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Keeping Track of Change: Developmental Insights into the Ability to Represent Objects in Episodic Terms

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Masters of Science Thesis

Keeping Track of Change: Developmental Insights into the Ability to Represent Objects in Episodic Terms

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Introduction:

We can always count on the world to change. We must keep track of change in order to know what to do now and what to do next. Despite similarities across multiple experiences, we only directly experience the world as discrete events or episodes. In other words, we don't directly engage with schema, concepts, or categories. When we interact with the world, we execute specific actions on specific objects at specific points in time. Therefore, we must represent the contents of events, the particular objects we interact with, in episodic terms. Specifically, we need to keep track of what happens to these objects in order to anticipate and facilitate new states of the objects, our world and ourselves. Such precision necessitates the formation and maintenance of dynamic object representations that are contingent upon our goals, the current state of the object, and immediate situational constraints. These representations must also be flexibly bound to other objects, past states, and to our knowledge of both the objects themselves and the consequences of our behaviors. In other words, our object representations are not confined to the current moment. Rather, they are dynamic trajectories of changes in state that traverse time and space. This means that at any moment, our representation of each object contains a history of the relevant prior events it was involved in. The object's own changes in state as well as its associations and interactions with other objects within and across events through time constitute this history and overlapping interacting object histories typify events (Altmann & Ekves, 2019).

Even though such dynamic representations of experience are fundamental for understanding itself, little is known about how we develop the ability to keep track of the changes that occur to the objects we encounter. The present study is the first, to our knowledge, to explore *when* the ability to represent objects as trajectories of token-states that traverse space and time first emerges in childhood. That is, we are asking when do children first exhibit the propensity to represent objects as tokens, as defined by their unique histories, or trajectories, of change? The question of tokenization is a tricky one. In order to accurately identify when the ability to represent an object in terms of its history we have identified 2 minimum requirements that the developing cognitive system must fulfill in order to support such dynamic representations of experience. These include the ability to:

1) recognize that a particular token remains the same token despite changes in its location or state

2) flexibly incorporate these transient changes in state (in the form of previous token-states and anticipated future states) into the token representation

Knowing an object at one point in time is the same object *despite* change is an important precursor to tracking the history of an object because it requires maintaining prior token states in memory and comparing them to novel perceptual input. When the current perceptual input is very different from previous input, it could indicate a change in state of a single object *or* the existence of a novel object. Thus, in order to accurately respond to new input, it is important to know when a single object simply changed state and when to form a distinct token representation for a new object. In addition to knowing that the objects we encounter are the same object *despite* changes in appearance, location, time, or even task demands, we also need to update our representations in response to transient changes in the state of a token from one moment to the next. Change entails new behaviors, and new consequences. Therefore, we must actively adjust our representations to incorporate new information what happens to these specific objects to successfully understand and interact with the world both in the here and now and in the future.

For example, when baking a cake, you must bind the current perceptual input specifying the fully baked cake to the internal representation of its previous unbaked state. By incorporating both states of the object into a single representation of its identity we can recognize that the batter we had mixed earlier is the same cake that we just removed from the oven. It is also not enough to know that the batter and the baked cake are the same object despite undergoing a change in state and location. We must also recognize that this isn't just any cake, it is a particular cake not interchangeable with other cakes. Therefore, we must also update our representation of the cake *because* it changed. We must know that the unbaked and baked cakes are different states of the same cake but each state in its trajectory of change affords different interactions. For instande, the cake that is now baked and edible was once an inedible mixture of ingredients.

At first glance, it seems likely that the of ability to represent objects in terms of their histories would emerge during the first year of life in parallel with the emergence of object permanence. After all, knowing that a particular object continues to exist despite occlusion, or movement requires knowing that the object was "here" and now its "there". The representational capacity putatively referred to as "object permanence" can be observed in infants as young as 4 months of age with developmental improvements in the flexibility and precision of these representations continue throughout the first year of life (Baillargeon, 1987; Smith & Thelan, 2003). Evidence for such early emergence stem from violation of expectation intermodal preferential looking (IPL) paradigms in which objects are either concealed by a screen or hidden in an opaque container and subsequently revealed. Infants must use the information provided (e.g. the spatiotemporal trajectory and/or the features of the objects) to form expectations about the number of objects participating in the occlusion event. Looking patterns and search behavior (e.g. number of reaches to retrieve the objects) serve as an index of infants' expectations about the concealed objects.

In a series of studies, Xu and Carey (1996) showed that preverbal infants capitalize on the predictable nature of spatiotemporal continuity to individuate perceptual features into numerically separable entities and keep track of them across occlusion events or changes in location. In their first study, 10-month-old infants watched two objects (e.g. a rubber duck and a toy car) simultaneously emerge from and return behind a single screen. Then, the screen was lowered to reveal either two objects (expected outcome) or one object (unexpected outcome). Based on observed differences in the infants' looking patterns during the expected and unexpected outcome condition, Xu and Carey (1996) concluded that the infants used spatiotemporal continuity to correctly individuate two objects. That is, infants knew that a single object could not be in two places at once and could use this knowledge to generate expectations about the *number* of objects that should be occluded by the screen. Knowing two things should exist does not necessarily entail representing their identity or even what happened to them. Infants in this paradigm only had to generate expectations about the number of entities that should be behind the screen. This task did not assess whether or not the objects that were initially hidden were the same objects that were subsequently revealed. Thus, infants did not have to track the episodic histories of the specific object because they did not have to know that each object was "here" and moved "there" or the order in which the objects were hidden, only that there should be 2 objects "there" now.

In their second manipulation, Xu & Carey (1996) showed that during the first year of life, infants use spatiotemporal continuity to parse cluttered perceptual into coherent, numerically separable entities divorced from identity. This time, 10-month-old infants watched one object (e.g. the duck) emerge from and return behind the screen. Then, they watched a second object (e.g. the car) emerge from and return behind the same screen. The infants expected only one object, not two objects, to be revealed when the screen was lowered because the spatiotemporal trajectory (only 1 object was in view at a time) was only indicative of the existence of at least 1 object. This means that without clear spatiotemporal evidence, 10-month-old infants could not generate accurate expectations about the number of hidden objects even when those objects possessed clearly different features. Spatiotemporal continuity is informative for individuating the existence of numerically separable entities, and generating expectations about the number of objects that participate in an event. But, spatiotemporal information is not enough to facilitate encoding of the identity of the individuated objects such that they are not interchangeable with other objects. Consequently, spatiotemporal continuity alone is not sufficient to support object representations that can flexibly accumulate an episodic history. Feature information provides important cues to the identity of a particular object. Therefore, featural information (in addition to spatiotemporal information) is necessary to accurately compare representation of the previous input to the current perceptual input. Without encoding featural information into an object representation, it is impossible to know that the particular object at one point in time is the same object despite changes in location or state. Therefore, preverbal infants do not represent objects as unique tokens capable of accumulating an episodic history because they could not maintain feature information in their object representations. However, 12-month-old infants can use features indicative of category membership to correctly infer that 2 objects should be concealed by the screen as long as the objects belong to different categories. When both objects belong to a single category (e.g. a dump truck and a tow truck or a big cup and a small cup), 12-month olds fail to individuate the correct number of objects even if those objects possess different features

(Xu, Carey, & Quint, 2004). Infants used type-specific information to individuate objects belonging to different categories, but represent all members of a single category as a single individual. Thus, without clear and persistent spatiotemporal evidence, even infants with category knowledge fail to represent multiple tokens belonging to a single category as unique individuals not interchangeable with other members of that category. Because infants consider all members of a category to be interchangeable, they could not use within kind feature contrast to keep track of the correct number of objects involved in an occlusion event. For similar studies, see e.g. Spelke, Kestenbaum, Simons, & Wein, 1995; Wynn, 1992; and Xu & Carey, 2001 for review.

The acquisition of categorical knowledge after the first year of life fundamentally changes how infants individuate and represent objects and events by providing a structure by which to organize, understand, and identify incoming perceptual information. Categories improve the resolution at which infants can represent experience because they facilitate rudimentary object-centered representations: When infants encounter objects in their environment, category knowledge biases attention towards relevant perceptual features for classification purposes (Smith, Jones, Landau, Gershkoff-Stowe, & Samuelson, 2002). Infants can readily bind together collections of perceptual features indicative of category membership and object features that do not match a known category can also be more easily segregated (Xu & Carey, 1996; Carey & Xu, 2001). Feigenson et al., 2003 showed that 14-month-old infants are insensitive to within-kind property differences during occlusion events. For example, after watching an experimenter hide 3 small balls in a box, infants do not continue to search for additional objects if they retrieve 2 small balls and 1 big ball. This means infants can represent the correct number of objects involved in the task, but they cannot detect mismatches between the identities of the objects hidden and those of the objects that were subsequently revealed. However, this task provided infants with clear spatiotemporal evidence for the number of objects participating in the event and did not include a condition where the retrieved objects did not belong to the same category as the hidden objects. Therefore, it is unclear if the infants were actually even maintaining type membership in their object representations.

