefore directly perceive the shape of holes. These results were not due to children's simply associating one hole shape with one sound because there were no significant differences in children's congruent responses when they were asked to report which one is “Bouba” or which one is “Kiki”.

Our study results are first to show that children exhibit a direct perception of hole shapes. In addition, our results suggest that 3-8-year-olds have an ability to detect, spatially integrate inner contour of the hole object and assign the contour to the hole, and that the direct perception of hole shape is not readily influenced by contextual factors (like adding eyes to the shape to yield perception of the hole as a mouth with teeth, Experiment 2). Furthermore, our study results have implications for broader perceptual and cognitive development research. For example, previous research showed that infants can discriminate between objects that vary on presence and absence of hole (e.g., solid square vs square with hole (Chien et al., 2012). Infants also use holes in objects to guide their physical reasoning and how to interact with objects (Baillargeon et al., 2012; Wang et al., 2005). Furthermore, we recently showed that, 3-8-year-old children use holes in objects to infer object category membership (Kenderla & Kibbe, 2023). Although these studies primarily manipulated the presence and absence of holes in an object (property of topology) to study myriad developmental processes, all these studies make an inherent assumption that infants and children, when not explicitly instructed to attend to holes in objects, would perceive the holes in objects as in some way “object-like”; that is, they have their own shape and can be referred to using language, can be counted, and can be used to make inferences about objects' affordances, functions, or category membership.

Our study findings show that 3-8-year-old children can directly perceive hole shape, therefore providing the evidence for the inherent assumptions in these studies. Although the youngest children in our sample were 3-year-olds, future studies should investigate using innovative methods at what age children start to perceive hole shapes.

We also observed a developmental increase in children's perception of hole shape in Experiment 1, but not in Experiment 2, and when we compared Experiment 1 and 2 responses with age as a covariate, we did not find any interaction between age and experiment. Therefore, it is difficult to draw any strong conclusions about developmental change in the perception of hole shape. Inspection of Figure 1 reveals the suggestion of overall age-related trend, albeit a weak one (i.e., not statistically significant). It is possible that developmental change that we observed is due to developmental change in sound-shape correspondence more generally, and not to the development of hole perception more specifically. Further studies would aim to replicate and extend the current studies by attempting to tease apart these two possibilities. For example, rather than asking children to match the shape of the hole with a nonsense word, we could ask which of the faces in Figure 1c or 1d looks “nicer”.

This is one of the first studies to our knowledge that tested whether 3-8-year-old children perceive the shape of holes. Similar to Kim (2020) we exploited children's sensitivity to sound-shape correspondence to study children's perception of hole shape. Our study findings were similar to the findings of the studies conducted on adults that argued for holes own a shape (Kim, 2020; Nelson et al., 2014; Palmer et al., 2008). Given sound-shape correspondence is observed in very different cultures and languages (Ćwiek

et al., 2021) future research should use this correspondence to study whether children in different cultures and children that speak different languages other than English show perception of hole shapes. Future studies should also manipulate attention toward the hole in objects with a hole to study the influence of attention on children's perception of hole shapes. One of the key findings of our study is that animacy of the stimuli enhanced the perception of hole shape, however, we do not know the exact mechanisms that drive these findings. Future studies should manipulate the animacy of the objects with hole and test whether that would influence the direct perception of the hole shape.

### **CHAPTER 3**

## **INFLUENCE OF ATTENTION ON TOPOLOGICAL PROPERTIES AND SURFACE FEATURES IN TODDLERS' WORKING MEMORY**

### **Introduction**

Visual working memory is the ability to maintain and manipulate visual information over brief periods (Luck & Vogel, 2013; Eriksson et al., 2015). Working memory is associated with concept formation (Cowan et al., 2013; Cowan, 2014), predicts academic achievement scores in children (Phye & Pickering, 2006), and plays a central role in higher-order cognitive functions like cognitive flexibility (Diamond, 2013). In this chapter's introduction, I will first describe research on visual working memory, and the interaction between visual attention and working memory, in adults. Next, I will describe development of visual working memory and attention research in children. Third, I will delineate research on the developmental interaction between attention and working memory in children. Finally, I will highlight the gaps in our understanding of interaction between attention and working memory in development and discuss the purpose of the current study.

Traditionally, working memory for visual information in adults is studied using delay recognition paradigms, in which arrays of items (e.g., colored squares) are presented to observers for brief periods, followed by a brief retention period. Observers are then presented with a probe and are asked to report whether it was present in the

stimulus array (Luck & Vogel, 1997). In these tasks, it is consistently observed that adults can actively maintain approximately 3 to 4 items in visual working memory simultaneously (Luck & Vogel, 1997; Cowan, 2001). However, there is variability across individuals in how many items can be maintained in visual working memory (Vogel et al., 2005). Several factors contribute to working memory performance. Two main factors that influence working memory performance in adults include the type of representations maintained in working memory and the deployment of attention before encoding representations into working memory.

#### *Contents of representations in working memory*

At the perceptual level of an object, features can be broadly categorized into surface and structural features. Surface features like color, orientations, and texture are considered lower-level features that are generally processed by the visual system without the deployment of attention (Treisman & Gormican, 1988; Marr, 1982). Several studies have shown that, working memory performance for surface features like colors and orientations decreases with increase in the number of features participants are asked to maintain in working memory (Luck & Vogel, 1997; Vogel, 1997; Cowan, 2001).

Structural features like topology can be conceptualized by their invariance across continuous transformations called “rubber-sheet” transformations, which include bending, twisting, and stretching but not poking holes in the objects, tearing the object into two, or gluing two objects into one. Topological properties of an object can be perceptually observed through the number of holes, connectedness, and inside/outside relationships of an object that remain invariant under continuous transformations (Todd

& Petrov, 2022, for review). Topological invariance of an object occurs even with changes to surface features like color, texture, and metric shape. Because of the invariance of topological properties across different contexts, they are ideal candidates to provide stability to representations in working memory.

Topological properties are found to be processed earlier in visual processing (Chen, 1982) and earlier in development (Chien et al., 2011). Wei et al. (2019) tested the role of topological properties by utilizing the repetition effect in working memory. The repetition effect occurs in the delay recognition task, when the same encoding array is presented during the delay period, the performance in the task increases significantly compared to when there was no repetition. As discussed above, noise in working memory representations increases with time and results in a decrease in precision, but repetition of an array allows participants to refresh their representations, therefore leading to increased performance in the task. They contrasted repetition trials – in which participants viewed the encoded array a second time during the delay period, with updated trials – in which a new set of stimuli were presented in the second array. Participants were tested on memory performance for the second array. Generally, performance in repetition trials is typically significantly higher than in updated trials because the updated trials demand the replacement of the first encoded array of items in working memory. In Wei et al.'s (2019) study, they asked participants to remember the color of 4 English letters (ex., red E, blue E, green E, yellow E), and they manipulated the shape (irrelevant feature dimension in the task) of these letters in the second array in repetition and update trials. In the topology change condition, they presented the 4 different colors of the same English letter, and in

the second array, they changed the topological properties of these features by keeping the colors of the letter constant (ex., red E to red P) in both repetition and updated trials. In no topology change condition, they manipulated the metric shape of the letters that did not disrupt the topological properties between arrays one and two while keeping the colors constant (ex., red E to red H). They observed that when topological properties of objects are changed (ex., E to P) albeit not relevant to the task, the participant's performance was similar in updated and repetition conditions. However, in no-topological change conditions, they found that performance on repeated trials was significantly greater than the updated trials. These results suggest that changes in topological properties albeit not relevant to the tasks disrupt the object identity representations in working memory and result in the construction of new object representations. However, changes to the metric shape of objects do not result in the construction of new object representations. These results further suggest that topological changes to objects automatically disrupt the representation of object identity, and changes in these properties are difficult to ignore or selectively inhibited like metric shape.

In a similar task, Wei et al. (2021) directly compared memory performance on repeated trials in three different conditions: topology change, non-topology change, and no-change. In all three conditions, participants were asked to remember a set of colors, and the colors in the encoding array and repeated array were always the same. In the no-change condition, the shapes of the objects were same as an encoding array, in the topology change condition, only the objects' topology was changed (ex., red solid square to red circle with a hole), and in the non-topology change condition only object metric

shape was changed but keeping the topology constant (e.g., red solid square into red solid circle). They found that performance in the topology change condition was significantly worse compared to non-topology change and no-change conditions, and there were no differences in performance between non-topology change and no-change conditions. These results suggest that change in the topology of objects although irrelevant to the task disrupts object representations in working memory, therefore resulting in decreases in performance, whereas changes in the metric shape of objects are ignored or selectively inhibited when they are not relevant to the task. Both studies' results suggest that topological changes in an object result in the construction of a new object representation in working memory, whereas changes to surface features like metric shape do not have a similar effect suggesting that topological properties of an object might be fundamental to representing object identity in visual working memory, and attention may operate over topological properties in a qualitatively different way compared to surface features.

#### *Influence of Attention on Working Memory*

Attention can be thought of as active selection of information in a cluttered environment (Carrasco, 2011). It biases competition between stimuli for further processing by enhancing relevant information or suppressing irrelevant information (Desimone & Duncan, 1995). Both top-down goal sets and bottom-up stimulus properties modulate the attentional selection of information (Corbetta & Shulman, 2002), and attention enhances the speed with which information is processed (Peterson & Posner, 2012; Posner, 2016). For example, when observers are cued to attend to a location, they detect the target appearing in that location faster compared to when the cue was

uninformative (Peterson & Posner, 2012). Furthermore, reaction times to detect targets increased if the target appears opposite to the cued location (invalid cues) indicating that observers move their attention covertly to the cued location and must then disengage attention from that location and shift their attention to the target object (Peterson & Posner, 2012, Posner, 2016). Similar cue benefits and cue costs are observed when the features of objects, like colors, shapes, orientations, are cued (Liu et al., 2007).

Attention and working memory influence each other (Chun et al., 2011; Gazzaley, 2011; Gazzaley & Nobre, 2012). Selective attention can influence what information is encoded and prioritized during the maintenance of contents in working memory (Woodman et al., 2003; Griffin & Nobre, 2003; Zanto & Gazzaley, 2009; Rutman et al., 2010; Zanto et al., 2010, 2011; Gazzaley 2011; Gazzaley & Nobre, 2012; Li & Saiki, 2015). The contents of working memory can influence which items are selected by guiding attention (Woodman et al., 2007). Griffin and Nobre (2003) combined the Posner cueing paradigm with a delay recognition paradigm to test the effect of spatial cueing on visual working memory performance. They presented observers with a spatial cue before the presentation of a stimulus array (pre-cue) or after the presentation of a stimulus array (retro-cue). They observed that recognition memory was significantly higher on valid pre-cue trials compared to neutral-cue and invalid pre-cue trials. In the retro-cue condition, recognition memory accuracy was significantly higher on valid retro-cue trials compared to invalid retro-cue trials. These results suggest that attention to spatial locations can selectively enhance the processing of information prior to encoding and during maintenance in working memory.

Gazzaley and his colleagues (Rutman et al., 2010; Zanto & Gazzaley., 2009; Zanto et al., 2010, 2011) directly introduced competition between stimuli during encoding by merely changing the instructions to ask observers to focus on different types of stimuli and tested the corresponding working memory performance for those stimuli. For example, in one study they presented overlapping images of houses and natural scenes and asked the observers to focus on faces or scenes, thereby introducing relevant and irrelevant stimulus types for the task during encoding (Rutman et al., 2010). They found that observers remembered face and scene stimuli better when they were presented alone compared to when face and scene stimuli overlapped. Importantly, event-related potential (ERP) P100 component amplitude was similar when observers attended to faces compared to face alone condition suggesting that top-down goal sets (whether to attend faces or scene in overlapping condition) can modulate early visual activity. In a similar paradigm, this time examining working memory for color and motion direction, Zanto and Gazzaley (2009) divided the observers' working memory performance at the median reaction time and measured modulation of ERP N1 and P1 components associated with instructions to ignore one stimulus and focus on another stimulus. They found that on average performing trials ERP N1 and P1 components amplitude increased when observers attended the color and motion direction stimuli respectively. However, on low-performance trials when observers were instructed to ignore color, N1 ERP component amplitude was similar in magnitude compared to when they were asked to attend to color, and similar findings were observed with motion direction stimuli on P1 component. These results show that high performance on the working memory task may result from

filtering out or suppressing irrelevant information during encoding. When irrelevant information was not filtered out, observers deployed their attention to these items, thereby cluttering working memory.

Early visual areas, which process visual information like orientation, color, motion direction, are modulated by the dorsal fronto-parietal networks during the deployment of selective attention while encoding relevant information into working memory (Zanto et al., 2010, 2011; Gazzaley & Nobre, 2012). Zanto et al. (2011) showed a causal relationship between prefrontal modulation of early visual areas during encoding in a delayed recognition task. They performed repetitive transcranial magnetic stimulation (rTMS) on the inferior frontal cortex while observers encoded color and ignored the motion direction of the stimuli. They found that working memory performance decreased when they perturbed the inferior frontal cortex with rTMS, thereby decreasing top-down modulation on early visual areas. In addition, they found observers with stronger fronto-posterior functional connectivity showed larger disruption in their performance during rTMS on the inferior frontal cortex.

Most of the research on attention influence on working memory performance was conducted on the representations of surface features like orientations and color. There is no research to our knowledge that directly examines whether and how attention influences the encoding of structural features like topology in working memory. One study tested the role of topology in the attentional tracking of moving objects (Zhou et al., 2010). In a multiple object tracking task, when participants were asked to track objects that change in their topological properties (ex., letter H to letter A or P) or change

in their metric shape with invariance in topology (ex., letter H to letter K), participants performance significantly decreased whenever the topology of objects changed, but their performance was similar when changes occurred to the metric shape of objects (Zhou et al., 2010). These results suggest that attention may be deployed to topological properties of objects, and topological properties appear to be central in determining objects' identities across space and time.

#### *Development of visual working memory*

Findings from various versions of the change detection task and working memory span tasks on children suggest that working memory capacity increases well into adolescence (Gathercole et al., 2004; Riggs et al., 2006; Cowan et al., 2010; Burnett Heyes et al., 2012; Simmering, 2012; Isbell et al., 2015; Heyes et al., 2016). However, efforts to pinpoint a true “capacity” for working memory have yielded mixed results. For example, Riggs et al (2006) showed that 10-year-olds' capacity was around 3.8 items, and for the same age group Cowan et al (2010) showed a capacity of 2 items. The difference in visual working memory capacity in children is due to differences in task instructions (Simmering, 2012), the nature of the task itself (Cowan et al, 2010), the stimuli children are asked to maintain in working memory, and the mode of response (Burnett Heyes et al., 2012; Heyes et al., 2016).

In an adapted version of the adult change detection task, Oakes et al (2013) tested 6- and 8-month-old infants' working memory capacity with eye-tracking. They presented two colors (encoding array) simultaneously for 517 milliseconds, followed by a delay of 317 milliseconds. They then showed infants the same two colors as in the encoding array,

or one old and one new color. They measured infants' looking times to the test individual-colored patches in the test array. They calculated a change preference score by dividing infants' looking times to the changed color by their overall looking times to both changed and unchanged colors for each trial. A change preference score of .5 suggests infants show no clear preference for the changed color, suggesting that they did not notice its change. They found that 8-month-old infants', but not 6-month-old infants' median change preference scores were above 50%, suggesting that 8-month-old infants could detect the changing color in a 2-item array and therefore could actively maintain two items in visual working memory. However, in a similar paradigm when the encoding array included two identical colors, 6-month-old infants preferred the changed stimulus. These results suggest that visual working memory is functional from at least 6 months and there is a rapid increase in how many items infants can maintain within a few months.

