

Hidden symbols: How informal symbolism in digital interfaces disrupts usability for preschoolers[☆]



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ARTICLE INFO

Article history:

Received 27 April 2015

Received in revised form

11 March 2016

Accepted 13 March 2016

Communicated by E. Motta

Available online 18 March 2016

Keywords:

Children

Child–computer interaction

User interfaces

Interaction design

Dual representation

ABSTRACT

Linking a symbol to the object it represents is a skill that develops gradually over the first few years of life. However, prior work shows that frequent use of this capacity makes it unintuitive for adults to recognize it as a challenge for young children. We hypothesized that this disconnect would manifest in software interfaces designed for young children, such that applications would embed symbols that the target audience would fail to understand. We conducted a randomized controlled trial with 34 preschoolers between the ages of 2 and 5 to assess their ability to work with user interface elements that require symbolic mappings. In particular, we assessed, (1) symbolic progress bars and (2) demonstrations of touch interactions by an on-screen cartoon hand. We found that these techniques are entirely inaccessible for children under 3 and that they require specific design choices to facilitate understanding in children between the ages of 3 and 5. Among a sample of 94 popular apps targeting children in this age range, we found that these symbolic techniques are incorporated into 44% of apps for preschoolers. We further found that embellishing symbolic elements with visual detail, a common practice in apps for preschoolers, increases children's cognitive burden and is an additional barrier to performing the symbolic mappings necessary to use these interfaces. We present design alternatives that make these prevalent user interface elements accessible to this user group.

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1. Introduction

More educational mobile and tablet applications are designed for children under 5 than for any other age group (Shuler et al., 2012), yet designers targeting young children routinely draw on design paradigms developed for adult users. While some design choices may work well for users of all ages, prior work has shown that not all standard interaction patterns are appropriate for technology's youngest consumers (Hourcade, 2008).

In this investigation, we examine common interaction techniques in mobile applications for children that expect users to understand symbolic representations. Mapping a symbol to its referent requires simultaneous mental representations of the symbol, the referent, and the link between them, and forming such representations is a skill that emerges over the first few years of life (DeLoache et al., 1997). Despite the mental gymnastics that go into such a feat, adults interpret symbols so frequently and automatically that it is unintuitive for

adults to think of this as a capacity that must be acquired (Uttal, 2003). For example, adults using a globe easily understand the globe to be both: (1) a physical object in its own right and (2) a symbolic representation of Earth, and they fluidly and automatically link these two understandings. Given the ease with which adults perform symbolic mappings, we hypothesized that user interface elements designed by adults may often have an embedded and unintended assumption that this skill comes easily to users. Given prior work demonstrating that very young children struggle to perform these mappings (DeLoache, 1989), we further hypothesized that this assumption would make certain user interface elements inaccessible to children.

As evidence that this gap between adult and child understanding is counterintuitive, we conducted a preliminary investigation examining 94 popular apps for preschoolers for evidence of user interface (UI) elements that require symbolic mappings. We selected two common elements: (1) progress bars, where the fill in the progress bar symbolizes the child's progress toward a goal, and (2) on-screen cartoon-hand demonstrations showing the child how to interact with the UI, where the cartoon hand symbolizes the child's hand. We predicted that both would be challenging for preschoolers.

We then conducted an experimental study to evaluate young children's ability to interpret each of these UI elements. By

[☆]This paper has been recommended for acceptance by E. Motta.

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selecting two elements that are visually dissimilar, serve unrelated purposes, and demand differing interactions from the child user, we aimed to isolate the effects of symbolic representation on children's understanding and thereby draw conclusions about children's ability to work with symbolic UI elements generally. Given a significant body of prior work showing that the capacity for symbolic representation develops over several years with significant gains between the ages of 2;6¹ and 3;0 (DeLoache, 2004), we conducted this investigation with preschool children between the ages of 2 and 5. We assessed participants' ability to successfully interact with interfaces with and without symbolic representation and measured the extent to which manipulating this property influenced children's understanding of the functionality of these interface components. Over three experiments, we explored the following research questions:

R1: Are toddlers and preschoolers able to interpret symbols commonly used in tablet applications for young children?