An extension of this last study suggests that it is not until 18 months of age that infants can maintain object representations that include identity at the level of category membership across changes in location or occlusion events: Zosh and Feigenson (2012) attempted to assess whether or not 18-month-old infants realized that the objects that they initially watched being hidden in a box, were the same objects they subsequently retrieved from the same box. 18-month-old infants watched an experimenter place 1,2, or 3 objects into a box (each object belonged to a different category). Before allowing the infants to retrieve the objects, the experimenter secretly replaced either one or all of the objects inside the box (thereby changing the identity of the objects). Objects could switch identity from one type to another (e.g. from cat to car) or even lose object status by switching from solid to nonsolid substance (from cat to gelatinous blob). When infants only had to maintain 1 or 2 object representations in memory, they could detect a mismatch between their expectations about the objects inside the box (based on prior representations of the objects) and the actual objects they retrieved. Search behavior depended on the total number of objects hidden inside the box but not the number of objects within a set that changed identity. In other words, infants searched for the same amount of time when only one of the hidden objects changed identity as they did when all of the hidden objects changed identity. Infants did not remember the 3-object set well enough to detect a type-level mismatch between the hidden and retrieved objects. But, after watching only 1 or 2 objects being hidden in the box, infants continued to search after detecting type level mismatches. This suggests that 18-month-old infants can encode and retain type-based representations for a finite number of hidden objects and compare these prior representations to new perceptual information provided by the retrieved objects.

Individuating objects on the basis of type membership is advantageous for generalizing learned behavior to novel contexts and for generating more accurate expectations or predictions about unfolding events. But, type based object representations lack the precision necessary to represent objects as trajectories of token-states. In order to form token representations that can flexibly acquire an episodic history, infants must discriminate between objects of the same type as well as maintain and update these representations across changes in state, shifts in location or context, and switches in attention. Zosh and Feigenson (2012) did not include conditions that manipulated within category changes in identity. Therefore, it did not address whether or not the infants were sensitive to within-type changes to identity. But, successful performance in this task was dependent upon the level of feature contrast (Zosh & Feigenson, 2012). Therefore, it is unlikely that 18-month old infants would be sensitive to within-kind changes in identity at the level of individual tokens because feature differences between tokens of the same type are less obvious than feature differences between tokens different types.

Using a forced choice paradigm, Ganea, Shutts, Spelke, and Delouche (2007) provided tentative evidence to suggest that infants cannot adjust representations of specific tokens based on described changes to those objects until they reach 22 months of age. In this study, 19 and 22-month-old infants were introduced to “Lucy” the stuffed frog. The experimenter then took “Lucy” out of view and explained to the infants that she had dropped “Lucy” in a bucket of water and gotten her all wet. The infants were then presented with 3 objects. 2 of these objects were stuffed frogs that were otherwise identical except that one was wet and one was dry. The third object was a different stuffed animal that was also wet. The infants were asked to find "Lucy". Older infants (22 months) correctly chose the wet frog while younger infants chose the dry frog (Ganea et al., 2007). The researchers concluded that by 2 years of age, infants can use linguistic and perceptual evidence to recognize and update a prior representation of a familiar object to reflect a change in state even when the change event was not seen by the infant. This suggests that, like the 18-month olds in Zosh and Feigenson (2012), these 19-month-old infants could maintain an initial object representation (at least at the type-level), but could not detect update this internal representation in response to external input. Ganea and colleagues (2007) did not include a within category contrast condition where infants had to choose between "Lucy" and another different stuffed frog. Thus, it was not clear if the infants could even form and distinct maintain distinct token representations in the first place. That is, it was not clear if these infants were representing "Lucy" as a particular stuffed frog (a token) or just as any stuffed frog (a type). In fact, the infants did not need to track the previous states of the object at all in order to make the correct choice in the study. Instead, they could have relied on semantic knowledge triggered by language cues used to describe the change (e.g. "wet") and the presence of explicit visual cues to the change (e.g. the water) to infer the current state of the object. In other words, the infants did not need to know that Lucy is a particular stuffed frog who *was* dry and *now* she is wet, they only needed to know that Lucy is a stuffed frog that *is* wet. Although the ability to flexibly adjust representations of particular objects to accommodate new information or changes in state did not emerge in this study until 22 months, it is not even clear that the ability had truly emerged (that is, the ability to bind the 'later' representation of the frog with its earlier self). That remains to be tested.

Tokenization requires representing an object as a unique instance of a particular type that is not substitutable with other members of the same type. While type membership affords representations of what can and cannot happen, a token's episodic history, its trajectory of change, makes it distinct from other tokens that belong to the same category. Even objects that are virtually identical in appearance and/or function possess unique histories because particular objects participate in particular events. Each token's idiosyncratic and ever-changing history is an inherent and necessary component of its unique identity. To successfully complete virtually any task in our cluttered world, we must simultaneously generalize on the basis of type and discriminate between members of the same type on the basis of their episodic histories (even if those tokens are identical). For example, if you are thirsty during a dinner party, it is not enough to know that cups afford drinking or even to individuate the existence of multiple cups with unique spatial locations around the table. You must distinguish between identical cups on the basis of what has happened to the them in order to know which cup to drink from. Therefore, accurate discrimination between 2 identical tokens solely on the basis of their episodic history is the minimum behavior necessary for a child to demonstrate to show they have acquired the capacity to represent objects as trajectories of changes in token-states. The few studies that have explored the developing ability to distinguish between identical or highly similar tokens suggest that the ability to precisely represent the identity of a particular object does not emerge until the early preschool years.

When provided with clear and persistent spatiotemporal evidence for the existence of multiple individuals of a single category (e.g. they are simultaneously presented and occupy distinct locations in space), 12-month-old infants can represent each object as a distinct token and interact accordingly in the moment (Feigenson, Carey, & Spelke, 2002; Feigenson, Carey, &

Hauser, 2002). But, these representations are inflexible and fragile because they cannot accumulate episodic history. 1-year old infants can reliably represent and compare across 2 unique tokens (or sets of tokens) belonging to the same category in order to specifically select 1 token over the other (Feigenson, Carey, & Spelke, 2002). However, they cannot update these token representations in response to changes in state or location, nor even maintain their initial token representations despite change (Moher & Feigenson, 2013; Feigenson & Yamaguchi, 2009). In addition, these young infants seem unable to utilize a highly salient history of repeated exposure to a specific object-action relation in conjunction with unambiguous spatiotemporal cues, to generate expectations about future events involving the token. Instead of forming an association between a particular object-directed action and the particular *token* that is the target of that action, infants associate the behavior with the *type* of object involved. (Spaepen & Spelke, 2007). This means that infants cannot even incorporate a semantic history (a specific object-action relation learned over repeated trials) with an existing token representation. Instead, they incorporate prior experience into their object representations at the level of type membership such that they can only form expectations about possible future events involving a type of object. For example, in Spaepen and Spelke, 2007, 12-month-old infants were presented with 2 objects belonging to the same category arranged side-by-side on a stage. The infants watched as an experimenter repeatedly reached towards 1 of the objects. The experimenter always reached for the same object during the familiarization period. Even though the experimenter never reached for the alternative during familiarization, the infants were not surprised when the experimenter reached for the alternative object in the test phase. This suggests that 1-year old infants consider any member belonging to the same category as the original object as a viable target of future reaches. Thus, even with discriminable spatial information and repeated highly specific experience and spatiotemporal evidence, 12-month-old infants are unable flexibly associate specific objects with their specific histories.