Káldy and Leslie (2005) tested 6-month-old infants' working memory using physical objects. They first familiarized infants with two differently shaped objects presented in the center of the stage repeatedly for four trials by alternating the shapes in two locations. In a test condition, the same two objects were shown to the infants and were then occluded by two opaque screens. When the screens were removed, the shapes had either swapped locations (Change condition) or remained in the same locations (No-Change control condition). They measured infants' looking times following the removal of the screens. They found that 6-month-old infants in the Change condition looked longer compared to infants in the No-change control condition. To test whether 6-month-

old infants were able to remember both shapes or whether they maintained only the last hidden shape, they further tested object memory for the first location by only removing the occluder for the first location. They found that infants did not look longer when only the first hidden object was revealed to have swapped shapes. These results suggest that 6-month-old infants can maintain a single object shape and its associated location in working memory but fail to maintain two object shapes and their corresponding locations. In the same paradigm with two locations and two object shapes, Káldy and Leslie (2003) found that 9-month-old infants could maintain two object shapes and their corresponding locations in working memory.

In a similar violation of the expectancy paradigm, Kibbe and Leslie (2013) tested 9-month-old infants with three object shapes and three locations. First, the infants were familiarized with three different shaped objects across four trials, with three objects being presented for a duration of eight seconds on each trial. In test trials, they presented the three different shapes sequentially in three locations and hid them in the same order, and they tested the infant's memory for the object hidden second by removing the center occluder. In the control condition, the same object shape hidden in that location was shown, in a difficult-swap condition the object shape in the first location swapped with the second location, and in the easy-swap condition, the object shape in the last hidden location swapped with the second location. The "difficult swap" was difficult for infants because they had only one means to detect the change in object shape: i.e., to remember the shape of the object at second location. However, in the "easy swap" condition, infants could either remember the identity of the object at the second-hidden location or

remember the last hidden object (and notice that it had suddenly appeared in a new location) to detect the change. They found that 9-month-old infants' looking times were similar in both the easy and difficult swap conditions compared to the control. However, when 9-month-olds were familiarized with three object shapes but only tested with two locations and two object shapes, they looked longer to the first hidden location even when the object shape in this location swapped with familiarized object shape but not hidden in any of the locations in that trial. These results suggest that 9-month-old infants can keep track of object identities hidden in two locations. However, when presented with three objects in three locations, they fail to remember even portion of object identities. By 12 months, infants can successfully keep track of three objects presented in three locations when tested on second location object identity (Kibbe & Leslie, 2013).

Kibbe and Leslie (2013) hypothesized that tracking multiple objects into occlusion demands attention resources that are taken away from maintaining bindings between features and locations in working memory. However, with increases in attention control with development, infants' ability to maintain information in working memory also improves.

Very few studies have tested working memory performance in toddlers (Cheng et al., 2020; Kibbe & Applin, 2022). A recent study by Cheng et al. (2020) used eye tracking to ask whether 2.5-year-old children could remember the locations of three unique objects presented for brief intervals. In their task, children were presented with four face-down "cards" on a computer screen. During the encoding period, three of the cards flipped to reveal unique images on their faces for one second. After a retention

interval of one second, the fourth card revealed its face: an image that matched one of the cards in the to-be-remembered array. They measured the card that children first looked at following the reveal of the probe card. They found that children successfully first looked at the correct object that matched the probe object above chance suggesting that 2.5-year-old children can successfully maintain 3 objects in their working memory under passive viewing conditions.

A more recent study by Kibbe and Applin (2022) tested 28-40-month-old toddlers' visual working memory with real-world objects. In their task, toddlers were shown sets of two or three different colored beads which were then hidden simultaneously (Experiment 1) or sequentially (Experiment 2). The experimenter then showed toddlers a probe card with a color that matched the color of one of the beads and asked children to point to bead's location. This task required toddlers to remember which color was hidden in which location, and thus to maintain feature-location bounded object representations in working memory. They found that overall toddlers represented two and three items in their working memory. However, they found that while toddlers' ability to remember two objects increased with age, their ability to remember three objects was consistent across the age range they tested, suggesting this capacity may be just emerging in these children. Other studies have shown that children's capacity to represent the location of feature-bound objects increases beyond age 3 (to about 4-5 objects at 5-6 years; Applin & Kibbe, 2020; Cheng & Kibbe, 2022).

While past research suggests that infants and adults may take topology into account in tracking objects and physical reasoning about object interactions (Zhou et al.,

2010; Hespos & Baillargeon, 2001a, 2001b; Wang, Baillargeon & Paterson, 2005; Hespos & Baillargeon, 2006; Baillargeon et al., 2012) as discussed in chapter 1 of this dissertation, few studies have directly examined the role of topological properties in representations of occluded objects early in development. Kibbe and Leslie (2016) examined 6-month-old infants' representations of objects that differed in topological properties. They showed infants two topologically distinct objects (a disk, and a disk with a hole in its center), and then hid the objects sequentially behind separate occluders. They then lifted one of the occluders to reveal either the object that had been hidden in that location, or the unexpected other object, and measured infants' looking time. When infants were tested on the object that had been hidden last, infants looked longer to the unexpected topological change outcome compared to the expected no-change outcome suggesting that 6-month-old infants represented topological properties in their representation of the most recently hidden object (consistent with previous results suggesting infants can remember color and shape of this object as well, e.g., Káldy & Leslie, 2005). However, when infants were tested on the first-hidden object, they failed to recall the topological properties of the object, or even the object's existence. This result is inconsistent with previous research (Kibbe & Leslie, 2011), which showed that 6-month-olds who fail to remember the surface features of this object (e.g., shape, color) are surprised when the object vanishes completely, suggesting they remember the objects' existence even if they fail to remember what the object looks like. This surprising discrepancy suggests that maintaining topological class in representations of objects might require more attentional resources compared to surface features. Similar results of

lower working memory performance for topological properties were observed in adults (Wei et al., 2019).

### *Attention development*

Newborns make visual fixations through a reflexive system (Schiller, 1985, Hendry et al., 2019). However, the visual orienting attentional network develops very quickly. By 3-6-months, infants can voluntarily disengage from a stimulus and shift their fixations to other objects (Courage et al., 2006). In a spatial cueing paradigm, Richards (2000) presented focal stimuli in the center of the screen to capture infants' attention and after 2 seconds presented a cue in the periphery. After that, on valid trials, a target stimulus appeared in the cued location, and on invalid trials the target appeared on the opposite side of the screen. Infants as young as 3 months were more likely to detect the target on valid cued trials compared to invalid or no cue trials. Importantly, they observed developmental change in this orienting attentional network from 3 to 6 months. Infants showed a different developmental pattern of enhancement and inhibition of return with exogenous cues: Inhibition of return develops slower than cue enhancement and contributes to learning by inhibiting the visual stimuli that infants just processed, thereby allowing infants to explore the environment (Markant & Amso, 2013, 2016).

Toddlers show selective attention by actively filtering out irrelevant content and attending to the relevant information in the task by exerting attentional control on visual information. For example, in a visual search task, when 37-month-old toddlers were asked to detect the target item in a set of distractors, their ability to detect targets got faster with decrease in the number of distractors in the display, suggesting that children

deploy attentional networks to inhibit irrelevant items and this ability is more efficient with small number of distractors (Vales & Smith, 2015).

*Interactions between attention and working memory during development*

The development of attentional networks allows infants to navigate the world efficiently, initially by following exogenous cues and eventually by filtering out irrelevant information and effectively selecting relevant information based on task goals. Therefore, the development of attentional networks has consequences for what information is encoded and maintained in working memory, which impacts learning and forming long-term memories (Astle et al., 2012; Shimi et al., 2014; Diamond, 2013; Amso & Scerif, 2015; Markant & Amso, 2013, 2016). For example, 9-month-old infants who showed stronger inhibition of return to a previously cued location showed higher recognition memory for target objects (Markant & Amso, 2013).

Ross-Sheehy et al. (2011) combined spatial cueing with an infant change detection task and tested whether attention cueing affects working memory performance in 5- and 10-month-old infants. They first presented an exogenous cue in one of the locations in the display. After that, an array of three colored squares was presented to infants while the cue stayed on one of the colors for 300 milliseconds. The cue and array then disappeared and then reappeared after 300 milliseconds. This stream continued for 20 seconds. On half of the trials the cued color changed with each display (valid stream), and on other trials, a non-cued object changed its color (invalid stream). Results showed that, after repeated exposure to the stimuli, 10-month-old infants looked longer to the valid stream compared to the invalid stream, whereas 5-month-old infants did not prefer

any stream. However, when cues spun around to attract their attention instead of remaining stationary, 5-month-old infants looking times increased for the valid stream compared to the invalid stream. These findings suggest that exogenous attentional cues drove 5-month-old infants' attention to the cued object location and therefore allowed them to encode the object in that cued location, effectively increasing working memory performance.

Astle et al. (2012) combined the spatial cueing paradigm with the delayed recognition task and tested how selective attention during encoding enhances working memory performance in older children. They presented a spatial pre-cue before the encoding period or a retro-cue during the maintenance period of a recognition memory task and measured working memory performance in 7-year-olds, 9-year-olds, and adults. The task included three types of cue trials: valid cue trials, invalid cue trials, and neutral cue trials. They found that working memory performance was higher on valid pre-cue and retro-cue trials compared with neutral cue trials for all age groups, and this cue benefit was smaller for 7-year-olds and higher for adults. Nine-year-olds' and adults' working memory performance was lower on invalid cue trials compared to neutral cues, while 7-year-olds' performance did not significantly differ between these two trial types. Comparison between the pre-cue and retro-cue valid and neutral cue trials showed that 7- and 10-year-olds benefited more from pre-cues than retro-cues, whereas adults benefitted more from retro-cues compared with pre-cues. These results suggest that 7-year-old children can improve their working memory performance by selectively encoding items

in the cued location but are less able to prioritize cued items during visual working memory maintenance.

The ability to selectively encode information into working memory develops beyond 10 years of age. In a similar task, Shimi et al. (2014) tested whether 7-year-olds, 10-year-olds, and adults benefitted more from peripheral compared with central pre-cues and retro-cues. The results showed that all age groups benefitted equally on valid pre-cue trials compared to neutral cues in both peripheral and central cue conditions for all age groups. However, on retro-cue trials, central cue benefits were higher compared to peripheral cue benefits on working memory performance. These results suggest that, from age 7, children's working memory performance can be improved equally by exogenous and endogenous spatial attentional pre-cues.

Overall, attention and working memory research in development show that the development of attentional networks contributes to filtering information that goes into working memory. The benefit of selective encoding of items was present for cues that operate bottom-up in infancy and top-down in middle childhood, optimizing limited working memory capacity.

#### *Purpose of Present Study*

Previous research in adults and children suggests that surface features and topological properties are maintained in working memory and the number of surface features that are maintained in working memory increases with age (Kibbe & Leslie, 2016; Káldy & Leslie; 2005, Kibbe & Leslie, 2013; Applin & Kibbe, 2020; Chen &

Kibbe, 2022; Kibbe & Applin, 2022). However, there is a significant gap in our understanding of how topological properties are represented in working memory across development and whether the nature of the representation in working memory for structural features varies or is similar to surface features. Because topological properties are extracted earlier in visual processing and in development, and because topology is more informative about an individual object's continued identity than surface features (Chen, 1982, Chien et al., 2012, Zhou et al., 2014), understanding how topological properties are represented compared to surface features in children would allow us to decipher whether performance in working memory task depends on the contents of the representations maintained in working memory. Toddlers' working memory appears to be extremely limited when they are asked to remember surface features, but it is possible that toddlers may have a great capacity for remembering objects' topological features, since these features are more likely to define the *structure* of an object representation. A goal of the present study is therefore to understand how toddlers - with extremely limited working memory capacities when asked to represent surface features – may represent objects' topological properties in working memory.

In adults, attention is central to what information is encoded into working memory and prioritized during the maintenance of surface features in working memory (Gazzaley, 2011; Gazzaley & Nobre, 2012; Amso & Scerif, 2015). Prior to encoding information in working memory, attention biases competition towards the relevant information in the cluttered environment based on task goals, thereby suppressing irrelevant information entering working memory (Woodman et al., 2003; Griffin &

Nobre, 2003; Zanto & Gazzaley, 2009; Rutman et al., 2010; Zanto et al., 2010, 2011; Li & Saiki, 2015; Astle et al., 2012; Shimi et al., 2014; Diamond, 2013; Markant & Amso, 2013, 2016). Previous research has also shown that exogenous pre-cues can influence working memory performance in infants as young as 5-month-olds (Ross-Sheehy et al., 2011), endogenous spatial pre-cues improve children's working memory performance in late childhood (7- and 9-year-olds), and the efficiency of attentional influence on working memory develops from late childhood to adulthood (Astle et al., 201; Shimi et al., 2014). There is a significant gap in our understanding of how attention and working memory interact across early development. As mentioned earlier, working memory capacity is limited and these limitations are even lower in children. Deployment of selective attention before the information is encoded into working memory would maximize the utility of working memory by allowing children to maintain relevant goal-directed information rather than cluttering working memory with irrelevant information. Although recent research has shown that toddlers can maintain two to three surface feature-bound objects in working memory (Kibbe & Applin, 2022; Cheng et al., 2020), there is no work to our knowledge that examines how selective attention influences the encoding of items in working memory in late infancy or early childhood, leaving a multi-year gap in our understanding during a period when working memory itself is undergoing significant development (Applin & Kibbe, 2020, Kibbe, 2015; Kibbe & Applin, 2022; Pailian et al., 2016; Simmering, 2012).

Furthermore, there is no work to our knowledge that examines whether and how selective attention influences topological representations in developing working memory.

It is possible that selective attention may operate over topological properties of objects differently than it operates over surface features. Attention is thought to support the active maintenance of bindings between surface features and objects in visual working memory, and limits on exogenous attention have been proposed to be the primary limiting factor in infants' and toddlers' visual working memory for feature-location bound object representations (Kibbe, 2015; Kibbe & Leslie, 2013; Kibbe & Applin, 2022). However, topological properties may not require the same attentional resources, since they define the structure of object representations rather than (potentially changeable) properties. The extent to which exogenous attentional cues impact encoding and maintenance of object properties that may make different demands on endogenous attention is not currently known. Toddlers are an ideal population in which to study this question because their exogenous and endogenous attentional capacities are undergoing development and their visual working memory capacities have been shown to be quite limited. Therefore, understanding whether toddler's selective attention influences surface features and topological properties in their working memory would allow us to decipher whether toddlers can exert selective attention to influence working memory contents and their deployment of attention on memory depends on the contents of object representations in it.

In this study, we planned to address these gaps in the literature by testing: 1. whether 24-40-month-old toddlers maintain topological properties similarly or differently compared to surface features (color) in working memory, and 2. whether object-based attention cues influence the maintenance of both surface features and topological

properties in working memory in 24-40-month-old toddlers. We adapted the method of Kibbe and Applin (2022) to examine the effects of attention cueing on toddlers' representations of color and topology in working memory. Kibbe and Applin (2020) showed 28-40-month-olds an apparatus in which six hiding locations were embedded. They then showed children sets of either two or three different-colored beads, which were then hidden simultaneously in two or three of the cups, respectively. After a brief delay, the experimenter showed the children a card depicting the color of one of the hidden beads and asked the children to locate that bead. Since Kibbe and Applin (2022) observed developmental change at set size 2, and since children's performance at set size 2 was not at ceiling, we tested children only with two hidden objects on each trial. We also simplified the task by reducing the number of locations in the task to two. Although this increases the possibility of proactive interference (which Kibbe & Applin, 2022 sought to avoid), we reasoned that it may reduce other sources of complexity in the task (e.g., visual complexity).