Gelman and colleagues (2014) showed that by 3 years of age, children possess a fragile capacity to represent objects as unique instances or tokens (distinct from other visually identical alternatives) that are capable of collecting a unique episodic history. In their first experiment, the researchers presented 3-year olds and adults sets of 3 novel objects arranged side-by-side on a table. The properties of the sets were manipulated across trials such that all of the objects in each set of 3 could either be the same shape but different colors or completely identical in all aspects of appearance. The experimenters also manipulated the semantic relevance of the objects. In the ownership condition, the experimenter denoted ownership status to one of the objects in the set (e.g. this is yours). Then, participants watched as the experimenter shuffled the spatial placement of the objects (e.g. the owned object and another object switched places). Immediately after this spatiotemporal transformation, the participants were asked to point to 'their' object. They were queried second time after a delay only on trials with sets of objects that were of different colors. The structure of the labeling condition was identical that of the ownership condition. But, rather than assigning ownership, the experimenter labeled a particular object in the set (e.g. "this is a sarn") and subsequently queried with this label (e.g. "where is the sarn?"). They found that adults performed equally well in all conditions. Children performed above chance (33%) on immediate retrieval queries for every condition. But the 3-year old's could remember the history of the target token (in both the identical and color varying object sets) more accurately when the experimenter designated ownership status to one of the objects than when the object was only labeled. In fact, they selected the correct object in less than half of the trials within the label condition. Whereas in the ownership condition, children accurately responded 75% of the time.

The children were also more accurate in trials with sets where each object varied in color than when presented with sets of identical objects regardless of whether they were in the ownership or label condition. But, a separate difference in average score on color-varying and identical sets for the ownership and label conditions was not included in this analysis. After a brief delay, children could only remember the spatial location of target objects that had been assigned ownership status and were part of color-varying sets. That is, even with obvious perceptual cues (different colors), the children's token representations could not withstand a brief shift in attention. Most importantly, even though the objects in each set were identical or highly similar and belonged to the same unfamiliar category, 3-year olds did not generalize the label to other members of the same category. Instead, they could not only represent the target individual as distinct from the other identical alternatives but also could keep track of its episodic history (its unique spatiotemporal trajectory). These results also imply that early episodic representational capacity is likely facilitated by highly salient semantic information, such as ownership while adults track both arbitrary and nonarbitrary episodic history. Preschool aged children demonstrate a fragile propensity learn arbitrary details about specific tokens they encounter after a single experience and momentarily keep track of their spatiotemporal trajectory. But, these representations are unreliable because they are vulnerable to switches in attention and the passage of time.

In another series of studies, Gelman and colleagues (2012, 2015) show that by 3 years of age, children show a weak inclination to use nonobvious perceptual cues indicative of a particular object's unique history of state change to make ownership judgments (Gelman, Manczak, Was, & Noles, 2015). In these studies, an experimenter showed preschool children identical objects and designated one for the child and *another* for someone else. Toddlers observed the experimenter make a small nonobvious mark on the child's particular object before removing both objects from view. The child was then presented with both identical objects, and told to identify which one they owned. Even when the perceptual traces were inconspicuous, and not directly referenced by the experimenter, children still spontaneously encoded the marking event as part of the object's history and used this history to determine ownership as evidenced by their search patterns. However, when the objects were not identical, children did not search for the mark as often and instead relied on the obvious perceptual differences. However, with increasing age, children became more and more likely to use historical cues to identify objects assigned to them both in tasks that require historical knowledge and in task that do not. Clearly the early preschool years are characterized by increasing ability to associate individual objects with their unique histories. Critically, in an earlier study, Gelman and colleagues (2012) illustrated that 2-year-old toddlers could not reliably use historical traces or spatial information to differentiate between otherwise identical objects at all. These young toddlers also conflated desirability with ownership when differentiating between 3 objects that belonged to different categories. (Gelman, Manczak, & Noles, 2012). Thus, it is not until at least 3 years of age that children seem to begin to encode the idiosyncratic contingencies that make up an object's unique history of change and subsequently use this history to inform their understanding of the current event. The primitive form of the ability to represent objects as dynamic trajectories of change is contingent upon salient semantic information. Events that evoke highly meaningful semantic relevance, such as ownership designations, increase the salience of cooccurring arbitrary details. Thus, this arbitrary history is more likely to be encoded and maintained because of its relevant semantic associations. However, these studies did not explore if and when children can discriminate between multiple historical representations belong to multiple different objects. If events are indeed represented as aggregates of overlapping interacting object histories, children must be able to simultaneously attend to, associate, *and* individuate multiple historical representations at the object level within an episode and at the event level across episodes. Finally, the observed memory advantage for self-owned items, and adult participant's tendency to examine the objects in trials with and without marking events warrants further examination of the emerging ability to represent objects in terms of their unique histories.

Tracking Object Histories – Experimental Studies

To gain insight into when the ability to represent specific objects in terms of their unique histories first emerges in childhood, we asked children between 2 and 4 years of age to choose between two identical objects on the basis of their unique histories of state change. We structured our task as a novel game in order to ensure we were reliably evoking the emerging ability to keep track of and represent objects as trajectories of change in its purest form. In our paradigm, the objects (and their histories) were relevant to the task context but did not carry personal value to participants themselves. Unlike Ganea and collegues (2007) mentioned above, the objects in our studies possessed unique histories (their color changes) but remained otherwise perceptually identical which, along with the novel context, prevented participants from relying entirely on systematic cues or prior semantic knowledge to complete the task. Unlike Gelman and colleagues (2012, 2015), we also gave both objects a unique history so that within each trial or event, the children had to differentiate between competing visually and historically similar representations in order to select the correct object. Across trials, task demands remained constant but each trial involved unique but perceptually identical stimuli. In addition, the spatial location of the placement of the objects and temporal order of the transformations were counterbalanced. In this way, we could investigate children's ability to form dynamic and hierarchical representations of their experiences.

<u>Method:</u>

This paradigm was centered around a novel game context. The goal of the game was to feed very hungry but very picky monster puppets, named Rom and Bam. Their "food" was actually colored wooden balls. We used a "magic" box (box with Ipad that plays an animation of balls changing from blue to red or yellow) to figure out which food is yummy and which food is yucky. We initially presented participants with 2 blue balls that when placed in the "magic" box (one at a time) briefly changed color (red or yellow) before becoming blue again. "Yumminess" and "Yuckiness" were defined by these transient color change animations. We asked participants to point to "yummy" object. Participants had correctly associate each history of color change to the correct object and remember the semantic mapping between color and "yumminess" in order to decide which of the 2 blue balls to feed Rom. That is, the participants had to discriminate between 2 identical tokens based solely on their unique episodic histories of color transformation.

<u>Participants:</u>

Forty-eight children between 2 and 4 years of age (N = 48; range = 22 - 52 months, M = 36.4))) participated in this study. An additional 6 participants were enrolled but their data was excluded due to inattention (2), experimenter error (3), parental interference (2), or failure to meet inclusionary requirements (1). All participants were typically developing, monolingual children with normal or corrected to normal hearing and vision. Participants were recruited from a departmental database of families who indicated potential willingness to participate in research. The majority of which were white, middle-class families living in central or eastern Connecticut. Children received a small giftupon completion of the session.

Materials:

Stimuli included wooden balls (2.5inches in diameter) colored red, blue, or yellow, two monster puppets (one red and one blue), a wooden box with an iPad replacing the front panel, and two plastic cups to prevent the balls from rolling across the table. Videos of the balls changing color (3-7 seconds in duration) were presented via the iPad.

Procedure:

Each child participated in a single experimental session between fifteen and twenty minutes in duration. Each session consisted of three phases: familiarization, training, and test. Thirty-four sessions took place in a laboratory testing room and four sessions took place in quiet rooms at the participants' respective daycares or preschools. All sessions were video recorded. During the session, the experimenter sat opposite the participate at a table. The box was placed in the center of the table with the iPad facing the child. The plastic cups were placed six inches to the left and right sides of the box (see figure 1). Parents were given the option to sit with their children but were instructed to refrain from helping their child complete the task. A second experimenter sat behind the child, and recorded their responses to each trial.

Familiarization:

The purpose of the familiarization phase was to introduce participants to the stimuli and explain the goal of the task which was structured as a novel game. First, the experimenter introduced the monster puppets as Rom and Bam, the very hungry but very picky monsters who only ate "special" food. Participants were given the opportunity to briefly touch or hold the puppets. Then, the experimenter presented the child with a red ball and explained it was "yummy" food before pretending to feed it to one of the puppets, Bam, who gobbled it up. Then, she presented the child with a yellow ball explained that it was "yucky" food before pretending to feed it to Bam, who closed his mouth and shook his head. The experimenter did not provide verbal cues to the colors or shape of the stimuli at any point in the session. After introducing the "yummy" and "yucky" food, the experimenter gestured to the box, and explained that they were going to play a game with the "magic" box to find the "yummy" food.