In our study, we manipulated two factors: the type of information children had to hold in working memory (surface feature (color) or topological property), and whether children were given an attentional pre-cue prior to encoding. With respect to the first factor, children were assigned to one of two between-participants conditions. In the color condition, children were asked to remember two objects that varied in color, and in topology condition, they were asked to remember two objects that varied in topology (i.e., one object had a hole, while the other did not have a hole). With respect to the second factor, children in both the color and topology conditions completed two within-

participants blocks: a cue block and a no cue block. In the cue block children received were given a cue before the encoding period that showed which object they would be asked to recall at probe, while in the no cue block children did not receive any such cues. Unlike previous studies, which used both valid and invalid cues, all cues in our study will be valid. We chose not to include invalid cue trials in our study because earlier research has shown that invalid cue trials have no significant effect on working memory performance in 7-year-olds (Astle et al., 2012). Excluding invalid cue trials allowed us to present the cue and no cue trials as separate blocks rather than intermixing the cue trials, thereby simplifying the task for the toddlers.

Comparisons between children's performance in the no cue blocks between the color and topology conditions provided allowed us to examine how these two types of representations are maintained in toddlers' working memory. Comparisons between the no cue and cue blocks within each condition allowed us to test whether attention cues influence working memory performance in toddlers and allowed us to examine whether attention impacts working memory for surface features or structural object properties differently early in development. I describe specific comparisons and predictions in the next section.

### *Comparisons and Predictions*

There are multiple reasons why we planned to study the 24-40-month-old age group. First, previous research on attentional cue effects on working memory is primarily done in infants and children in late childhood (Ross-Sheehy et al., 2011; Astle et al., 2012; Shimi et al., 2014), therefore leaving a gap in our understanding of how these two

processes interact. Very recently, studies have tested children in late infancy or early childhood and found that they can maintain 2 and 3 items in the working memory. Therefore, 24-40-month-old children would provide a detailed picture of developmental changes in the influence of attention on working memory. Second, because of the developmental nature of working memory, and based on evidence from earlier research that 6-month-olds can maintain one topological object similar to one color object (Kibbe & Leslie, 2011, 2016), we planned to compare working memory performance between these two types of objects features in toddlers, therefore allowing us to find whether 24-40-month-old children can maintain topological object properties in working memory and how this compares to objects' surface featural properties (i.e. color) and whether the contents of toddlers' representations are maintained differently with an increase in age. Overall, the efficiency of attentional deployment and working memory capacity increases during 24-40-month-old children, therefore ideal age group to test our hypothesis.

Previous research has shown that 26-40-month-olds can represent two different colors in working memory (Kibbe & Applin, 2022) and there is a developmental increase between 26-40-month-olds for set size 2, therefore we predicted that children's performance in the color no cue condition would be significantly greater than chance and there would be an increase in performance with age in our sample (replicating Kibbe & Applin, 2022). We have two predictions for the topological no cue condition: 1. Given that previous research with infants and adults showed that topological properties are primitive and fundamental for object perception and representation (Chen, 2005; Wei et al., 2019), and potential candidates for deploying attention in visual search tasks (Wolfe

& Horowitz, 2017), and therefore encoded automatically with demanding less attentional resources, we expect that children in our sample would be able to encode and maintain in working memory two topologically distinct objects (however, we did not have strong predictions about whether toddlers' visual working memory capacity for topological properties of objects would increase with development in this period). 2. If topological properties of objects are represented with lower attentional or working memory "cost" compared to surface features of objects, we predicted that children in the topology condition would perform better overall than children in the color condition.

Previous research has shown that the efficiency of attentional deployment increases throughout development (Vales & Smith, 2015; Crone & Steinbeis, 2017; Conejero & Rueda, 2017), therefore we would expect toddlers to benefit from attention in the color condition. Research in adults suggests that topological properties are fundamental in tracking objects which demand focused attention (Zhou et al., 2010) and topological properties are likely candidates for the deployment of attention in visual search (Wolfe & Horowitz, 2017). However, there has not yet been research on how selective attention interacts with topological properties and whether this interaction differs from the interaction between selective attention and representations of surface features. We expected children to benefit from attentional cues similarly in the topology condition but did not have strong predictions about whether attentional cues may operate differently over different object features for toddlers. On the one hand, since maintaining topology and color may make different demands on endogenous attention, exogenous attentional cues may operate differently over these features. If toddlers can take

advantage of attentional cues, they may benefit more from such cues in the color condition, which is more attentionally demanding. On the other hand, attentional cues may operate similarly to orient attention to object features; once toddlers' attention is oriented to one of the features, they may ignore or filter out the other object, effectively storing only one object in working memory (which even young infants can do). If this is the case, we would see no difference in the effects of attentional cues on toddlers' working memory as a function of condition.

## **Method**

### *Participants*

We tested 41 24-40-month-old participants with  $n=21$  in the color condition (mean age = 31.1 months), and  $n=20$  in the topology condition (mean age = 31.25 months). Parents reported their children to be female (24), male (15), or decline to report (2). Parents reported that their children's racial demographic information was white (23), Asian (4), Hispanic or Latinx (1), multiracial (7) or declined to report (6). An additional  $n=15$  children were tested but not included in the analysis because they declined to complete the study ( $n=12$ ), or they failed to respond in more than half of the trials in a block ( $n=3$ ).

Our sample size was estimated using a power analysis using G\*Power 3.1 with a planned repeated measures ANOVA to detect a small-to-medium main effect of condition, block, and a small-to-medium interaction between condition and block with

80% power ( $f = .25$ ). The suggested sample size was 34 participants total. However, we planned to collect  $n=48$  total participants (24 participants in each between-participants conditions) to better detect any effects of age within and across groups. All participants' caregivers gave written consent for their children to participate in the study. The Boston University Charles River Campus Institutional Review Board approved all study procedures.

### *Materials*

Materials consisted of animated objects that could be hidden inside two black “cups” on each trial. In the color condition, the stimuli consisted of a total of six color “beads” (blue, red, yellow, orange, violet, and green), all of which were hexagonal and had the same topology (with no hole in the objects) On each trial, a subset of two of the six beads were shown to children. Colors on each trial are selected pseudorandomly so that adjacent trials in the task did not contain same color beads. In the topology condition, the stimuli consisted of six pairs of blue beads (pentagons, circles, hexagons, triangle ellipse, and diamond) which differed only on topology (whether one had a hole). On a single trial within each block, children would view one of these sets (i.e. a blue square with no hole, and a blue square with a hole). Cue and probe “cards” in both the color and topology conditions were rectangular in shape and presented in the top center of the screen. In the color condition, there were six color cue and probe cards (blue, red, yellow, orange, violet, and green). In the topology condition, cue and probe cards were always blue in color and differed only on the presence or absence of a hole in the middle of the card. All the stimuli are designed in Adobe Illustrator and presented using

Microsoft PowerPoint. We added shadows to the stimuli to make them appear to be 3D. Stimuli were displayed using Zoom's screen share function. Figure 4 shows an example of the stimuli used in the study.

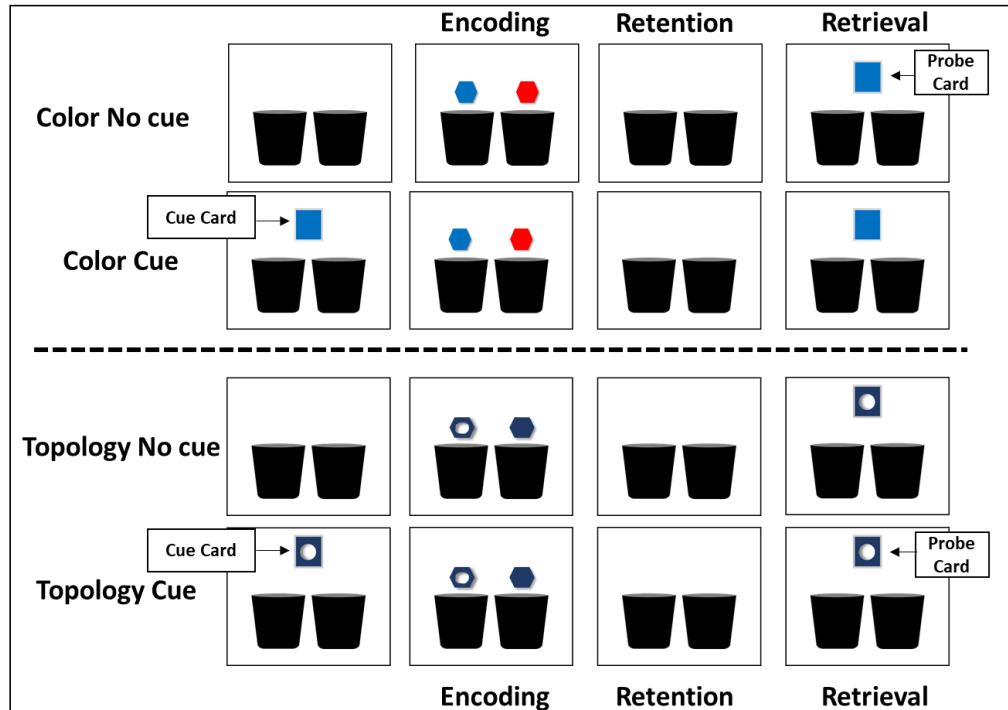


Figure 4. Example trial for both cue and no cue blocks for color and topology conditions.

### *Design*

The study design included two between-participants conditions (color and topology). Within each condition, children completed 12 test trials presented in two blocks of six trials each: a no cue block and a cue block. In addition, children completed one practice trial at the start of each block. The order of the blocks was counterbalanced within participants. In both conditions, the cue block included 100% valid cues: the cued stimuli always probed.

The to-be-remembered objects (the “beads”) used in each trial varied depending on whether children were in the color or topology condition. In the color condition, on each trial, the beads were different in color but the same shape and topology. The probe and cue cards were always presented as squares which matched one of the colors on that trial (that is, the shape of the probe card did not match the shape of the objects on that trial).

In the topology condition, on each trial, the beads always differed in topology (one with a hole and another without a hole) but had the same shape and color. The probe and cue cards were always presented as a blue square on every trial, and either did or did not contain a hole.

Children completed the study from their homes using a device with at least a 10-inch screen (37 used a laptop, 4 used a tablet or chrome book). The experimenter first walked caregivers through a set-up procedure, which included instructions on how the study would proceed. Children completed a series of warm-up trials before starting the procedure. The entire procedure is described below.

## Procedure

### *Online setup*

Parents were asked to enter full-screen mode in Zoom, disable side-by-side view, and hide self-view so that children could not see themselves on-screen during the experiment. We then asked parents to move the experimenter video to the top right corner of the Zoom screen to ensure that children see the full stimuli. Caregivers were asked to

use a device with a screen that is at least 11 inches (e.g., a tablet or a laptop computer, but not a phone) before the study. Before the set-up, we obtained consent from parents to record the experiment.

*Color or Topology matching warm-up*

We first familiarized the children with the process of matching objects that are of the same color or the same topology with the probe card. In the color condition, children were presented with three colored beads at the bottom of the screen and the experimenter said “See these beads? See the different colors?” The experimenter then showed three square color cards corresponding to the colors of the beads and said “Now see these cards? See how they have different colors like beads?” All three cards went away from the screen after, and the one-color card is presented on the screen the experimenter asked, “Can you show me which bead matches this card?” Children are encouraged to point to the bead using their fingers. Caregivers confirmed whether the children pointed to the left, right, or middle beads. Once the child correctly picked the same color bead as the card color, the experimenter said “Great Job! See, it’s a match” This procedure was repeated for all three bead colors.

The topology condition matching warm-up procedure was similar to the color warm-up except that children were presented with two beads that differed only on topological properties (hole, no hole). The cards also varied on the topological properties (hole, no hole). The experimenter asked the children to match beads that look the same as the card one at a time. Children were presented with a card that matched the topology of one of the beads, and experimenter asked children “Can you show me which bead

matches this card?" Children were encouraged to point to the beads using their fingers and caregivers confirmed whether children pointed to the left or right bead on the screen. Once the children picked the bead that matched the card, the experimenter said "Great Job! See its' a match" The procedure was repeated for all two topological properties. The experimenter then proceeded with the test trial blocks. Within each block (cue and no cue), children first completed one practice trial followed by six test trials.

**No cue Block.** In a practice trial, the experiment first introduced a hiding apparatus to children and said "Now we are going to play a game. I am going to hide these beads in these cups, and you have to remember which beads are hiding in each spot. Okay? Let's try one!" Two beads descended from the top and rested above each cup. The experimenter said, "Look at these beads! Now these beads are going to hide in these cups. You have to remember which bead is hiding in which cup. Okay?" The beads then descended into the cups. After a retention period of 2 seconds, the probe card appeared above the cups. The experimenter then said, "OK, where is this bead?" After children responded by pointing to a cup, the beads hiding in both cups emerged from the cups. The experimenter then said, "Look! Here are the beads! Did you find the right bead?" If children pointed to the correct cup, the experimenter said, "You did!" and circled the card and bead on the correct cup using a mouse cursor and reiterated "See they match, great job! Let's try another one!" If children pointed to the wrong cup, the experimenter then said "Oops, see the bead that matches the card is hiding in the other cup" The experimenter circled to the card and bead on the cup that children chose with a mouse cursor and mentioned "see these two don't match" and then circled the card and the bead

on correct cup and said “see these two match” to make sure children understood the match between the beads and the probe card, and then said, “Let’s try another one!” and proceeded to the second practice trial using the same procedure. Caregivers were asked to report to the experimenter which side (right or left) their child pointed to. Overall, 25 out of 41 (60.9%) children correctly remembered the bead that matched the probe card (color no cue block = 15/21 (71.4%); topology no cue block = 10/20 (50%)) on the practice trial. After the child completed both practice trials, the experimenter then proceeded to the test trials.

Test trials followed a procedure similar to that of the practice trials (see Figure 4). On each trial, two beads simultaneously descended from above and rested above the edge of each cup. The experimenter directed the children’s attention to the beads by saying “Look!” After the experimenter made sure children had attended to the beads (by making sure that children were watching the screen when the beads were shown), the beads descended into the cups. The entire array (both beads) was visible for ~4 seconds. After the retention period of 2 seconds, a probe card appeared on the screen and the experimenter said, “Can you show me where this bead is?” Once the children pointed to the location, (parents informed the experimenter if their child pointed to the left or right cup), the beads moved out of the cups. If the children's response was correct, the experimenter said, “Great job, let’s try another one!” and if the children's response was incorrect, the experimenter said, “That’s ok, let’s try another one!” The beads moved out of the screen and the experimenter said “All these cups are empty now. Let’s play again!”

**Cue Block.** The two practice trials at the start of the Cue block were similar to the practice trials in the no cue block except that after introducing the cups, a cue card appeared in the top center of the screen. The experimenter said “See this? You have to remember this bead. You have to remember where this bead is going to hide!” Following that the two beads descended from above and followed the same procedure as in the no cue practice trials. Overall, 31 out of 41 (75.6%) children correctly remembered the bead that matched the probe card (color cue block = 16/21 (76.2%); topology cue block = 15/20 (75%)) on the practice trial. After children completed the two practice trials, the experimenter then proceeded to the test trial.

Cue block test trials were similar to the test trials in the no cue block, except that a cue card referring to the color or topology of the object was shown to the children before the beads descended on the screen. After the appearance of the cue card, the experimenter said “See this, you have to remember this bead. You have to remember where this bead is going to hide!” Following that the two beads descended from above and followed the same procedure as in the no cue block.

In both conditions (color and topology) and in both blocks (cue and no cue), both cup locations probed equally often (the object hidden in the left cup was probed on half of the trials in each block, and the object hidden in the right cup was probed on the other half). Probed cup locations were randomized before the experiment and were presented in the same order for all the participants (no cue: LLRRLR; cue LRLRRL). Probed locations within the blocks varied between the cue and no cue blocks. The order of the

blocks within each condition are counterbalanced between the participants, but the order of trials within each block was fixed across participants.