Training Phase:

The purpose of the training phase was to familiarize participants with the task structure and reinforce their memory for the "yummy" and "yucky" food. The training phase consisted of a minimum of 4 forced-choice two-alternative trials between objects with obvious perceptual cues to their identity. Each trial always consisted of a choice between a "yummy" and a "yucky" object. Each trial progressed as follows. First, the experimenter showed the participant a blue ball and placed it inside the magic box. Then, the child was encouraged to touch the green button on the iPad screen that initiated the first change video. The child then watched a video of the blue ball changing color to red. The experimenter then retrieved a red ball from the box and placed it in an adjacent plastic cup out of reach from the child. Then the experimenter showed the child another blue ball and placed it in box. The child was again encouraged to initiate the change video by touching the green button on the iPad screen. The second video was identical to the first video except the blue ball turned yellow. The experimenter then retrieved a yellow ball and placed it in the other empty cup. Then, the experimenter asked the child to point to the "yummy" food. Every trial contained a blue-yellow and a blue-red change, but the order of the changes was counterbalanced both across trials within a session and across sessions. Feedback was given after each trial. If the child chose the red ball, the experimenter verbally assured the child that they were correct and pretended that Bam enjoyed eating the food. (e.g. Good job! You're right, that is yummy food! Let's watch Bam eat the yummy food!) If the child incorrectly chose the yellow ball, the experimenter explained to the child that it was "yucky" food and pretended that Bam refused to eat it. Then, the experimenter reminded the child that the other choice was "yummy" (e.g. Uh-oh, that's yucky food! See, Bam says No no!, yuck yuck! But this is yummy food! Watch Bam eat the yummy food! Mmm mmm yummy yummy!). Upon completion of all four training trials, the experimenter reminded the child what "yummy" and "yucky" food looks like one more time before moving on to the test phase.

A follow-up assessment was administered to participants who failed to learn the semantic mapping within the 4 training trials. The experimenter showed the child a red ball and prompted the participant to verbally identify that it was "yummy". The experimenter reinforced the correct response with verbal affirmation and by pretending to have Bam eat it. Then the experimenter showed the child a yellow ball and prompted the participant to verbally identify that it was "yucky". Again, the experimenter reinforced the correct response with verbal affirmation and by pretending to have Bam refuse to eat it. Participants that consistently failed each trial on the training phase were excluded from the analysis if they could not demonstrate an understanding of the rules after this follow up assessment. Only 2 participants required this additional training and they exhibited knowledge of the correct semantic mapping after just a single query. Therefore, all participants successfully learned the rules of the game by the conclusion of the training session.

Test Phase:

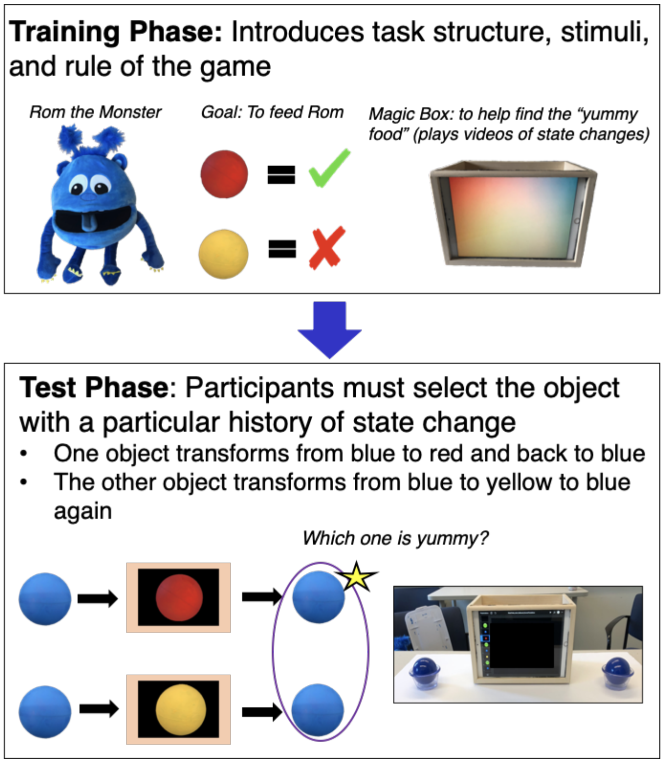
The test phase consisted of between 8 and 12 trials in total. Pilot data suggested that children tended to lose interest, forget the rules, or become confused after multiple repetitions of the test trials. Therefore, we restricted the first analysis, to the first 4 test trials where the child demonstrated sustained attention. No feedback was provided to participants after any of these first 4 test trials, regardless of whether the child chose correctly or incorrectly.

Trials 5 to 12 were used to give, and assess the benefits of, feedback to a proportion of the children (no feedback was provided after each of the first 4 trials). 4 participants dropped out after completing trials 1-4. Their data is not included in this analysis. A subset of participants did not receive feedback at all during the test phase (range = 28-52months, N= 16, M=37.6). The participants in the no feedback group completed a total of 8 test trials. The second group of participants (range = 22-52months, N= 28, M=35.04) endured a total of 12 test trials because they received feedback following their responses in trials 5-8, and completed a third set of 4 test trials (trials 9-12) without feedback. They are reported in Analysis 2 below.

Trials 1 – 4

Like the training phase, the test phase consisted of forced choice two-alternative trials between a “yummy” and “yucky” object (see figure 1). However, unlike the training phase, the objects did not possess perceptual cues to their identity, they looked exactly the same. Participants needed to remember each object’s unique history of state-change in order to make the correct selection. Each trial consisted of the following steps: First, the experimenter put Bam out of sight, and presented Rom to the participant. The experimenter explained that Rom eats “yummy food just like Bam” and that now they were going to use the “magic box” to feed Rom but Rom’s food is “extra-special” because it is “extra-hidden”. The experimenter then put Rom out of sight and placed a blue ball into the box. But this time, the child watched a video of the ball changing from blue to red/yellow and then back to blue. When the ball was turning back to blue, the experimenter emphasized the shift back to blue in order to keep the child’s attention and reinforce their understanding of the task (e.g. Look at that! See, it’s extra-hidden!). Afterwards, the experimenter retrieved the blue ball from the box and placed it in one of the adjacent cups. Then, the process was repeated with a second identical blue ball but with the alternate color change video. After the second color change, the child was asked to identify which of the identical blue balls was “yummy” food. That is, they had to select the blue ball that had been red. No feedback was given to participants after any of these first four test trials, regardless of whether the child chose correctly or incorrectly.

Figure 1: Visual representation of paradigm structure



Trials 5-8: Feedback

After 20 participants had completed this study, we began to wonder if the low success rate could be attributed to lack of understanding rather than lack of ability. That is, participants may have been able to track the history of an object but simply could not infer that "yumminess" was a persistent and intrinsic property of the object that did not require explicit perceptual cues. Although all participants demonstrated understanding of the arbitrary mapping between the color of the stimuli and "yumminess", and the link between the training and test phase was explicitly explained to participants before the test phase was administered, it is still possible that some participants failed to understand the expectations of the task. We provided a subset of participants (range = 22 – 52 months, N = 28, M=35.1) with explicit feedback after their responses on each trial within the second block of 4 test trials (e.g. trials 5 – 8). Following the block of trials with feedback, these participants experienced a third and final block of 4 test trials in which no feedback was provided. The other set of the participants did not receive feedback on trials 5 – 8 and did not complete a third block of 4 test trials (range = 28-52months, N= 16, M=37.5). That is, they did not complete trials 9-12.

As mentioned above, the second block of 4 test trials were identical as the first block of trials except that feedback was provided to a subset of participants after each trial. Order of transformations within each trial and across trials was counterbalanced so that it was unpredictable. When a participant chose correctly to a trial within the feedback set, the experimenter verbally confirmed their correct response and provided additional reinforcement by pretending to feed the puppet the correct stimuli (e.g. “Good job, that’s right. This is yummy! Let’s watch Rom eat the yummy one! Rom says Yum Yum Yum”). When participants chose incorrectly during test trials within the feedback set, the experimenter verbally corrected the child and reinforced the correct choice by pretending to feed the puppet (e.g. “Oh no! *That* is the yucky one!” “*This* one is yummy! See Rom eat the yummy one! Rom says Yum Yum Yum!”).

Trials 9-12: Post-feedback

The third (final) block of 4 test trials was also identical in structure to the first although again, the order of transformations within each trial and across trials was counterbalanced. Participants did not receive feedback after each trial in this block.

Coding:

Videos were coded for explicit response accuracy and compared with the record sheet for each participant. In order to ensure reliability, 50% of the videos were independently coded by a second research assistant without access to the record sheet and compared with the initial pass. Mean percentage of agreement between the coders was 96%.