**Coding.** We coded children's responses from the videos as correct and incorrect on each trial. Two independent observers coded children's responses based on the direction of children's points (left or right) and verbal confirmation from caregivers. Videos were coded by one of two independent observers, and twenty percent of the videos were coded by both observers to assess coder agreement; there were no disagreements between the coders. We computed the mean percentage correct (accuracy) across the 6 trials in each block (cue or no cue) in both conditions (color or topology). We also computed a "cue benefit score" for each condition separately by subtracting the no cue block mean percent correct from the cue block mean percent correct.

## Results

First, we asked whether children were able to select the location of the probed object at rates significantly above chance (.5) using one sample t-tests to compare children's mean percent correct in each block within each condition to what would be expected if they were responding at random. In the color condition, children's mean percent correct was significantly higher in both the cue block (mean = 62%,  $t(20) = 2.75$ ,  $p = .012$ , CI[2.88- 20.92], Cohen's  $d = .60$ ) and no cue block (mean = 65%,  $t(20) = 3.19$ ,  $p = .005$ , 95% CI[5.21-24.94], Cohen's  $d = .7$ ) blocks. In the topology condition, the children's mean percent correct also was significantly higher than chance in both the cue

block (mean = 59%,  $t(19) = 2.146$ ,  $p = .045$ , 95% CI[.22-17.3], Cohen's  $d = .48$ ) and the no cue block (mean = 65%,  $t(19) = 4.42$ ,  $p < .001$ , 95% CI[7.88-22.11], Cohen's  $d = .99$ ).

See Figure 5.

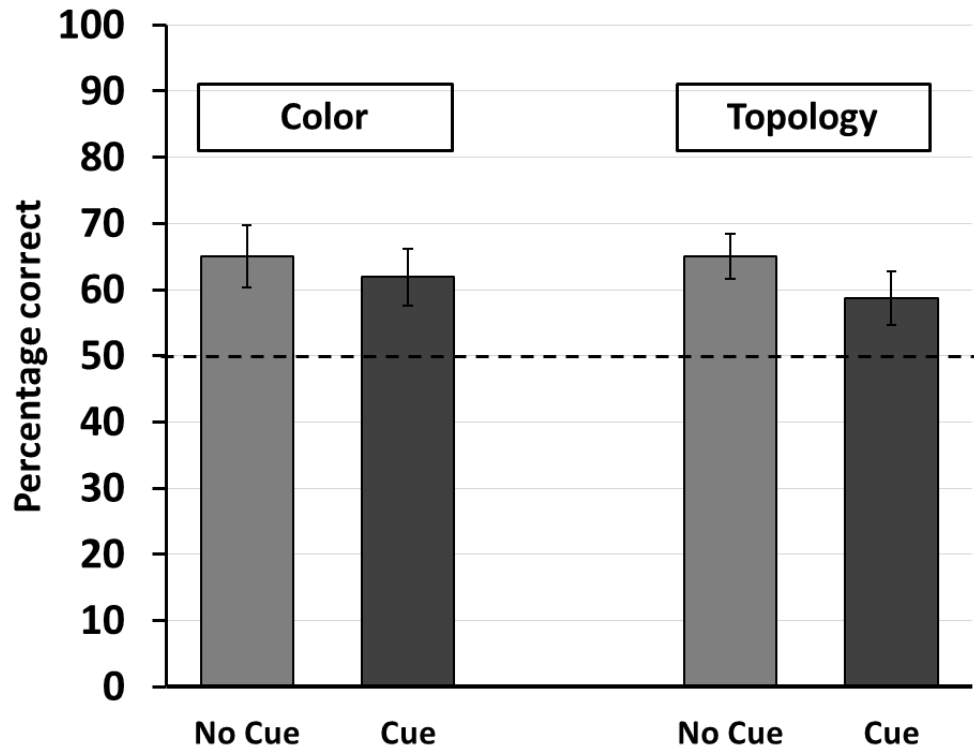


Figure 5. Accuracy for both color and topology conditions in cue and no cue blocks.

Error bars represent standard error.

Next, to examine whether there were differences in children's accuracy as a function of attentional cues or the types of features they were asked to maintain in visual working memory, we conducted a repeated measures ANOVA with condition (color or topology) and block order (no cue block first and cue block second or vice versa) as a between-participants factor, block (cue or no cue) as a within-participants factor, and age

in months as a co-variate. We found that none of the main effects were significant (condition:  $F(1,36) = .028, p = .868, \eta^2 = .003$ ; age in months:  $F(1,36) = 1.24, p = .273, \eta^2 = .033$ ; block order:  $F(1,36) = .16, p = .69, \eta^2 = .004$ ; block:  $F(1,36) = .41, p = .53, \eta^2 = .011$ ) and no interactions were significant (block x age in months:  $F(1,36) = .18, p = .67, \eta^2 = .005$ ; block x block order:  $F(1,36) = .575, p = .453, \eta^2 = .016$ ; block x condition:  $F(1,36) = .45, p = .51, \eta^2 = .012$ ; order x condition:  $F(1,36) = 1.432, p = .24, \eta^2 = .038$ ; block x condition x block order ( $F(1,36) = 2.451, p = .126, \eta^2 = .064$ ). These results suggests that the children's performance was similar between color and topology conditions and between the cue and no cue blocks. See Figure 6.

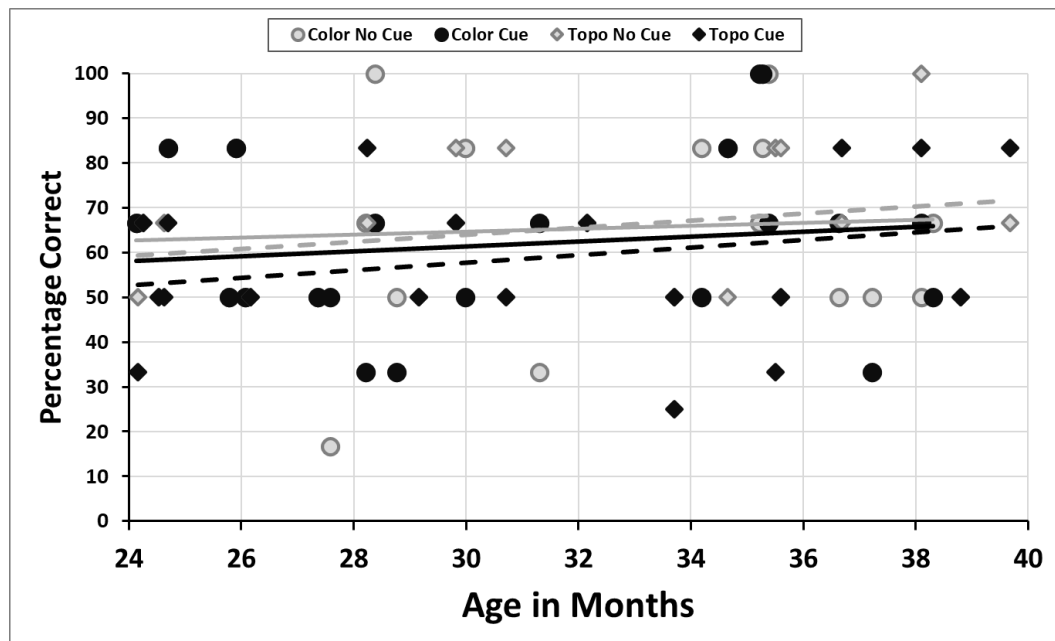


Figure 6. Children's mean percentage correct for both color and topology conditions in each block as a function of age in months.

Finally, we investigated whether individual differences in working memory performance in no cue block influenced how much children benefitted from attention cues in cue block. We split children into two groups based on the median percentage correct in the no cue block. Children were categorized as having higher working memory if their mean percent correct was higher than the median or were categorized as having lower working memory if their accuracy was lower than the value of the median split. We conducted independent sample t-test between the low and high working memory group on children's cue benefit score (we did not include condition and block order in the analysis because we did not find effect of these variables on children's accuracy in the omnibus ANOVA). We found that there were significant differences between the low and high working memory group in children's cue benefit scores ( $t(39) = 2.146, p = .038$ , Cohen's  $d = .680$ , CI [.037-1.316]) with children in the low working memory group (cue benefit mean = 3.43%) benefitting more from the attentional cues compared to the children in high working memory group (mean = -10.41%). Furthermore, we compared the low and high working memory group children cue benefit score to 0 (no cue benefit) using one sample t-tests. We found that children in the low working memory group had cue benefit scores that did not significantly differ from 0 (mean = 3.4%,  $t(16) = .789, p = .442$ , Cohen's  $d = .191$ , 95% CI [.291-.668]), while children in the high working memory group had cue benefit scores that were significantly lower than 0 (mean = -10.41%,  $t(23) = -2.33, p = .029$ , Cohen's  $d = -.476$ , 95% CI [-.894 - -.049]). These results are illustrated in Figure 7. Potential implications of these results are discussed below.

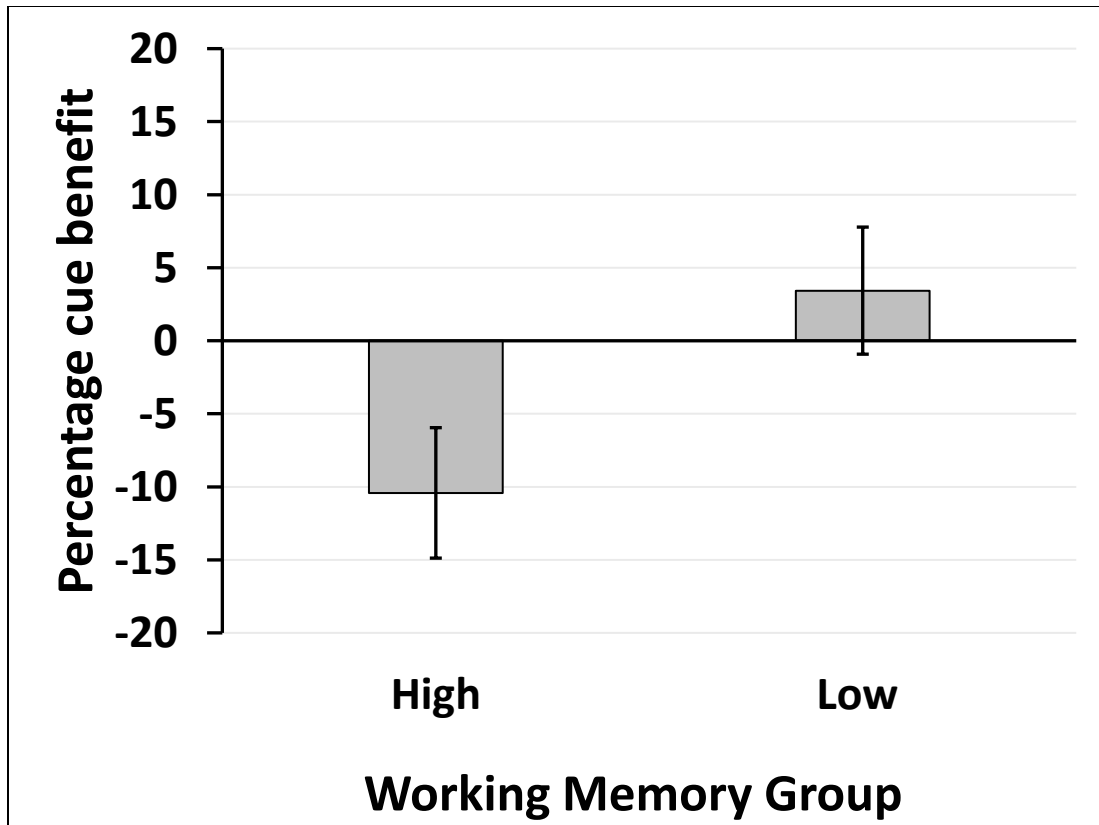


Figure 7. Percentage cue benefit score for children in low and high working memory spank groups. Error bars indicate standard error.

## Discussion

In this study, we investigated the developmental interaction between attention and working memory in early childhood. We had two main aims; one is to test whether 24-40-month-old children's working memory performance depends on the content of representations maintained in it. Second is to test whether attentional cues influence working memory performance in 24-40-month-old children, and if so, whether that influence depends on the contents of representations maintained in working memory. In

our study, we varied types of working memory representations based on the type of perceptual features of objects that were relevant to the task. We were primarily interested in whether children would represent structural object features like topology compared to surface features like color in their working memory. Given that topological properties inform about object identity and can provide stability to the object representations across continuous transformations compared to surface features, we tested whether 24-40-month-old children working memory performance depends on whether they maintain topology or color properties of objects. Furthermore, we tested whether attentional mechanisms differentially influence these representations in working memory in 24-40-month-old children.

First when we compared children's working memory performance against the chance (50%), we found that children in our sample successfully maintained two surface features and topological properties in working memory. Our findings in the color no cue block are in line with the previous studies suggesting that 3-4-year-olds can maintain two color-location bound object representations in working memory (Kibbe & Applin, 2022; Cheng et al., 2020). We are the first to find that 24-40-month-old children remember two objects that vary in topology, suggesting objects that differ on topology are maintained in working memory in the toddler years, and there is a similar developmental pattern for surface features and topology in terms of how many items toddlers can maintain. Our results add a developmental data point between 6-month-olds (who can hold one surface feature and one topological property in working memory; Kibbe & Leslie, 2011, 2016) and adult studies.

In our study, when we compared how children represented surface features and topological properties, we found that children showed a similar level of performance for both types of features. These results also suggest that topological properties are similar to surface features when it comes to the number of object features maintained in working memory, at least under the conditions tested here. Previous research on topological properties in perception has shown that topological properties act as structural properties of the object therefore might demand less attention when they are maintained in working memory (Chen 1982, 2005).

There are two possible reasons why we did not observe differences between the representation color and topology in toddlers' working memory. One is that there is a generic increase in working memory capacity with age from infancy to early childhood and this generic increase in capacity is limited by the number of objects features rather than the type of object features maintained in it. Although it is possible, we think this possible reason is unlikely given that the argument for the working memory capacity limited by number of objects is derived from the comparisons between objects with multiple surface features (ex., red square, blue triangle) conditions with single feature objects (ex., red, square) conditions (Luck & Vogel, 1998; Cowan, 2010; Cowan, 2016). Because we have tested different types of features that inform about different properties of objects rather than comparing the multiple feature objects with single feature objects, we think that it is unlikely that our results are due to generic increase in working memory capacity that is limited by the number of objects maintained in it. A second possible reason for the lack of difference between topology and color conditions in the no cue

block could be due to higher proactive interference in the topology condition. Because the topology of objects varied dichotomously in our study (i.e., hole or no hole), while there were six possible colors, children in the topology condition might have encountered larger proactive interference compared to children in color condition. If this is the case, we may have underestimated children's ability to remember topology. Future work would more systematically investigate children's capacity to maintain topological object properties in working memory while attempting to minimize such proactive interference (e.g., by varying hiding locations of the objects across trials, as in Kibbe & Applin, 2022).