Scoring:

Participants received separate scores for both the training and the test phases. Performance was based on explicit response (e.g. pointing or reaching). For both the training and test phases, participants received an accuracy score calculated as the percentage of correct responses out of the four total trials completed. One point was awarded for every correct response and the highest possible score for each phase was 4/4 or 100%. We also assigned each participant categorical scores indicating overall success or failure in each phase. Participants were given a 1 if they successfully completed ¾ or 75% of the test trials. A 0 was assigned to participants with accuracy scores of 0/4, ¼ , or 2/4.

Results:

Training Phase:

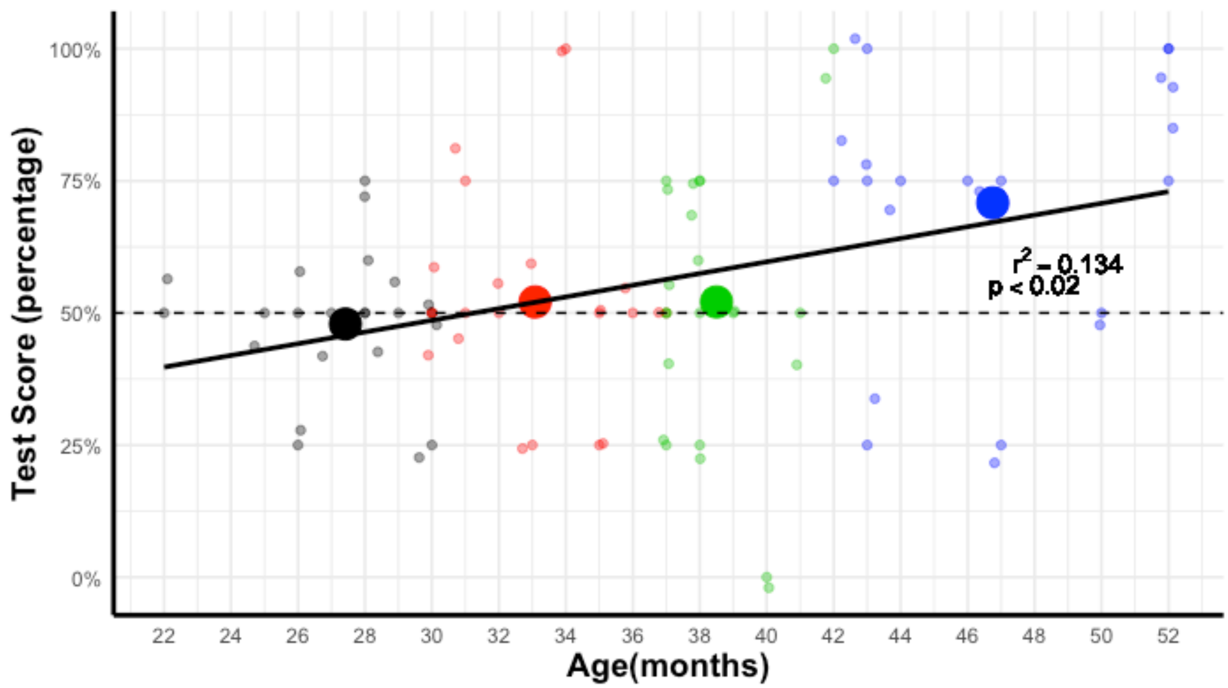
Age as a continuous variable did not predict performance in the training phase ($F(1,46) = 2.34$, $p = .133$). Likewise, performance in the training phase did not predict performance in the test phase ($F(2,45) = 4.98$, $p = .113$).

Results: Analysis 1

Test phase: initial 4 trials (Trials 1-4)

Performance on the first 4 trials of the test phase improved with age. A general linear regression analysis revealed that age as a continuous interval significantly predicted score on the first 4 trials of the test phase (R(46)= .36, $F_{(1,46)}$ =7.096, p = .01; see figure 2). These data suggest that marked improvement in children's ability to successfully discriminate between visually identical objects based solely on their history occurs during the early preschool years. The ability to represent changes in the state of an object begins to emerge by around 30 months of age and can be reliably observed in behavior by 52 months. [1]

Figure 2: Linear relationship between age and score (final response) on trials 1-4

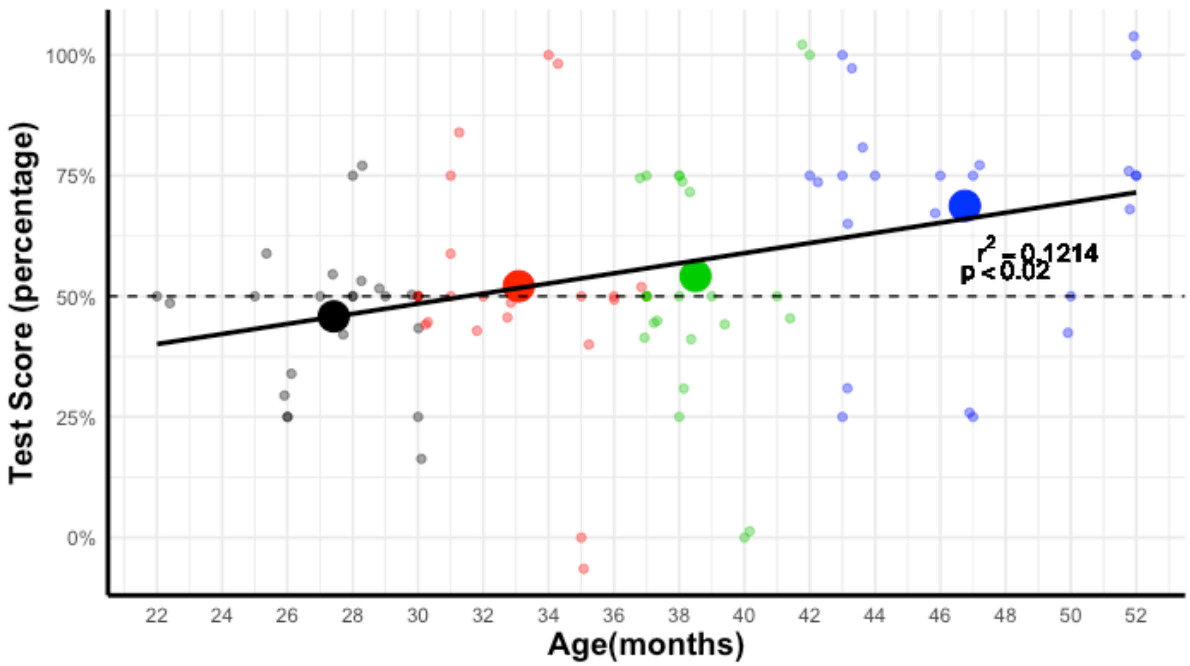


We observed a significant linear relationship between test score (final responses) and age as a continuous interval (black line). Participants were grouped into quartiles (n=12), and the means for each quartile (large colored dots) are superimposed on the trend line. The scores for each individual participant are represented by the small colored [2]points. The dotted line at y = 50% represents chance performance.

[1] Fitting a nonlinear function (for exponential growth curve) to the regression equation accounts for almost the same amount of variance as the linear function ($F_{(1,46)}$= 6.17, p = .017, R^2 = .12; see Figure A1 in Appendix A)

A few participants (n=5) switched their initial choice without receiving any input from the experimenter. Scores in the above analysis reflect participants final response. We ran a second linear regression on participants' scores calculated according to initial responses (see figure 3) before the participants changed their selection. Again, age as a continuous interval significantly predicted score on the first 4 trials (R(46)= .35, $F_{(1,46)}$ =6.35, p = .016). The data are very similar.

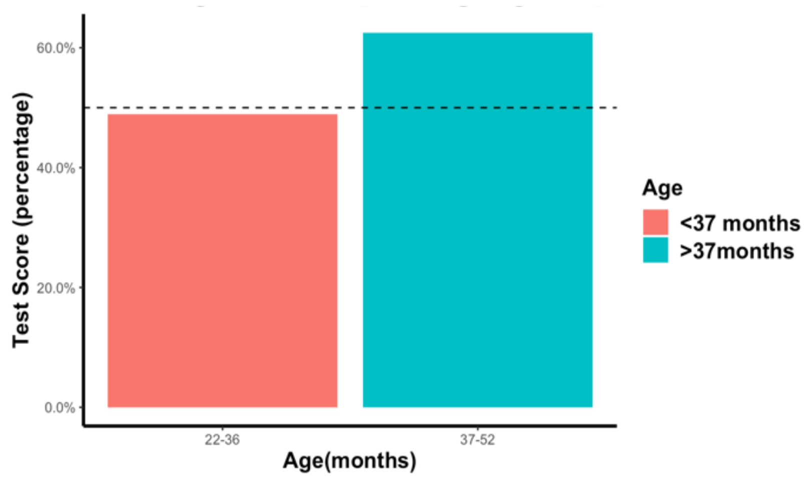
Figure 3: Positive linear relationship between age and score (initial response) on trials 1-4



We observed a significant linear relationship between test score (initial responses) and age as a continuous interval (black line). Participants were grouped into quartiles (n=12), and the means for each quartile (large colored dots) are superimposed on the trend line. The scores for each individual participant are represented by the small colored points. The dotted line at y = 50% represents chance performance.