We also found that attention cues did not influence working memory performance in either the color or topology condition, suggesting that 24-40-month-old children *as a group* do not necessarily use object-based attention to filter out irrelevant information or actively select the relevant information to encode into working memory. However, when we divided children into lower and higher working memory groups based on performance in the no cue block, we found that children in the lower working memory group cue benefit score was higher than the children in higher working memory group. Further examination of this effect revealed that the differences between the low and high working memory groups resulted from *worse* performance on cue trials compared to no cue trials from children in the high working memory group (the low working memory group showed no difference between cue and no cue trials). This was not predicted, and we can only speculate about the cause. Although we explicitly mentioned in the task that the feature shown on the cue card tells children what object they have to remember in that

trial, it could be that children with higher working memory might have automatically encoded the cue card as *another object to be remembered* in addition to the two objects in the trial. Previous research in toddlers showed they can reliably remember two color-location bound objects and have an emerging capacity to hold three feature-location-bounded objects in working memory (Kibbe & Applin, 2022). Children in both groups may have encoded the cue card in working memory, but only children with higher working memory capacities were able to maintain that representation along with the two other two objects they needed to remember, while for children in the low working memory group, the initial representation of the cue card may have been overwritten by the two new objects to be remembered. Because children in the high working memory group were remembering three objects and not just two, they may have been more susceptible to binding errors, resulting in slightly lower performance in the cue block. These preliminary results would serve as a basis to test under what circumstances young children may be able to take advantage of attentional cues. For example, a location-based cue (in which children see an arrow point toward the location of the object that will eventually be probed) may be more intuitive for young children to understand. Future work would be needed to explore this possibility.

Our study findings showed that 24-40-month-old children in our sample did not show improvement with age for both color and topology conditions. The lack of developmental differences in the color condition is in contrast with the previous research findings that observed developmental improvement in working memory performance between 28-40-month-old children (Kibbe & Applin, 2022). We think the main reason

why we did not find developmental differences in our study is that we conducted our study online and therefore used the animated objects rather than real-world objects that are used in Kibbe and Applin's (2022) study. Future studies should test how the working memory performance for topological properties increases with age and compare it with working memory for surface features.

Overall, our study shows that 24-40-month-old children can maintain two objects that vary in surface features and topological properties, and attention cues did not differentially influence representations of topological properties and surface features in working memory (indeed, we speculate that children were not sensitive to the attention cues in our study). Our study is the first to our knowledge to directly compare the working memory performance for topological properties in 3-4-year-olds and how attention influences the representation of both surface features and topology. Our study findings provide a bridge in documenting the nature of the development of working memory for surface features and the interaction of attention cues on working memory between infant and middle childhood studies. Furthermore, our study findings on topological class are the first to document that 24-40-month-old children maintain topological items. Future studies should test how working memory for different representational types increases with age and how these representations interact with attentional mechanisms.

**CHAPTER 4**  
**COMPETITION BETWEEN OBJECT TOPOLOGY AND SURFACE FEATURES**  
**IN CHILDREN’S EXTENSION OF NOVEL NOUNS**

**Introduction**

The ability to rapidly categorize objects allows us to efficiently store and retrieve large amounts of information and to make inferences about objects that we have never seen before (Gelman & Meyer, 2011). For example, a toddler learning that “ball” refers to “a round toy that can be thrown, rolled, and caught” can immediately refer to other ball-like objects that they never encountered before as “ball” and can infer those objects’ categories and functions. Object categorization is thus a powerful means for children to efficiently learn about and interact with the world around them.

To categorize objects, children must treat objects of a category as similar in some way, and an object’s shape can be an important cue in forming categories and learning new words. Evidence for this comes from studies that show that children extend labels of objects to other objects that are similar in shape over other surface features like color, texture, or size, a phenomenon known as “shape bias” (Landau, Smith & Jones, 1988, 1992; Smith, Jones & Landau, 1996; Diesendruck & Bloom, 2003). Shape bias is often examined using the name generalization task (Landau et al., 1988, 1992, 1998a; Diesendruck & Bloom, 2003; Booth & Waxman, 2008; see Colunga & Smith, 2008; Markson, Diesendruck & Bloom, 2008; Elman, 2008; and Kucker et al., 2019, for reviews). A single trial of the name generalization task proceeds as follows. An

experimenter presents an object (the standard) and gives the object a novel label (e.g., “Look, this is a *toma!*”). The experimenter then presents three test objects that each share one feature with the standard object (but differ from the standard in their other features): for example, one is the same shape, one is the same texture, and one is the same color as the standard object. The experimenter asks children to point to the object that they think would have the same label as the standard (e.g., “Which one of these is also a *toma?*”). Children are more likely to select the object that shares the same shape as the standard over objects that share other surface features (like color or texture), suggesting that an object’s shape is rapidly associated with a count noun, and the extension of the noun is taken to refer to objects with similar shape (Landau et al., 1988, 1992; Diesendruck & Bloom, 2003).

There have been a number of controversies about the interpretations of the shape bias: Whether this bias results from the perceptual or conceptual salience of shape; whether it is specific to this name extension task; whether it is a consequence of learning object names; and how it is associated with knowledge of object function (e.g., Booth & Waxman, 2002; Booth, Waxman, & Huang, 2005; Diesendruck & Bloom, 2003; Landau, Smith, & Jones, 1998; Soja, Carey, & Spelke, 1991; Smith, 1995, 1999; Zuniga-Montanez et al., 2021; see the general discussion section below for our discussion of these in the context of the current research). Despite these controversies, the idea that shape plays a critical role in object categorization is widely accepted. Object kinds, particularly those at the basic level, tend to have similar shapes (e.g., Rosch, 1978; Rosch et al., 1976), and thus sensitivity to shape may help children make ecologically valid

generalizations of new labels. Related to this, shape can further provide strong inductive potential to the categories of artifacts, which children may use as a proxy for the object's function (Nelson et al., 2000; Ware & Booth, 2010; but see also Landau et al., 1998b). Most importantly, the shape of rigid objects is relatively stable across different contexts while other surface features may vary depending on lighting conditions. If a caregiver holds up and moves a rigid object in different ways during naming, an infant will be able to abstract invariant shape across different views of the same object undergoing different transformations, and this invariant shape could be useful for children learning to name objects, as they could more easily extend the labels they learn to similar objects they encounter (Gogate & Hollich, 2010).

Despite its importance in object categorization, however, shape is a complex concept and what aspect of shape is invariant can depend on the level of description in both perception and geometric theories (i.e., what is invariant in one level of description can be not invariant in a different level). In this study, we questioned what geometric properties (invariances) can influence children's judgments of which objects have the "same shape", which can therefore be referred to with the same label. To answer to this question, we were interested in two different geometrical approaches to shape, Euclidean geometry and topology, in the context of the name generalization task. According to the mathematician Klein's transformational geometry framework, theories of geometry and their associated shape properties can be classified into a hierarchy with increasing levels of abstraction (i.e., Klein hierarchy), in terms of their geometrical transformations (i.e., invariant transformations) under which certain geometric properties remain unaltered

(Klein, 1893). Thus, the notion of shape can be defined by the properties that are stable under different geometrical transformations (see Todd & Petrov, 2022 for a review).

In classical Euclidean geometry, there are four types of invariant transformations, called similarity transformations: translation, rotation, reflection, and uniform dilation (resizing).<sup>1</sup> These transformations alter an object's position, orientation, handedness, and size, respectively, but preserve its angle and length ratios (which are properties associated with people's intuitive notion of shape); thus, differences in objects' location, orientation, handedness, and size are irrelevant, but variability in properties of angle and length ratio are relevant in characterizing objects for Euclidean geometry. In other words, a large square and a small square in different orientations and locations are considered equivalent, i.e., having the same Euclidean (or metric) shape.

If people represent forms according to their Euclidean properties, or people's intuitive sense of geometry corresponds to Euclidean geometry, they would be sensitive to transformations which alter metric shape, but not sensitive to transformations of the properties that are irrelevant to defining objects in Euclidean geometry, such as position, orientation, and size. The notion of Euclidean shape indeed seems consistent with the findings of the shape bias in literature such as Landau et al.'s original study and many others, which showed that children extend object labels despite size changes of the same

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<sup>1</sup> The former three transformations, called Euclidean (or rigid) transformations, preserve both shape (i.e., angle and length ratios) and size, but the latter one, uniform dilation, preserves shape alone (but not size). According to a more conservative view, Euclidean geometry is characterized by rigid transformations alone, and thus, figures are defined by both size and shape. See Izard et al. (2022) for discussion on different characterizations of Euclidean geometry in Psychology.

Euclidean shape, but not to changes in angular properties of the objects (e.g., from a “U”- to a “L”-shaped object) (e.g., Landau et al., 1988; Landau & Leyton, 1998).

In spite of metric shape’s stability under various geometric transformations, there are more abstract shape properties like structural properties describing relations between object parts (Hoffman & Richards, 1984; Hummel & Biederman, 1992; Marr & Nishihara, 1978), which survive changes in viewpoints and can provide stability to perceptual representations in the face of changes in the environment. When making perceptual judgments about forms, these abstract cues tend to take priority over variations in metric shape (Amir et al., 2014; Lazareva et al., 2008; Lowet, Firestone, & Scholl, 2018). In the Klein hierarchy of geometry, the most abstract level is topology. Topology can be conceptualized by its invariant transformations, often called “rubber-sheet” transformations, which include continuous deformation of objects such as twisting, stretching, and bending; however, they do not include tearing an object in two, poking holes in an object, or gluing two objects together. Topological properties -- the number of holes, connectedness, and inside/outside relationship of an object -- remain invariant under rubber-sheet deformations, and these invariants remain unaltered under the transformations of all lower-level geometries (i.e., projective, affine, and Euclidean geometries) as well, but not vice versa, making it the most abstract form of geometry (Todd & Petrov, 2022, for review). Owing to the generality of topological transformations, two objects are topologically equivalent if they contain the same number of holes, even if they have distinct shapes. For example, a cup with a handle and a donut are topologically equivalent because they each contain a single hole, and a solid sphere

and a solid triangle are topologically equivalent because they each contain no holes; but a donut is not equivalent to a sphere because it is not possible to continuously deform a sphere into a donut.

Visual perception research has revealed that objects' topological properties, as stable structural properties, can supersede objects' surface features (including metric shape) in various visual tasks involving object representations in adults, such as the perception of apparent motion (Chen, 1985; Zhuo et al., 2003), numerosity perception (He et al., 2015), visual working memory (Wei et al., 2019), and multiple object tracking (Zhou et al., 2010). For example, adults can discriminate topologically distinct objects significantly faster than objects that differ in metric shape (Chen, 1985). And in a multiple object tracking task, adults' accuracy to track items decreased significantly when they tracked objects that changed in topological properties as they moved (e.g. a target object with one hole changed to have two holes or no holes), but their performance was not hampered when they tracked objects that morphed in shape as they moved (e.g., a target object changed from triangle to square; Zhou et al., 2010). Compared to changes in metric shape, topological changes to objects are highly salient and more readily detected (Todd, Weismantel, & Kallie, 2014). Each of these studies provides evidence that the visual system is able to abstract invariant topological features from objects that have very different metric properties, such as size and shape, and this information is then used by the visual system in various object-related processing, such as forming persistent object representations and computing motion correspondence.

Objects' topological properties also are fundamental to object perception and cognition early in development (Turati et al., 2003; Chien et al., 2012). Chien et al. (2012) showed that infants by around 1 month of age discriminate objects based on topological properties, but not until 3.5 months do infants discriminate different shapes, suggesting that infants process topological properties earlier in development than surface features. Infants' expectations about how objects should interact is constrained by topological properties (for example, infants have different expectations about what can happen to an object that hides inside a tube compared to behind an occluder; Hespos & Baillargeon, 2001a, 2001b; Wang, Baillargeon & Paterson, 2005; Hespos & Baillargeon, 2006; Baillargeon et al., 2012), and, like adults, infants' object tracking is impacted by changes in objects' topologies (Kibbe & Leslie, 2016). By at least 3 years, children also can explicitly identify and count holes in objects (Giralt & Bloom, 2000), suggesting a role for objects' topology in higher-level processing early in childhood.

Given the primacy of topology over surface features like metric shape for object representation, and given that previous work showed that children have a strong bias toward object shape when categorizing objects, here we asked what role topology might play in children's inferences about the extension of novel nouns. Because topological properties are fundamental to the *invariant structure* of an object, these properties could carry different information about objects than shape or other surface features. Like shape, topological properties can be diagnostic of an artifact's category or function (e.g. despite their similar shapes, a needle can be threaded while a pin cannot). Topological properties may also be associated with labels in the real world. For example, despite changes in

shape, the label ‘ball’ can be used to an inflated ball and a deflated ball. Topological properties of objects also impact the way humans interact with objects even when those objects have similar functions. For example, to take a drink we may grip the (topologically open) handle of a mug, but the (topologically closed) outside of a cup. Thus, topological properties of objects may play a different role in inferences about objects’ categories than shape does. And because topological properties play a more primary role in object representation than surface featural properties such as shape, they may compete with or even supersede surface features as the relevant object properties in children’s inferences about the relevant perceptual dimensions to which a novel label refers.

In this study, we examined the role of topological properties in 3-7-year-old children’s extension of novel labels to objects. In three experiments, we used the classic name generalization task that has consistently revealed children’s shape bias (Landau et al., 1988, 1992; Diesendruck & Bloom, 2003). In Experiment 1, we manipulated the topology of the standard object (by manipulating whether or not the object had a hole), gave it a novel label, and then asked children to choose from three test objects which object shared the same label: an object with the same metric shape but different topology than the standard, an object with the same topology but different metric shape than the standard, or a distractor object. Experiment 2 served as a perceptual control for Experiment 1. Finally, in Experiment 3, we pitted topology against another surface feature that is not typically diagnostic of object category in children’s extension of novel count nouns – color.

We considered three potential hypotheses for the role of topology in children's extension of novel labels to objects. One possibility is that, just as topology supersedes surface features like shape and color in object representation and object-based attention, topology supersedes surface features in children's label extension. Under this possibility, we would observe a strong "topology bias" when children are asked to extend novel count nouns to novel objects. Another possibility is that topology does not play a significant role in children's label extension. Despite the primacy of topology in vision and its potential inductive role for objects' categories or affordances, objects' topologies may not always be a reliable cue to objects' categories or functions (as in the example of the cup and the mug), and changes to objects' topologies do not necessarily change an object's category, even if they change the object's structure (for example, a t-shirt with a hole in it can still be worn). Under this possibility, shape should supersede topology, and we should observe the classic "shape bias" when they are pitted against each other. A third possibility is that, because topology and surface features play different roles in object representation and can provide somewhat different information about objects' categories, we may observe *competition* between topology and shape (or color) in children's label extensions. That is, we may observe that children view both topology and surface features as relevant dimensions along which to extend a novel label to other objects, and when faced with a forced choice between topology and surface features, may choose topology on some trials and surface features on other trials. Under this possibility, we should not observe a strong bias toward either topology or surface features in children's extension of novel nouns.

## Experiment 1: Topology versus Metric Shape

### *Methods*

#### *Participants*

Participants were 66 2-7-year-old children (mean age = 5.0 years, range = 2.39 - 7.55). Parents reported their children to be female (34), male (25), or declined to report (7). Four additional children participated but were not included in analyses due to experimenter error (1), inability to speak English (1), or choosing to terminate the experiment early (2). Data were collected in the Museum of Science, Boston. All participants' parents gave written consent for their children to participate in the study. Demographic information was not collected from participants. The Institutional Review Boards of the Boston University Charles River Campus and the Museum of Science, Boston approved all study procedures.

Our sample size was 4-5 times larger than samples obtained in previous studies using a similar method (e.g. Diesendruck & Bloom, 2003,  $n = 16$ ; Landau et al., 1988,  $n = 12$ ). This was because we were not certain how topology would impact children's responses. We reasoned that a larger sample size would allow us to detect subtle effects of topology (e.g. competition between shape and topological class, which would yield similar response rates for these objects).

We also reasoned that the larger sample size would also allow us to potentially detect any effects of age on children's responses. Previous work had revealed somewhat contradictory evidence about the extent to which shape bias develops in early childhood, with some work showing increases in shape bias between the ages of 2 and 3 years (e.g.,

Landau et al., 1988), and other work showing similar shape bias effects across 2- and 3-year-olds (e.g., Diesendruck & Bloom, 2003). Our age range encompassed these younger years, but also older children, because we wanted to examine the potential influence of topology in children in whom the shape bias is relatively well established, and because we were not certain whether and when such an influence would emerge in development.