We then divided the participants into 2 age groups along a median split (<37months: range =22-36months, n = 24, M = 30.25; >37months: range = 37-52months, n = 24, M = 42.6). T-tests revealed that the younger group's scores did not significantly differ from chance (M = 50%; t(23)= 0, p=1) but on average, participants in older group scored above chance (M = 62%; t(23)=2.04, p=.027; see figure 4). [3]

Figure 4: Age group differences in average score



This graph shows the average score for the initial 4 trials for each age group. The dotted line at y = 50% represents chance performance (a score of 2/4). The average score of participants >37 months was 50% and the average score of participants <37 months was 62%.

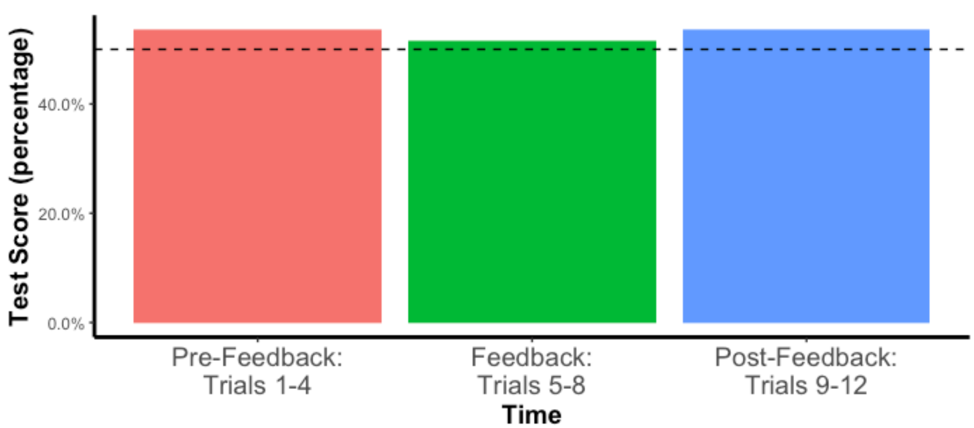
[3] Due to the high probability of selecting the correct object by chance (50%) and small number of trials, we also ran a chi^2 analysis on these data. This analysis confirmed results from the T-tests. Significantly more participants in the older group completed the task successfully compared to the younger group ($X^2(1, N = 48) = 9.38$, p=.002). For a graph of the chi^2 square results see figure 2 in the appendix.

Results: Analysis 2

Test Phase: pre-Feedback vs post-feedback

Trials 5 to 12 were used to give, and assess the benefits of, feedback to a proportion of the children (range = 22-52months, N= 28, M=35.04 months). No feedback was provided after each of the first 4 trials nor following responses in trials 9-12. We compared scores on the first block of 4 test trials to scores on the final block of 4 test trials to ascertain whether or not feedback had an effect on performance. Paired sample t-tests revealed that scores on the first block did not differ significantly from scores on the last block of test trials (t(27)=0, p=1, figure 5). Overall, the average score on trials 5-8 also did not significantly deviate from the average score on trials 1-4 (t(27)=.39, p=.697) nor from the average score on trials 9-12 (post-feedback (t(27)=-0.45, p=.658; figure 5).

Figure 5: Impact of feedback on average score



This graph shows the average scores of all participants in the feedback group(n=28) before, during, and after receiving feedback. The average score after receiving feedback (Trials 9-12: Post-feedback M = 54%) was not significantly different from the average score on the initial 4 trials (Trials 1-4: pre-feedback M = 54%) nor from the average score on trials 5-8 (M = 52%

GLM analysis with score on the last 4 trials as the outcome revealed that age as a continuous interval was a significant predictor of score on the last 4 test trials (post-feedback) (R(26)=.42, $F_{(1,26)}$ = 5.42, p=.028) in this sample. Score on the initial set of 4 test trials (pre-feedback) was not a significant predictor of score on the last 4 test trials (post-feedback) after controlling for age ($F_{(2,25)}$ =3.74, p=.184). These data imply that feedback did not have an impact on performance in this task.

Comparisons between feedback and no-feedback groups

The average score on the initial set of 4 trials (pre-feedback) for subset of participants who received feedback on trials 5-8 did not differ from that of the participants who did not receive feedback (feedback group: n=28, no feedback group: n = 16; t(42)= -0.58, p=.57). The difference between the average score on trials 5-8 for the no feedback and the feedback groups was trending towards significance (t(43)=2.02, p=.05). However, one sample t-tests revealed that neither group performed significantly greater than chance on the trials 5-8 (see table 1). This suggests that the observed trend towards significant group differences in average score on trials 5-8 was likely due to the unequal group sizes. There were no significant differences in performance between initially unsuccessful participants in the no feedback group and initially unsuccessful participants in the feedback group on trials 5-8 (t(29)=-0.89, p=.38, table 1).[4]

Table 1: Average scores for feedback and no feedback groups

Grouping	Average age (months)	Average Score Trials 1-4	Average Score Trials 5-8	Average Score Trials 9-12	Total N
Feedback	35	54%	52%	54%	28

[4] There were only 7 participants in the feedback group who scored about chance in trials 1-4 and only 5 participants in the no-feedback group who scored above chance in trials 1-4 who also completed trials 5-8. 3 additional participants were successful in trials 1-4 but did not complete trials 5-8. Therefore, we could not compare the initially successful participants in the feedback group to those in the no feedback group because the sample size was too small.

No Feedback	37.6	58%	40%	NA	16

Results: Summary of Key findings

- There is a significant linear relationship between age as a continuous interval and test score. [5]
    - Older participants (>37 months) were more likely to score above chance in trials 1-4.
    - Younger children (<37 months) were more likely to score at chance in trials 1-4.
- Feedback did not improve performance of initially unsuccessful participants.
    - Participants who started off scoring at chance tended to keep scoring at chance in subsequent trials regardless of whether or not they received feedback following their responses in trials 5-8.

[5] Children in general became fussier with repeated trials. Initially successful children may have gotten worse because later trials may surpass the limits of their attentional resources and/or because of memory interference from previous trials.

General Discussion:

In this study, we asked children between 2 and 4 years of age to choose between two perceptually identical objects each with a unique history of state change. We structured the forced choice two alternative task around a novel game context in order to investigate the developing capacity to represent objects as tokens capable of accumulate an episodic history. We found a significant relationship between performance on the first four trials of this task and age as a continuous interval. That is, as age increased, score increased. Children older than 3 years of age were more likely to score above chance in this task. Conversely, most 2-year olds and some young 3-year olds in our dataset failed to surpass chance performance. The ability to successfully differentiate between perceptually identical tokens on the basis of their unique histories within an event entails tracking each token unique trajectory of change in state. Therefore, these data show that the ability to represent changes in the state of an object begins to emerge after 30 months of age and can be reliably observed in behavior by 52 months.

Developmental improvements in representational precision

In our study, children 3 years old and above could successfully represent objects in terms of their histories. The location (the cup) where each object was placed following its transformation served as the only cues to the distinct identity (and consequently the history) each object in each trial. In our task, children only had to choose between two identical objects, but the spatial organization of the objects did not remain constant across the encoding and retrieval portions of each trial. They had to track each token's trajectory of movement through space in addition to its change in state across time. Thus, children had to discriminate between two-highly similar histories of state change and correctly associate these histories to the token's final spatial location. In order to make the correct choice, children had to attend to both histories, discriminate between them, and assign each history to the correct object in space without the presence of any other obvious external cues. Given that spatial location was the only physical distinction between the two objects when children were provided the opportunity to respond, success in this task at least in part requires the capacity to represent the spatiotemporal trajectories of particular objects and discriminate between highly similar objects near in space. Single-trial allocentric memory, or the ability to discriminate between multiple similar objects in space after just a single experience also seems to improve after 3 years of age (Ribordy-Lambert, Lavenex, Banta-Lavenex, 2016). Such shared developmental origins suggest that the protracted trajectory for tokenization may be because we require the same relational binding machinery to represent the contents of events across time as we do to form episodic representations of the spatial contexts of those events. Age related improvements in the resolution at which spatial representations can be maintained are accompanied by enhanced ability to remember the location of hidden rewards in more complex arrays of virtually identical but spatially distinct objects, and increased capacity to remember the locations of multiple hidden rewards within a single trial (Ribordy-Lambert, Jabes, Banta-Lavenex, & Lavenex, 2013; Ribordy-Lambert, Lavenex, & Banta-Lavenex, 2015; Ribordy-Lambert et al., 2016).