### *Materials*

On each of the four trials, children viewed a set of four cardboard cutouts (each approximately 5 cm x 6 cm). Each set included a standard object, and three targets: an object of the same shape as the standard but with different topology (hole or no hole), an object with the same topology as the standard but with a different (metric) shape, and a distractor object of a different shape from the standard with “bite” taken out of its contour. The “bite” served to roughly equate the contour complexity of the object with the hole. We created shapes that were not likely to be nameable by children. The holes in the open objects (approximately 1.5 cm x 2 cm) were all differently shaped to prevent children from responding based on shared shape of the holes. We chose to construct flat cardboard cut-outs to remove the depth of the hole as an added dimension of the stimuli, which diverges somewhat from previous studies that used real-world artifacts that were unfamiliar to children. Although the stimuli were flat, children could see that the objects were three-dimensional since the objects were manipulated by human hands, moved through 3D space, and were placed on a surface such that the surface could be viewed surrounding the stimuli and through the holes in the stimuli.

In each of the four trials, children viewed a standard object and three target objects. In two of those four trials, the standard object had a hole, and in the other two trials the standard object did not have a hole. Each child saw one of two possible sets of four trials. Across the two sets, we varied which of the objects contained the hole. Figure 8, left panel, shows one of these two sets of stimuli. Templates that can be used to construct both sets of stimuli can be accessed at

[https://osf.io/k3hzn/?view\\_only=e046ab287e6343ac9549269387748e90](https://osf.io/k3hzn/?view_only=e046ab287e6343ac9549269387748e90)

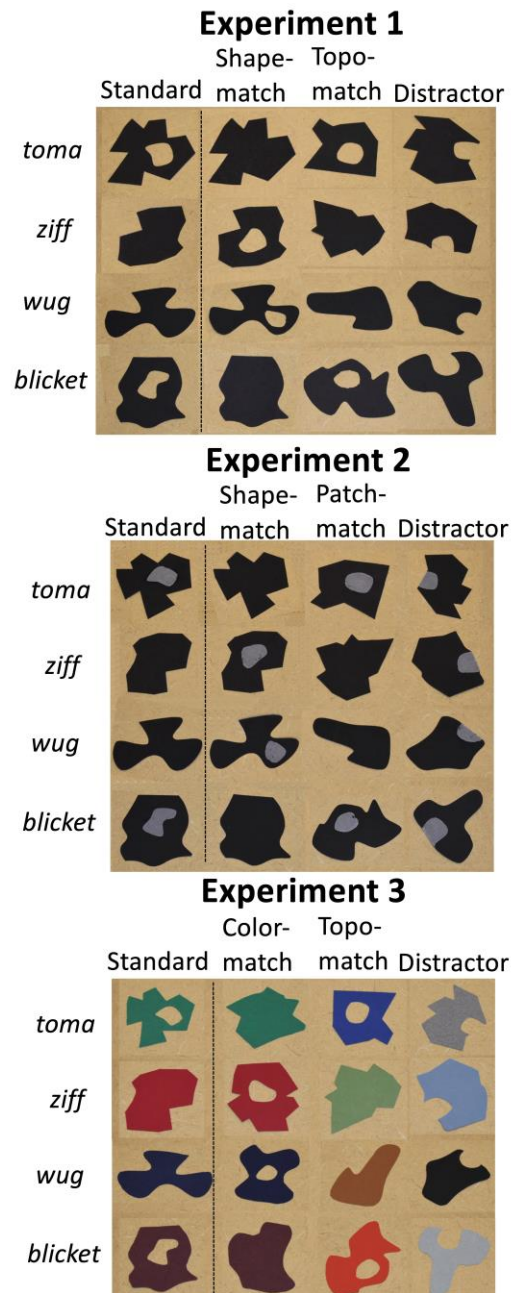


Figure 8. Examples of stimuli from Experiment 1 (top panel), Experiment 2 (middle panel), and Experiment 3 (bottom panel). Each row represents a trial from one of the eight possible orders. Children saw the objects placed with random orientations.

*Procedure*

Children were tested individually in a dedicated research area in the museum. Children sat across a table from the experimenter. The experimenter told children that they were going to play a “name game”. On the first trial, the experimenter showed the standard object from the first set, and gave the object a novel name, e.g. "Look at this. It's a *toma*. See, it's a *toma*. This is a *toma*". He next placed the three target objects on the table below the standard (the order of the objects was randomized across children). The experimenter then prompted children to select one of the three potential target objects, saying, “Ok, see these? Which one is also a *toma*?” After children chose, the experimenter noted their choice in a notebook, cleared the table, and then proceeded with the next three trials in the same way.

Children always chose between a shape-matched object (different in topology from the target), a topology-matched object (different in shape from the target), and a distractor object with a conspicuous divot in its outer contour. Including a distractor object on each trial allowed us to distinguish guessing from competition between the shape- and topology-matched objects. If children select the test objects at random, they should choose the distractor object in about a third of the trials. If children show competition between topology and shape, they should choose roughly equally between the shape- and topology-matched objects, and choose the distractor object only rarely.

The standard object on each of the four trials was given a unique label (*toma*, *ziff*, *wug*, or *blicket*). Whether a given label was associated with a standard object with a hole or without a hole was counterbalanced across children. All the objects were placed with

random rotations (that is, there was no canonical “upright” position for any of the objects). If children attempted to touch the objects, we discouraged them from doing so (very few children attempted to touch the objects). The order of the trials was counterbalanced across participants.

### *Results*

Data for Experiments 1-3 are available at

[https://osf.io/k3hzn/?view\\_only=e046ab287e6343ac9549269387748e90](https://osf.io/k3hzn/?view_only=e046ab287e6343ac9549269387748e90)

We first asked whether children’s responses were different than what would be expected if children were simply choosing randomly among the three objects in each trial. Children chose the shape matched object on 126/264 trials (46.3%), the topology match on 102/264 trials (37.5%), and the distractor object on 36/264 trials (13.3%). The distribution of children’s responses was different than would be expected if children were choosing randomly (chance = 33.33%,  $\text{Chi}^2(2) = 49.41, p < .0001$ ). The majority of children’s choices consisted of the shape- or topology-matched object, with children choosing the distractor only infrequently.

To examine whether shape and topology competed with each other in children’s responses, we computed a “Bias Score” for each child, taken as the difference between the proportion of trials on which they chose the shape match minus the proportion of trials on which they chose the topology match. For example, if a child chose the shape-matched object on 1 trial and the topology-matched object on 3 trials, they would receive a Bias Score of  $(.25 - .75 = -.5)$ . If a child chose the shape-matched object on 2 trials and the topology-matched object on two trials, they would receive a Bias Score of  $(.5 - .5 =$

0). A positive score thus indicates a tendency to choose shape, a negative score indicates a tendency to choose topology, and a score close to 0 indicates no bias (maximum score = 1, minimum score = -1). Computing Bias Scores for each child allowed us to test the directional hypothesis that children prefer either shape (scores significantly above 0) or topology (scores significantly below 0), or show no strong preference (scores not significantly different from 0). To do so, we compared these Bias Scores to 0 using a one-sample t-test and Bayes factor analysis. We found that children's Bias Scores were not significantly different from 0 ( $M = .09$ ;  $t(65) = 1.20$ ,  $p = .235$ , 95% CI [-.06 .24]), with Bayes factor analysis offering support for the null hypothesis ( $BF_{01} = 5.13$ ). Children's Bias Scores were not correlated with their age in years (continuous) ( $r(65) = .167$ ,  $p = .180$ ). Figure 9 shows children's mean Bias Scores. Figure 10 shows individual children's Bias Scores as a function of age in years (continuous).

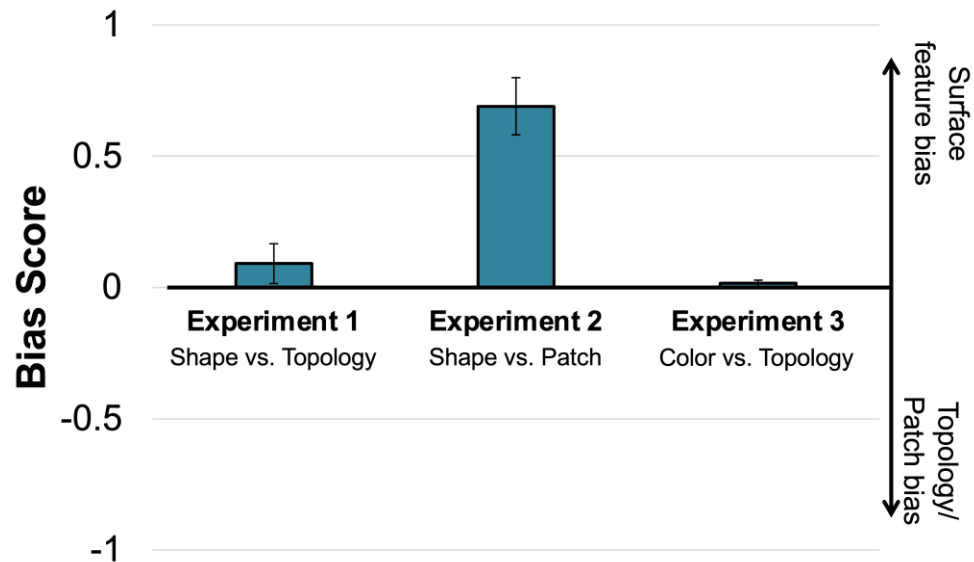


Figure 9: Mean Bias Scores for Experiments 1, 2, and 3. Error bars indicate  $\pm 1$  standard error of the mean.

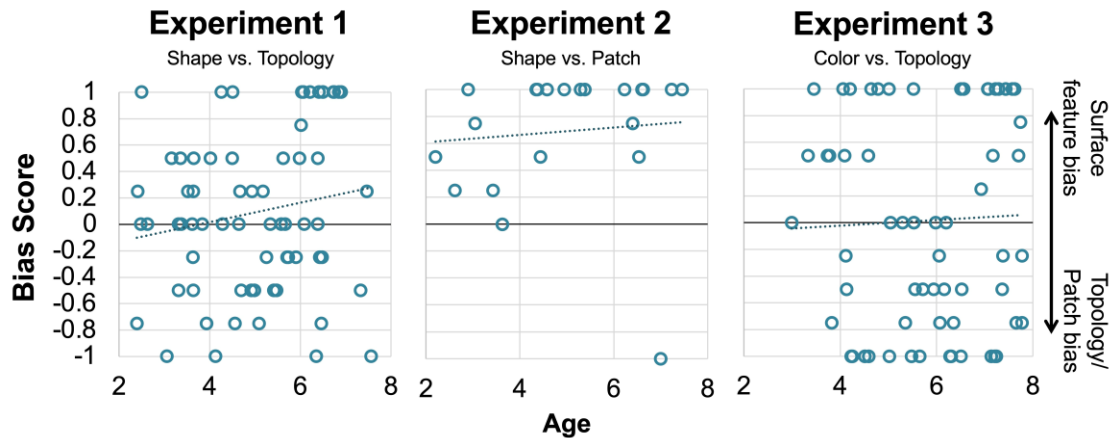


Figure 10. Individual children's mean Bias Scores as a function of age for Experiments 1, 2, and 3.

Inspection of Figure 10 provides some insights into how individual children respond across trials. Recall that a score of 1 means that a child consistently selected shape across the 4 trials, while a score of -1 means that a child consistently selected topology across the 4 trials. We found that around a quarter of the children (17/66, 26%) were “consistent choosers”. The remaining 74% of children chose topology on some trials and shape on some trials. These results suggest that, within individual children, topology competed with shape in children's extension of novel nouns.

We next asked whether children's responses differed when the standard had a hole versus when the standard had no hole. We separately computed Bias Scores across the two trials in which the standard had a hole and the two trials in which the standard did not have a hole and compared these using a paired samples t-test and Bayes factor analysis. Children's patterns of responses did not differ significantly between the two

trial types ( $t(65) = -1.82, p = .073, 95\% \text{ CI } [-.38 .02]$ ), although Bayes factor analysis offered only anecdotal support for the null hypothesis ( $\text{BF}_{01} = 2.10$ ). When the standard had a hole, children's Bias Scores were not significantly different from 0 ( $M = 0; t(65) = 0, p = 1, 95\% \text{ CI } [-.19 .19]$ ) with Bayes factor offering strong support for the null ( $\text{BF}_{01} = 10.33$ ). When the standard did not have a hole, children's Bias Scores were significantly different from 0 ( $M = .18, t(65) = 2.11, p = .039, 95\% \text{ CI } [.01 .35]$ ), although Bayes factor offered only anecdotal support for the alternative ( $\text{BF}_{01} = .81$ ).

### *Discussion*

Previous work pitting shape against other surface features like color and texture found that children had a strong bias to extend novel nouns to objects that share shape over objects that share other surface features. In Experiment 1, when we pitted shape against a structural object property – topological class – we observed competition between shape and topology when children are tasked with extending novel labels to novel objects. These results suggest that topology and shape both may contribute to children's generalization of object labels.

However, before accepting this conclusion, it is important to rule out a potential alternative explanation for children's selections that do not exclusively rely on topology. Despite the fact that the objects visibly moved through 3D space and the texture of the table was clearly visible around the objects as well as through the objects' holes, children may not have viewed the holes as holes, but instead as “patches” on the objects' surfaces – essentially a figure on top of a background shape. If so, children may have matched objects based on whether or not they had this surface feature when deciding which of the

objects was in the extension of the novel label. We tested this hypothesis in Experiment 2.

### **Experiment 2: Perceptual Control**

To examine the alternative possibility that the holes in the objects in Experiment 1 were perceived as a material surface in front of a surrounding object, in Experiment 2 we replaced the holes in the stimuli from Experiment 1 with grey patches. If children's responses in Experiment 1 were driven by perceiving the holes as figures on top of a background shape, we expected to observe similar results as in Experiment 1. However, if children in Experiment 1 were attending to topology (hole vs. no hole) as a structural property of an object, we should observe the classic shape bias effect in Experiment 2 in which the topological differences of Experiment 1 were turned into featural differences (patch vs. no patch).

#### *Methods*

##### *Participants*

Participants were 21 2-7-year-old children (mean age = 5.01 years, range = 2.21 – 7.46). Parents reported their children to be female (15), male (5), or declined to report (1). One additional child participated but was not included in the analyses because their parent did not provide their exact date of birth and we were therefore unable to determine their exact age. All participants' parents gave written consent for their children to participate in the study. Children were tested in the Museum of Science, Boston, as in Experiment 1.

We anticipated collecting data from 24 children, but before we reached our planned sample size, we were forced to terminate data collection at the museum due to the ongoing COVID-19 pandemic. Our planned sample size was informed by previous work with young children demonstrating a shape bias using a similar procedure. For example, Diesendruck and Bloom (2003) included  $n = 16$  children in a similar procedure and observed very large effects comparing children's selection of the shape-matched object to chance using a one-sample t-test ( $d > 1.5$ ). A power analysis using the more conservative estimate of the size of the effect  $d = 1$  suggested a total sample size of  $n = 10$  ( $\alpha = .05$ ,  $1 - \beta = .9$ ). Diesendruck and Bloom (2003) also compared children's responses in a condition in which the standard was labeled with a novel noun (as in the present study) with children's responses in another condition in which their choices were expected to be evenly distributed across the three objects. They again observed a large effect size for this between-subjects comparison. A power analysis for an independent samples t-test with effect size  $d = 1$ ,  $\alpha = .05$ , and  $1 - \beta = .8$  suggested a sample size of  $n = 17$  per group. Given the novelty of our stimuli, we had opted for a target sample size of  $n = 24$ . However, our final sample of  $n = 21$  is sufficiently powered to detect effects of interest.