Coincidentally, or perhaps, consequently, the neural structures in the hippocampus that are responsible for encoding the spatial relations between objects encountered during unfolding experience also support the formation and maintenance of episodic memories (Collin, Milivojevic, & Doeller, 2015; Poppenk, Evensmoen, Moscovitch, & Nadel, 2013; Nadel, Hoscheidt, & Ryan, 2012). After all, in order to associate the correct history with the correct object, it is important to individuate and discriminate between similar objects cooccurring in nearby space within the current event and between previous representations maintained in memory. In other words, in order to know what happened to which object, and when it happened to that object, we need to not only discriminate one object from nearby objects in space but also between their highly similar temporal histories. In fact, this assertion is outlined in the intersecting object histories (IOH) account for object and event representations. The IOH suggests that the mechanism that underpins episodic representations of experience – relational binding, the formation of indiscriminate associations between multiple objects in space (Cohen & Eichenbaum, 1993) – may also underpin the ability to associate states of a single token in time (Altmann & Ekves, 2019). That is to say, relational binding through time may underpin the ability to track the history of individual tokens and use these trajectories of change across time, space, and perceptual state to construct dynamic representations of experience (Altmann & Ekves, 2019). The precision at which spatial information is encoded and maintained in memory may therefore parallel the precision at which temporal information is also encoded. Therefore, the ability to form such episodic object representations, likely requires hippocampal dependent relational binding mechanisms.

The age effects we observed suggest that children seem to exhibit the fragile ability to associate tokens with their histories at the same age that they first exhibit the capacity for relational binding of the non-systematic elements of an experience into an episodic representation (Ribordy-Lambert et al., 2015; Ribordy-Lambert et al., 2016; Newcombe, Balcomb, Ferrara, Hansen, and Koski, 2014). Relational binding of episodic details is a well-known function of the human hippocampus (Collin et al., 2015; Mclelland, McNaughton, & O'Reilly, 1995; Hannula & Ranganath, 2008, Konkel & Cohen, 2009). The protracted developmental trajectory for episodic memory skills can be attributed to the maturation of the hippocampus and surrounding structures in the medial temporal lobe (MTL) that extends through early and even middle childhood (Tamnes, Bos, van de Kamp, Peters & Crone, 2014; Riggins, Blankenship, Mulligan, Rice & Redcay, 2015; Lloyd, Doydum, & Newcombe, 2009; Demaster & Ghetti, 2013; see Ghetti & Lee, 2011 for review). Specifically, each subfield within the hippocampus reaches maturity at a different point in early childhood (Lavanex & Banta Lavenex, 2013). These maturational processes mediate both early memory capacity and the characteristics of these representations (Gomez and Edgin, 2015). Infantile amnesia refers to the phenomenon where most adults seem to have no episodic memories from the period between birth and 2 years of age because the hippocampus has not yet matured enough to support episodic encoding (Gogatay et al., 2006; Bhatt & Rovee-Collier, 1997; See Mullally & Maguire, 2013 for review).The infant hippocampus undergoes a period of rapid neurogenesis and synaptic proliferation until it reaches adult-like volume (but not necessarily structure) by two years of age (Gogatay et al., 2006). Consequently, the early preschool years following the second birthday mark the offset of infantile amnesia with the emergence of relational binding skills and accordingly, the ability to form durable episodic memories (for review see Olson & Newcombe, 2014).

Although we observed clear parallels in the age at which participants succeeded in our task and the age at which children succeed in single trial allocentric spatial memory paradigms, our experiment did not include an allocentric spatial memory task. Therefore, we can only make predictions about the relationship between high resolution pattern separation in the spatial domain and the ability to track changes in the state of each object within an event. Future studies will investigate whether or not individual differences in allocentric spatial memory predict success in this task by comparing participants' behavior in this task to their performance on a spatial memory task of comparable difficulty.

<u>The role of feedback in episodic encoding</u>

To our surprise, feedback did not ameliorate performance. In fact, feedback did not seem to influence performance at all. Initially successful participants remained successful in later trials. Participants who were initially unsuccessful did not improve after receiving feedback. Instead, they continued to perform just as poorly after receiving corrective feedback. This suggests that poor performance demonstrated by most participants was not due to a lack of understanding of the task demands. The training trials adequately familiarized participants with the expectations and structure of the paradigm.

These data imply that participants who performed poorly likely lacked the necessary neural machinery to complete the task. In other words, even though we provided repeated and explicit instructions children could not keep track of each object's history because this ability requires specific neural structure to support adult-like episodic encoding that is not yet fully developed in the brain at such a young age. In fact, the substructures of the hippocampus that are implicated in high resolution relational binding (e.g. Dentate Gyrus) exhibit the lengthiest developmental trajectory of all the hippocampal subfields extending even into middle childhood (Lavenex & Banta Lavenex, 2013). Most participants younger than 3 years of age performed at chance even after we provided them with multiple trials of explicit feedback. This suggests that success may necessitate high resolution relational binding abilities that require mature hippocampal circuitry that is not immediately available to toddlers and early preschool aged children. Future research will expand the age range of participants and explore the neurobiological origins of relational binding through time using fMRI. Neuroimaging studies will provide clear evidence for the neural mechanism proposed here because they will allow us to directly examine hippocampal activity as participants track object histories and compare this to relational binding processes.

However, it should be noted that we only tested a particular kind of feedback in this study: we reinforced accurate responses and corrected inaccurate responses. It could be that this form of reinforcement-based feedback was inadequate and a different type of guidance is necessary to bolster performance of initially unsuccessful participants. Another strategy to potentially improve performance would be to actively provide children to provide additional cues to alleviate some of the memory demands. For example, during the animation of the color transformation from blue to red to blue and while taking the ball out of the box, the experimenter could have verbally emphasized the “yumminess” (e.g. by saying “Look it is yummy! This one is yummy! I am going to put the yummy food here!”). The same process could be repeated for the “yucky” food as well (e.g. Look it is yucky! This one is yucky! I am going to put the yucky food here!”). This strategy could also be implemented in the training phase. That is, rather than waiting for the color change animation (from blue to red or yellow) is complete to label the “yummy” and “yucky” food, we could label the objects during the transformation. By providing verbal cues we would attenuate some of the burden on the participants’ memory system because the participants would not have to use the semantic mapping between the color change and the type of food in conjunction with episodic memory for the particular transformation to infer “yumminess”. Instead, they would just have to remember the location of the ball designated by the experimenter as yummy. While this would negate the need to track the changes in state of each object, it would still assess whether or not the children could differentiate between 2 perceptually identical tokens. While this would not necessarily entail tracking the histories of state change, children would still have to track each object's history in that they would have to remember where the object labeled as yummy had been placed. In addition, we only provided 4 trials of feedback, younger children may have needed more repetitions in order to benefit from the feedback. But, despite the limited scope of our conclusions, the fact that performance was not impacted by additional feedback in our task still provides evidence in support of a shared mechanism for representing episodic details in the spatial and temporal domains.

Precision of encoding across trials

Initially successful participants tended to become less successful with repeated trials and in general, children became fussier over time. The deterioration in performance in our task could be attributed to interference from prior trials and the preschoolers' limited capacity for attention. Even though the entire session (including both training and test trials) was very brief, lasting only around fifteen minutes and blind coders also indicated that participants consistently attended to the stimuli during each trial and the few trials where children were judged as inattentive were excluded from the analysis this task placed high demands on preschoolers limited attentional resources. In every trial of our task, the objects were unique (different blue balls) but the correct response was always determined by the same type of transformation (the red color change). The order of the transformations and corresponding spatiotemporal trajectories of the objects (the side each ball was placed) were unpredictable from trial to trial. This means that even though all trials had the same structure, each trial was unique. Within each trial, participants had to discriminate between highly similar objects on the basis of their histories within the current trial while inhibiting interference from an increasing number of highly similar previous trials. That is, relative to the current trial, prior trials overlapped in task demands, involved objects that looked similar and possessed similar histories, occupied the same spatial context, and took place near in time.

Later test trials may require increasingly precise token representations capable of standing up to interference from previous highly similar trials which may place a high demand on the children's waning capacity for attention and inhibition. Therefore, it is not surprising that most participants around 3.5 years of age performed above chance initially and deteriorated over time. This also may explain why only two participants, both of whom were 52 months of age, remained consistently successful across trials, with one of those participants able to select the correct object in every single trial.

Conclusion:

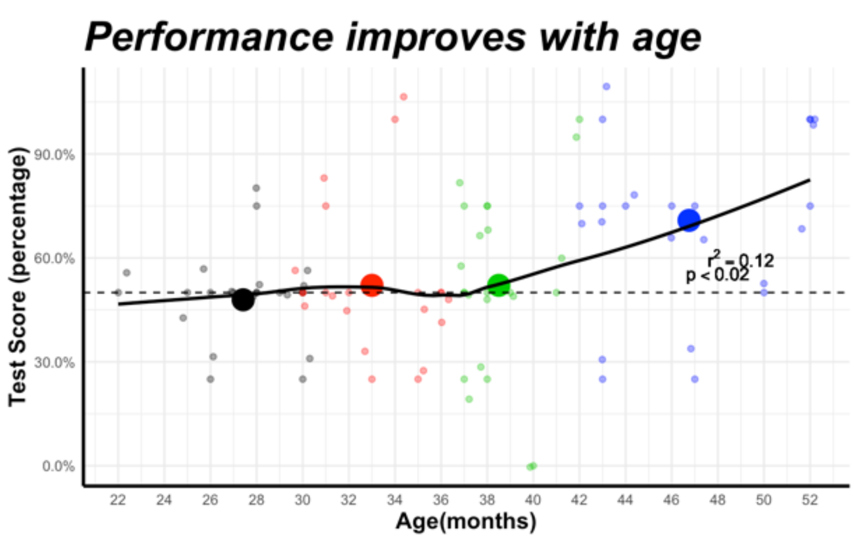
Events entail objects that undergo change. Previous research on object individuation reduces the contents of object representations to number and type-membership. This highly constrained framework for object representation fails to account for tokenization because it does not consider the history of the object independent of its current state. The current research has shown that in order to accurately represent the particular objects (the tokens) we encounter, we must form object representations that extend beyond what is necessary for individuation. We must represent each object in terms of its unique episodic history. The purpose of this work has been to show how, on the one hand, research thus far has not considered this aspect of individuation, or "tokenization", and on the other how the emergence of ability to represent tokens capable of accumulating episodic histories and individuate objects on the basis of those histories is amenable to empirical investigation.

In conclusion, this research sheds new light on complex cognitive processes that contribute to our ability to form flexible and precise representations that capture the idiosyncratic properties of episodic experience. These data suggest that during the early preschool years, children develop a fragile propensity to form token representations capable of accumulating an episodic history. The developmental trajectory for tokenization observed here implies that the relational binding mechanisms that underlie representations of the spatial relations between the objects within an episode may also support representations of object histories through time. Future research will dig deeper into the neural and developmental origins of the spatial and temporal aspects of episodic experience.

Appendix A: Additional Analysis of Trials 1-4

In addition to our GLM analysis, we also tested the fit of a nonlinear model. We hypothesized that these data may be better described by an exponential function because the relationship between the participants' age and raw scores appeared somewhat curvilinear. However, our regression analysis of test score on log transformed age revealed that that the application of a nonlinear (exponential) function of the relationship between age and test score did not fit the data any better than the GLM. Fitting a nonlinear function to the regression equation accounts for almost the same amount of variance as the linear function ($F_{(1,46)} = 6.17$, $p = .017$, $R2 = .12$; Figure A1). The standard error of the variance explained by the residuals in the nonlinear regression (Res. SE = 0.2202) is equivalent to the residual standard error of the linear regression equation (Res. SE = 0.2186).

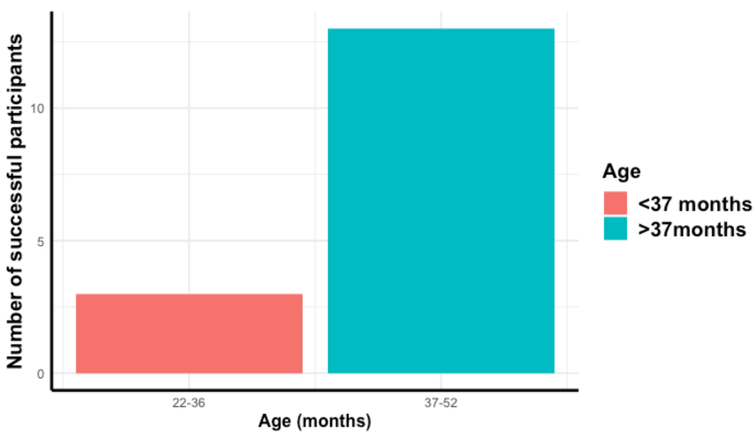
Figure A1: Testing a nonlinear relationship between age and test score on trials 1-4



The black regression line models an exponential relationship between age (log transformed) and individual test score. The trend line closely corresponds to mean score for each age quartile (large colored dots). The scores for each individual participant are represented by the small colored points. The dotted line at y = 50% represents chance performance.

We also performed a chi^2 analysis on the 2 age groups (<37 months: M = 30.3 months, range = 22-36 months, n = 24; >37 months: M = 42.6 months, range = 37-52 months, n = 24) due to the high probability of selecting the correct object by chance (50%) and small number of trials. This chi^2 analysis allowed us to see if the proportion of successful participants differed between groups. The criterion for success is defined as a score greater than or equal to ¾ or 75%. Significantly more participants in the older group(>37months) demonstrated success in the first 4 test trials compared to the younger group (X2(1, N = 48) = 9.38, p=.002, figure 2A).

Figure A2: Age group differences in the number of successful participants



This graph shows differences in the number of successful participants in the younger age group (<37 months) and the older age group (>37 months). Only 3 participants younger than 37 months of age scored ¾ (75%) or greater on trials 1-4. Whereas a total of 13 participants older than 37 months correctly responded on at least 3 out of 4 of the first 4 test trials. Chi^2 analysis confirmed age group differences in test success (X2(1, N = 48) = 9.38, p=.002).

Appendix B: Additional analysis of the impact of feedback on performance

We examined changes in performance before and after feedback for initially successful and initially unsuccessful participants in the feedback group separately. Additional paired sample t-tests indicated that participants who scored at chance in trials 1-4 (N=21, Mean age = 32,4, Mean pre-feedback score: 44%) continued to perform at chance in trials 5-8 (M = 48%; t(20)=-0.6, p=.72) and in the post feedback trial set (M = 49%; t(20)=-0.24, p=.59). Only 3 of the 21 initially unsuccessful participants achieved a score above chance in trials 9-12.[6]

Paired sample t-tests also revealed that participants in the feedback group who scored above chance in trials 1-4 (N=7, Mean age = 42.9, Mean pre-feedback score: 82%) continued to score above chance in trials 5-8 (M= 64%; t(6)= 2.08, p = .04) and in the post-feedback trials (M= 68%; t(6)=2.5, p=.023). Although these initially successful participants remained successful in the last set of 4 trials, it should be noted that the average score did decrease from 82% in the pre-feedback set to 64% in the post-feedback set. In addition, only 4 of the 7 initially successful participants actually remained successful after the first set of 4 trials. A follow-up Chi2 analysis confirmed that the number of successful participants in the first 4 ("pre-feedback") trials did not significantly differ from the number of successful participants in the last 4 "post-feedback") trials (X2(1, N = 28) = 2.1, p=.147). However, this does not mean that all initially successful participants remained successful. In fact, only 4 of the 7 initially successful participants continued to be successful on the "post-feedback" block of test trials. In addition, only 3 out of the 21 initially unsuccessful participants achieved success in the final block of trials after receiving feedback.

[6] The same 3 initially unsuccessful participants that became successful in trials 9-12(post-feedback) were also successful in trials 5-8.

Participants who initially scored at chance were not likely to improve after feedback. Older participants were more likely to be initially successful and remain successful across repeated trials. Although older participants that scored above chance initially were more likely remain successful across subsequent trials, they tended to become less accurate in later trials regardless of whether or not they received feedback.

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