### *Materials & Procedure*

Materials were identical to Experiment 1, except that the holes (and bites of distractor objects) were replaced (or filled) by gray patches in the same position and of the same shape as the holes/bites in Experiment 1 (see Figure 8, middle panel). Templates

of the stimuli are available at

[https://osf.io/k3hzn/?view\\_only=e046ab287e6343ac9549269387748e90](https://osf.io/k3hzn/?view_only=e046ab287e6343ac9549269387748e90)

The procedure was otherwise identical to Experiment 1.

### *Results*

The distribution of children's responses was different than would be expected by chance (chance = 33.33%,  $\text{Chi}^2(2) = 86.08$ ,  $p < .0001$ ) and reflected the shape bias observed in previous studies (e.g., Diesendruck & Bloom, 2004; Landau et al., 1988, 1992). Children chose the shape-matched object on the majority of trials (68/84 trials, 70.8%). Of the remaining trials, children chose the patch-matched object on 10/84 trials (10.4%) and the distractor object on 6/84 trials (6.3%).

As in Experiment 1, we computed Bias Scores for each child by subtracting the mean number of trials on which they chose the patch-matched object from the mean number of trials on which they chose the shape-matched object. We found that children's Bias Scores were significantly greater than 0 ( $M = .69$ ;  $t(20) = 6.34$ ,  $p < .001$ , 95% CI [.46 .92]), with Bayes factor offering decisive support in favor of the alternative hypothesis that children's Bias Scores are reliably different from 0 ( $\text{BF}_{10} = 6493.5$ ) (see Figure 9). Children's Bias Scores were not correlated with their age in years (continuous) ( $r(20) = .09$ ,  $p = .699$ ; see Figure 10). A little over half of the children were consistent choosers (13/23, 57%), with 12 of those 13 children choosing shape on all four trials, and the majority of the remaining children biased toward shape (see Figure 10 for distribution of children's bias scores). There was no significant difference in children's Bias Scores on trials in which the standard had a patch versus when the standard had no patch ( $t(20) =$

-1.00,  $p = .329$ , 95% CI [-.44 .16]), with Bayes factor offering modest support for the null hypothesis ( $BF_{01} = 3.74$ ). Bias Scores were significantly different from 0 both when the standard had a patch ( $M = .62$ ;  $t(20) = 4.24$ ,  $p < .001$ , 95% CI [.31 .92],  $BF_{10} = 80.02$ ) and when the standard did not have a patch ( $M = .76$ ;  $t(20) = 6.78$ ,  $p < .001$ , 95% CI [.53 .99],  $BF_{10} = 15,625$ ).

#### *Experiments 1 and 2 compared*

Children's Bias Scores in Experiment 2 were significantly higher than in Experiment 1 ( $t(85) = 4.05$ ,  $p < .001$ , 95% CI [.31 .89]), with Bayes factor analysis offering decisive support for the alternative hypothesis ( $BF_{10} = 199.12$ ). Children's Bias Scores were not correlated with their age in days, controlling for Experiment ( $r(89) = .09$ ,  $p = .414$ ).

#### *Discussion*

In Experiment 2, when the interior region enclosed by the object changed from an empty hole into a material surface attached on it, children showed the classic shape bias - children extended novel labels to objects that shared the same shape as the standard object. These results suggest that results of Experiment 1 were not due to children perceiving the objects' holes as figures on top of a background object, but instead suggest competition between objects' structural properties (hole or no hole) and surface featural properties (shape) in children's extension of novel nouns.

Most previous research on topological perception reviewed above has (implicitly) treated a hole as a 2D image region—a uniformly connected region surrounded by another region of a 2D image (e.g., 2D concentric discs forming a doughnut), and thus

did not consider whether the interior region enclosed by the surrounding object was indeed seen as a background surface (a hole). A comparison between Experiments 1 and 2, however, suggests that the perception of topological properties is not based on image-level representations, but mediated by surface-level representations (i.e., surface depth order), much as motion perception, texture segregation, and object recognition are based on surface-level representations (Nakayama et al., 1995).

Experiment 2 also addressed an additional potential alternative explanation for the results of Experiment 1. In Experiment 1, because we placed the objects with random rotations, children could have been less likely to match the objects based on shape, since doing so required a bit of mental rotation (in order to match the rotated target shape to the standard). However, in Experiment 2 in which objects also were placed with random rotations, children generalized a novel name to orientation changes of the same Euclidean shape (i.e., a standard shape bias), suggesting that the rotations of the objects did not drive the diminished shape bias we observed in Experiment 1. Further, in line with the notion of Euclidean shape, this suggests that orientation is not a relevant property characterizing objects in the name generalization task.

### **Experiment 3: Topology versus Color**

In Experiment 3, we asked whether topology competes with other surface features more generally, or whether the effect is limited to metric shape, by pitting objects' topologies against objects' colors. Children viewed a standard object, and then were shown three target objects: one with the same color as the standard but different

topology, one with the same topology as the standard but different color, and a distractor object. We considered two possible outcomes for this experiment. On the one hand, both topology and shape can provide cues to the categories or functions of artifacts, and therefore the competition observed in Experiment 1 may be specific to the case in which these two object properties are pitted against each other. On the other hand, children may focus *either* on structural properties or surface features when extending labels to novel objects, in which case we may observe competition between color and topology, similar to the competition between shape and topology observed in Experiment 1.

### *Methods*

#### *Participants*

Participants were 64 3-7-year-olds (mean age = 5.83 years; range = 2.99 – 7.77). Parents reported their children to be female (27), male (26), or declined to report their child's sex (11). Sample size for this experiment was chosen using the same criteria as in Experiment 1. Three additional children participated in the study but were excluded from the analysis due to unwillingness to finish the experiment (1), developmental disability (1), or inability to speak English and therefore to understand the task instructions (1). Children were tested at the Museum of Science, Boston, as in Experiments 1 and 2.

#### *Materials and Procedure*

The materials and procedure were similar to Experiments 1 and 2, with the following exception. Each trial included one standard object and three target objects: an object with same color but different topology than the standard, an object with same topology but different color than the standard, and a distractor object with bite taken out

of its contour, different in color from all the other objects in that trial (See Figure 8). As in Experiment 1, the shape of each hole varied across all of the objects to prevent children from responding based on hole shape.

As in Experiment 1, we created two sets of trials, varying which objects had the hole across the two sets. In each of the sets, there were two trials in which the standard object had a hole and two trials in which the standard object did not have a hole (see Figure 8 for an example of one of these sets). The order of the trials was counterbalanced between the participants. Stimuli were constructed from different colored cardboard using the templates for Experiment 1 (available at [https://osf.io/k3hzn/?view\\_only=e046ab287e6343ac9549269387748e90](https://osf.io/k3hzn/?view_only=e046ab287e6343ac9549269387748e90)). The colors used are shown in Figure 8.

### *Results*

Children's responses were different than would be expected if they were choosing randomly between the three target objects (chance = 33.33%,  $\text{Chi}^2(2) = 65.299$ ,  $p < .0001$ ): children selected the topology-matched object in 113/254 trials (44.48%), the color-matched object in 117/254 trials (46.06%), and the distractor object in 24/254 trials (9.44%).

As in Experiments 1 and 2, we computed a Bias Score for each child by subtracting the proportion of trials in which children selected the topology match from the proportion of trials in which children selected the color match. A positive bias score here indicates a tendency towards color, a negative bias score indicates a tendency towards topology, and a bias score closer to 0 indicates competition. Bias Scores were not

significantly different from 0 ( $M = .02$ ,  $t(63) = .16$ ,  $p = .874$ , 95% CI [-.18 .21]) and Bayes factor analysis resulted in strong support for the null hypothesis over alternative hypothesis ( $BF_{01} = 1.499 \times 10^{-12}$ ), see Figure 9. Children's Bias Scores were not correlated with age in years (continuous) ( $r(64) = .037$ ,  $p = .773$ ; see Figure 10). Around half of the children consistently chose either color or topology across the four trials (31/64, 48%), with the remaining children choosing color on some trials and topology on other trials suggesting competition between color and topology (see Figure 10 for bias score distributions).

There was a small but significant difference in children's responses on trials in which the standard had a hole compared to trials in which the standard had no hole ( $t(63)$ ,  $p = .047$ , 95% CI [-.501, -.003]) although Bayes factor analysis yielded only anecdotal support for the alternative hypothesis ( $BF_{10} = 1.441$ ). Bias Scores across trials in which the standard object had a hole were not significantly different from 0 ( $M = -.07$ ,  $t(63) = -.629$ ,  $p = .532$ , 95% CI [-.293, .153]) and Bayes factor analysis showed moderate support for null hypothesis ( $BF_{01} = 8.381$ ). For trials in which the standard object did not have a hole, Bias Scores also were not significantly different from 0 ( $M = .101$ ,  $t(63) = .994$ ,  $p = .324$ , 95% CI [-.102, .305]) and Bayes factor analysis again showed moderate support for null hypothesis ( $BF_{01} = 6.276$ ).

#### *Experiments 1 and 3 compared*

We compared the distribution of children's Bias Scores in Experiments 1 and 3 using a Kolmogorov-Smirnov Test. We found children's response distributions did not

vary between Experiments 1 and 3 ( $p = .372$ ) suggesting that shape and color compete with topology in a similar manner.

Children in Experiment 3 were slightly older on average than in Experiment 1. To examine whether children's ages impacted their responses across the two experiments, we ran an ANOVA on children's Bias Scores with Experiment (1 and 3) as a between-participants factor and Age (in years, continuous) as a covariate. This revealed no significant effects of Experiment ( $F(1,127) = .80, p = .374$ ) or Age ( $F(1,127) = 1.16, p = .284$ ).

### **General Discussion**

Past work has shown that objects' surface features – particularly metric shape -- play an important role in children's extension of labels to novel artifacts (Landau et al., 1988, 1992, Diesendruck & Bloom, 2003, Dewar & Xu, 2007, 2009, Graham & Diesendruck, 2010). In a series of three experiments, we asked whether objects' *structural properties* - specifically topology – also play a role in children's extension of labels to novel objects. Topological properties of objects are processed earlier in perception than surface features like shape (Chen, 1985, 2005), have inductive potential for object categories, and can be associated with count nouns in real world (Giralt & Bloom, 2000). Our goal was to examine whether and to what extent topological properties drive 3-8-year-old children's extension of count nouns to novel objects.

In Experiment 1, when topological class was pitted against shape in a name generalization task, 3-8-year-old children's extension of novel labels to novel objects suggested competition between shape and topology: children chose the shape- and

topology-matched target objects at similar rates when asked which target object had the same label as a standard object. These results were not due to children choosing randomly – children very rarely chose the distractor object, instead selecting between the shape- or topology-matched objects. The results also were not driven by children using the shape of the hole to generalize the label, since the shape of the holes in the test and standard objects varied across all objects. We did not find any statistical differences in children’s responses when the standard object had a hole compared to when the standard object did not have a hole, suggesting that children in our sample were extending labels based on objects’ topology (with or without a hole) and not simply treating the hole as a salient feature. In Experiment 2, we further confirmed that children’s responses in Experiment 1 were driven by objects’ topologies by replacing the objects’ holes with gray patches, reversing the figural status of an interior region enclosed by the surrounding object, from an empty hole (background) to a material surface (foreground). We observed the classic shape bias effect in Experiment 2, and children’s responses in Experiment 2 were significantly different from those in Experiment 1, suggesting that in Experiment 1 topology indeed competed with shape when extending labels to novel objects. This between-experiments contrast also suggests that unlike a patch on an object, which is not an intrinsic property of the object (and thus potentially detachable), a hole is an intrinsic and ontologically parasitic property of its host object (Casati & Varzi, 1994; Kim, 2020), which is stable over changes in viewpoints, and thus counted for name extension. Finally, in Experiment 3, we pit another surface feature, color, against topology in the name generalization task, and found competition between color and topology in children’s

extension of novel nouns to novel objects. Together with the results of Experiments 1 and 2, these results suggest that objects' structural properties complete with objects' surface featural properties in children's extension of labels to novel objects.

Previous work has shown the primacy of topology for object perception and attention, leading to the suggestion that topological invariance is a core of object representation (e.g., Chen, 2005; Zhou et al., 2010). Nevertheless, we did not observe that topology also superseded surface features in children's label extensions. One possibility is that the competition we observed between objects' topologies and surface features in our name generalization task is driven by subtle differences in the inductive potential of these properties. Topological class and surface featural properties both have inductive potential for making inferences about objects' functions, but each may provide different types of information about object category. Consider two objects with similar topologies: a coffee mug and a handbag. These two objects vary substantially in their surface features and in their basic functions (one is for holding a beverage which is then consumed, one is for carrying your personal items), but their similar topologies dictate how the objects can be interacted with by humans (e.g. both are grasped by the handle). Now consider two objects with different topologies: a needle and a pin. These two objects are very similar in shape, but their different topologies dictate how the objects can be interacted with by humans (a needle can be threaded and used for sewing, a pin cannot be threaded and is used for fastening). Both topological and shape properties of objects map onto objects' affordances, but do not necessarily map consistently onto objects' functions. That is, while the different functions of a pin and needle solely depends on the difference in the

*topology* (and not shape) of these objects, the different functions of a mug and a handbag depend on *surface featural and material properties*, such as size and texture, and not topology. In everyday situations, we likely use *both* topology and surface features to make these different types of inferences about object categories. In our experiments, we set up a situation where children needed to use one or the other, but could not use both, and we therefore speculate that this therefore drove the competition we observed in our experiments – at least in the context of a name generalization task.

We admit that this line of argument is speculative and requires further investigation. However, it not only provides a plausible explanation of our results, but also does not conflict with extant accounts of the shape bias in the literature. The attention learning account proposes that children extract statistical associations between the linguistic input (e.g., ‘This’), labels (e.g., ‘toma’), and perceptual categories (e.g., solid, nonsolid) that exist in the real world and use these associations to guide their attention to historically relevant perceptual features for the object or artifact in question to inform about the object category (Landau et al., 1998a, Colunga & Smith, 2008). According to this account, children associate metric shape with artifacts because objects that belong to same category often share shape in the real world, and therefore shape can act as a default bootstrapping mechanism for children to generalize count nouns in the absence of a prior category knowledge (Landau et al., 1998a, Colunga & Smith, 2008). Like shape, count nouns also may be associated with structural features like topology in the real world and may therefore drive attention to topological properties. For example, the label “straw” is associated with elongated objects with holes through their center that

can vary in color, size, and texture. Children may therefore use these past associations between labels and topology to generalize in a novel situation in which topology is a potentially relevant feature.

Another account (e.g. Diesendruck and Bloom, 2003, Markson, Diesendruck & Bloom, 2008) proposes that shape acts as a cue to kind membership; children generalize count nouns to objects that share the same shape because they understand that count nouns are used to refer to object kinds, and shape provides reliable information about objects' kinds. Similarly, children also may have an expectation that topology can provide reliable information about object kinds, even when overall shape does not. For example, a straw can be used to drink from, while a chopstick cannot; a needle can be threaded, while a pin cannot; a colander can be used to drain pasta, while a bowl cannot; a tank-top can be worn comfortably, while a pillowcase cannot. Children may recognize the inductive potential of topology as they do shape, and may also expect count nouns to refer to topological properties of objects, at least under some circumstances.

Indeed, there also are plenty of cases in which objects' topologies do not impact their function. It is possible that unless topological differences result in obvious functional differences, holes may not necessarily play a critical role in categorization. For example, both ring doughnuts and filled doughnuts are called doughnuts in spite of their topological differences. And accidentally generated holes (which are not originally the feature of the objects) usually do not influence the identity or function of objects. For example, worms can create little holes in leaves and friction can cause pinholes in T-shirts, but the introduction of these holes does not change the objects' categorical

identities. In our task, we did not provide children with explanations for the causal origin of the holes (or lack thereof) in the objects, which may have reduced the inferential potential of topology in our task. We also used flat objects whose “artifactness” might not have been as readily apparent to children (that is, children may not have readily inferred that the objects could be used for some purpose). This was by design, since we wanted to carefully control the perceptual dimensions of the stimuli. However, the structure of the stimuli may also have reduced the inductive potential of topology in the task. Future work would investigate whether providing information on specific functions of holes and/or the causal origins of holes would impact the inferential role of object topologies versus surface features in children’s object categorization.

Previous work using the name generalization task to understand children’s extension of labels to novel objects focused on very young children, with some studies finding that shape bias increases between 2 and 3 years of age (e.g. Landau et al., 1988) and other studies showing no change in shape bias in this age range (Diesendruck & Bloom, 2003). Our experiments, by contrast, included participants from a wider age range (3-8-year-olds) in order to investigate whether children’s use of objects’ structural properties versus surface featural properties for noun generalization changed over development. We investigated a wide age range because our goal was not to find the emergence of a bias, but instead to test whether topology competes with shape in children for whom the shape bias is relatively well established, and whether the extent of this competition may change over the course of development. We did not find significant developmental change in children’s bias towards topology or surface features across our

sample. These results suggest that, even with extensive experience with language and object categorization, topology may play a fairly consistent role in children's generalization of novel nouns across the lifespan. It is possible that a finer-grained examination into the younger end of our age range, or in children older than 8, could reveal subtle developmental affects that were not revealed in our study. Future work could examine this possibility.

Our results provide some potential insights into the role of topology in object representation. Previous work showed that topological class is processed earlier in vision (e.g. Chen, 1985), earlier in development (e.g. Chen, 2003; Chien et al., 2012; but see also Tang et al., 2021), and plays a significant role in the way objects are represented, tracked, and attended to across the lifespan (e.g. Baillargeon et al., 2012; He et al., 2015; Hespos & Baillargeon, 2001a, 2001b; Hespos & Baillargeon, 2006; Kibbe & Leslie, 2016; Rips, 2020; Wang, Baillargeon & Paterson, 2005; Wei et al., 2019; Wolfe & Horowitz, 2017; Zhou et al., 2003; Zhou et al., 2010). Our results suggest that objects' topological properties may also play a role in the formation of object categories, but topology does not necessarily take precedence over surface features in the extension of labels. More work is needed to investigate the generalizability of this finding to contexts outside of label extension in which children are asked to make inferences about objects' categories or kinds. It is possible that the phenomenon we observed is limited to label extension in general, or to the label extension task more specifically. For example, by asking children to choose among alternatives with narrowly-defined parameters, we artificially narrowed the hypothesis space of the possible extensions of the novel nouns

(see Fodor, 1970, for broader discussion). In other, more real-world scenarios, topological properties of objects may play a different role in children's inferences about object kinds. Or, our results could reflect a more general predisposition to attend to topology as a category- or kind-relevant feature. Future work would examine these possibilities.

In this study we only tested one aspect of topology (holes). However, there are a range of other topological properties of objects, including inside/outside relationships and connectedness between objects, which may play different roles in children's label extension. It is possible that holes may provide stronger cues to object category membership than other topological properties, perhaps because holes may be predictive of objects' functions. Also, our manipulation of topology (presence versus absence of a hole) may have elicited a more dichotomous representation than surface featural properties of objects like shape or color, making matching on topology easier than matching on shape or color. Future research should study the role of different topological properties in children's extension of novel objects, including examining the inductive potential of these features for object categorization, under what circumstances children may (or may not) use these features in their extension of new nouns, to what extent topological features compete with each other during label extension, and the factors that may influence competition between topology and surface features (including the relative salience of these different object dimensions).

## CHAPTER 5

### GENERAL DISCUSSION

The studies in this dissertation were designed to address three main questions regarding the role of topological properties in cognitive development. Previous research showed that global topological properties take precedence over surface features in visual processing, ontogeny, and phylogeny (Chen, 1982; Chen et al., 2003; Chien et al., 2012). However, most of the research on how topology influences a myriad of processes like visual working memory, apparent motion, and visual discrimination is conducted in adults (Chen, 1982; Chen, 1985; Wei et al., 2019; Wei et al., 2021), and some of the studies that tested the role of topological properties in development are conducted in newborns and infants in the first year of life (Turati et al., 2003; Chien et al., 2012; Kibbe & Leslie, 2016), leaving a significant gap in our understanding of how these global properties of objects are processed, represented, and contribute to the cognitive process in children. The studies in this dissertation were designed to systematically address three main questions regarding the role of topological properties at three different levels of information processing (perception, working memory, and categorization) in children.

First, we studied whether children show a direct perception of the shapes of holes in objects and found that they assign the inner contour to the hole automatically, therefore showing the ability to perceive the shape of holes directly. Second, we tested whether the limits on toddlers' ability to concurrently represent objects with distinct properties depends on whether those properties are global topological properties or local surface features. We found that toddlers represent these objects similarly, and that attention cues

did not differentially impact the content of the object features they maintained in working memory. Finally, we investigated whether children use topological properties on par with surface features when they infer object categories in a name generalization task. We found that children use topological properties to infer object categories, similar to the way they use surface features like metric shape and color. Overall, these studies are the first to systematically study the role of topological properties in perceptual and cognitive development in children. In the general discussion, I will discuss the broader implications of these studies' findings in the context of perceptual and cognitive development and provide directions for future studies.

#### *Broader implications and future directions*

One of the fundamental visual perceptual processes used to navigate the world is the ability to segregate objects in the visual scene into figure and ground. To detect the figure and ground of any visual scene, our visual system should recognize the edges of the objects (i.e., where one object ends and another object start), integrate the local convexities and concavities of the contour (edge), and assign the integrated contour to the object (border ownership or edge ownership) to perceive that object as a figure and the remaining scene surrounding the object is perceived as background. In the figure-ground segregation of the visual scene, the objects that own the border are considered as figures and therefore have a shape, whereas the surrounding of the figure is considered as surround and because of the lack of border ownership these surrounding figure is perceived as shapeless. Although research in infants showed that 4-month-old infants can identify and segregate objects from the background by grouping contours, there has been

little to no research regarding whether infants or children show similar phenomena for the negative mass. In Chapter 2, our two experiment findings show that children can detect, integrate, and assign contours to the negative space (i.e., the hole). Reporting the shape of holes in objects is a psychological reality for adults, and as Kim (2020) showed - adults do perceive the shape of the hole through direct perception meaning that they can assign the edge borders to the hole objects to the hole and process the shape of the hole in objects automatically. Our results suggest that children also directly perceive the shape of holes.

Children's ability directly perceives hole shape has some broader implications on children's spatial cognition, physical reasoning, and predictions about the interaction between objects. For example, take a child trying to build Legos. First, they have to identify the shape of the aperture of the Legos even when they are not explicitly directed toward attending to the holes, and they have to recognize the shape of the protrusion of another and put them together. Research in the development of spatial cognition showed that 15-30-month-old infants have difficulty in fitting different material object shapes (e.g., solid square, circle, cylinder) into different-shaped holes, and this ability to fit different Euclidean geometric objects into similar-shaped holes develops with age (Shutts et al., 2009). Success in object fitting tasks depends on children's perception of hole shapes and material shapes and understanding the spatial relations between two types of shapes (negative – holes, positive – material objects). Much of this work has suggested that children's difficulty may come from challenges with spatial reasoning. Our results suggest one potential important source of limitation that also needs to be considered: the

development of the ability to perceive the shape of holes. Children in Chapter 2 showed developmental increases in sound-shape correspondence for holes, and while it was not precisely clear from the evidence that children's improvements came from increases in hole perception (as opposed to increases in sound-shape correspondence), the results suggest the possibility for developmental change in hole shape perception, supported by the development of global perceptual processing. Future work would examine the role of topological perception in the development of spatial reasoning.

In Chapter 3 we studied whether toddlers' (24-40-month-old) working memory performance depends on the type of object representations they maintain in working memory. Particularly we tested whether toddlers could represent objects that varied in topological or surface features in working memory. We found that toddlers represented topological properties and surface features similarly in their working memory. To our knowledge, this is the first study in the literature to investigate whether toddlers can represent topological properties in working memory. Previous research on visual working memory development has most often tested working memory performance for surface features like colors or metric shapes, and findings from these studies are often taken as evidence for the generic capacity of working memory (Oakes et al., 2013; Cheng et al., 2020; Kibbe & Applin, 2022; Burnett Heyes et al., 2012; Heyes et al., 2016; See review by Cowan, 2015). Because working memory is central to several higher-level cognitive functions like problem-solving and executing goal-directed behavior, and is associated with academic achievement and self-regulation, it is imperative to develop a more comprehensive theory of working memory. To do that, we have to study how different

feature types of an object are represented in visual working memory in development. Importantly, this investigation will inform us about at what age some object feature types may be prioritized by the visual system. Therefore, it will allow us to predict what kind of object features children use for goal-directed behaviors.

Our experiment in Chapter 3 of this dissertation is a step towards this approach and our results suggest that toddlers are sensitive to the topological properties that differentiate the objects and represent this information in their working memory. By design, children in our experiment were not given a task beyond remembering which object was hidden where. This was by design, in order to examine the kinds of representations that children might deploy “by default” across different feature types. However, encoding and representation of topological information may be shifted based on the task at hand. For example, topological representations in working memory can influence action planning and act as affordances if children’s task is to physically interact with objects (e.g., children planning to hold (action) a cup differs based on whether a cup has a handle). It is currently unclear whether and to what extent topological information may be prioritized in limited working memory by young children whose working memory capacities and motor systems are still undergoing development. Future work would examine the role of physical reasoning processes and task- and goal-relevant object properties in children’s early representations of objects.

Studying topological representations in working memory can inform us about the fundamental unit of working memory. Because topological invariance provides stability to the representations, act as primitives in visual processing, these properties are

considered prime candidates for the fundamental unit of working memory (Chen, 2005; Wei et al., 2019). For example, Wei et al. (2021) showed that changes to the topological properties of objects significantly decrease the performance in working memory task suggesting that topological change in objects results in a perception of a new object, therefore topology acts as a fundamental unit to working memory. Studying working memory for topologically distinct objects in young children can inform about whether children associate object identity with the invariance properties of that object and if so, how this relationship develops with age. Our results suggest that children may not prioritize topology in working memory like adults do, suggesting a potential discontinuity between children and adults. Future work would examine this potential discontinuity further, mapping out the space over which development occurs in working memory.

In Chapter 3 we also investigated whether object-based attentional cues influence toddlers' working memory for topology properties and surface features. We found that attention did not influence working memory performance for both surface features and topology. Previous research with infants, children over 7 years of age, and adults showed that attention cues benefit working memory performance because attention cues can selectively encode the relevant item into the working memory or actively ignore the irrelevant items from encoding into working memory (Astle et al., 2012; Gazzaley & Nobre, 2012). Our study findings showed attention cues that cued object *features* (i.e., color, topology) did not influence representations of either topology and surface features in working memory. Future studies should test what type of attentional cues influence topological representations in children by manipulating attention through exogenous and

endogenous spatial cues. Attention's influence on topological representations will help us answer questions like whether children can maximize their working memory for topological properties of objects or whether these properties are encoded automatically into working memory without demanding attention. Based on our Chapter 3 experiment results, we believe that children may deploy attention to topological properties similar to adults (Wolfe & Horowitz, 2017). In addition, future studies should test at what age children start representing topological change as a marker for the change in object identity using multiple object tracking tasks, like those used in adults (Zhou et al., 2010).

In Chapter 4, we investigated whether children use the topological properties of an object to extend novel labels to novel objects. We found that topological properties compete with surface features when children extend labels to novel objects. Our results are the first in the literature to find that topological properties of an object have inductive potential, that children associate these properties with count nouns, and that children categorize new objects based on these properties.

The results of Chapter 4 raise several important questions regarding the role perceptual features play in infants' and children's object categorization and word learning. To categorize objects, children have to identify the perceptual or conceptual feature that can be generalized, and associate a word with this generalized property to provide meanings to the words. Does this bias toward topological properties contribute to object categorization in infants? Answers to these questions could provide us with unique insights into how attention guides language learning in children who are just beginning to acquire expressive language. There are two major reasons that topological properties

might play a central role in infants' categorization of objects: one is that the topological invariance of an object informs about the object's identity, and another is that because of its invariance across different changes can provide stability to the representations, this invariance may allow infants to generalize topology of an object to initiate object categorization. Future work would investigate the role of topology in infants' inductive inferences.

### *General Conclusions*

Perceptual and cognitive development research has only scratched the surface of research on topological properties. The aim of this dissertation was to shed light on the importance of the topological properties of an object at different levels of information processing (perception, representation, and categorization). The findings of all the studies in this dissertation point to the direction that toddlers and children perceive and represent topological properties and use these properties to categorize objects. Studies in this dissertation point to several future directions.

One of the central unanswered questions is whether perceptual development occurs from global-to-local or local-to-global – that is, whether infants first extract global topological properties earlier in development followed by extraction of surface features, or vice versa. Piaget and Inhelder (1967) long ago argued that perceptual development proceeds with first extracting features that provide the most invariance to object representations, and then with features that provide the least invariance (i.e., topology to Euclidean geometry). According to them, perceptual development patterns follow the opposite of the hierarchy in Klein's engram theory of geometry i.e., topology first and

metric shape at the last with projective, affine geometrical properties between these two feature types (refer to page 7 of this dissertation for more details). Despite this theoretical assertion made almost half a century ago, there is very little research that explicitly investigated the nature of perceptual development in terms of the invariance of the features. Some studies conducted on newborns and 2-4-month-old infants showed that topological properties are extracted earlier in development (Turati et al., 2003; Chien et al., 2012), but there is little to no research whether all different types of topological properties (i.e., presence of holes, connectedness, inside/outside relations) are extracted at the same time in infancy or that some of these features are extracted earlier and other develop later. In addition, future studies should conduct research on whether perceptual development follows in terms of invariance of features as Piaget and Inhelder (1967) argued.

The second line of research that this dissertation points is how perceptual categorization influences conceptual categorization. For example, previous research showed that conceptual categorization of objects emerges around 7-9-months-of-age (Mandler & McDonough, 1993) and Mauler (2000) argues that infants first perceive the similarity between the perceptual features of objects, and this eventually translates to the development of conceptual (entity that goes beyond perceptual features) categorization. However, there is little to no research on how exactly this translation from perceptual categorization to conceptual categorization occurs. Topology, because of its invariance, can be a strong candidate to inform about object category which might translate to conceptual information with the intersection of language development (e.g., infants by 9

months start using nouns to categorize objects). The extent to which topology *drives* language or conceptual development is uncharted territory and should be investigated in future work.

Future studies should test whether different topological properties of objects play different roles in cognitive development. One research area that topological properties might be central is perception of numerosity in the visual domain. For example, infants' and children's representations of the numerosity of visual objects might depend on whether these objects are connected, or whether they are enclosed – topological properties of objects that may be more relevant to object numerosity than the number or type of holes inside an object. These topological properties could play a role in the way numerosity is represented, with implications for how early numerical processing influences later formal numerical knowledge. In addition, future research should investigate whether combination of topological properties and surface features like metric shape, color, and texture provide rich inferences about object properties.

In conclusion, I believe that data presented in this dissertation show the importance of understanding the role of object topology in children's object perception, representation, and categorization, and the research questions raised in this dissertation are timely and important. This research urges for the systematic study of topological invariance in children's perception and cognition.

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