R2: How does this ability change with age?

R3: What are the design implications of children's emergent capacity for interpreting symbols?

To date, this broadly relevant challenge for young children has not been translated into concrete design recommendations for digital interfaces. Though others have speculated that children's challenges with symbolic representation could affect their ability to use digital interfaces (Antle, 2007; Hourcade, 2008), to our knowledge, this is the first empirical investigation to assess the challenges that common UI elements pose to children who have not yet acquired this capacity. We also provide the first documentation of the extent to which these challenges are disruptive to these child users and how designers can best support this user group.

2. Related work

2.1. Designing interfaces for adults versus children

A large body of prior work has investigated the ways in which interfaces can best accommodate the physical and behavioral needs of children, contrasting these design principles with those used when building interfaces for adults. Preschoolers benefit from touchscreen interfaces more than adults (Scaife and Bond, 1991), as they struggle to use mice and keyboards but can use direct-manipulation touch interfaces and master simple gestures as early as age 2 (Aziz et al., 2013; Hourcade et al., 2015). Children's gesture-performance and touch interactions improve steadily between the ages of 3 and 6, though adults are still 30% more successful in performing gestures than children in this age range (Vatavu et al., 2015). One study documented that at age 4, children were able to learn and successfully perform all of the seven common touchscreen gestures the researchers attempted to teach them: tap, flick, slide, drag and drop, rotate, pinch and spread (Aziz et al., 2013). Children in this age range (3–6) are also capable of learning to use a stylus, though they still suffer from usability issues that adults do not face (Couse and Chen, 2010). Other work demonstrates that between the ages of 8 and 11, school-aged children approach adult-like maturity in their performance of basic one-handed gestures such as tap, drag, swipe, and pinch (Aziz et al., 2013; Rust et al., 2014), but that even older children and teens still perform complex and custom gestures less skillfully than adults (Anthony et al., 2012; Brown and Anthony, 2012).

In addition to work examining children's physical usability challenges, other HCI research has examined the cognitive disparity between adults and children and its impact on their use of interfaces. McKnight and Fitton (2010) evaluated the effectiveness of interface-embedded language and terminology choices in written and audio instructions for 6- and 7-year-olds. They report that at this age children are unfamiliar with touchscreen terms such as "select" or "press and hold," but are able to understand terms with real-world applicability, such as "slide" and "swipe." Based on their analysis, the research team developed a set of design guidelines for creating mobile device interfaces for children age 7–10 (McKnight and Cassidy, 2010). Other prior work has documented common ways in which websites are inaccessible to children between the ages of 3 and 5 (Gutierrez et al., 2015), difficulties that preschoolers have in responding to prompts to perform specific interactions (Hiniker et al., 2015), and struggles of school-age children in deciphering search results (Druin et al., 2009). Our work builds on these prior investigations by studying a known cognitive difference between young children and adults that has not yet been explored from the perspective of HCI.

2.2. Interaction design and theories of child development

When designing interfaces for children, existing theories of child development can provide valuable guidance (Wyeth and Purchase, 2003), and extensive, concrete design implications have been drawn from developmental theory (Chiasson and Gutwin, 2005). For example, Piaget's constructivist learning theory was the foundation of Papert's constructionism and has been the basis of numerous educational technologies (Blikstein, 2013; Kafai and Resnick, 1996). Gelderblom and Kotzé (2009) extracted 10 principles of interaction design for children by broadly scouring literature on child development and educational theory, distilling recommendations such as enabling children to go directly to their favorite parts of a system to repeat favorite content, and designing with the assumption that young children will not remember audio instructions. Hourcade (2008) provides a survey of both child development and design principles for children's technology in his highly cited manuscript, "Interaction Design and Children."

Researchers have used such implications for design to inform the creation of novel technologies. Ryokai and colleagues developed e-books that incorporate elements of pretend play, an evidence-based practice for nurturing social and emotional development (Ryokai et al., 2012). Antle (2007) created the Child Tangible Interaction framework (CTI), which supports developers in creating digitally enhanced manipulatives for children under 12 and accounts for developmental changes in spatial awareness, embodied cognition, and understanding of semantics that children acquire as they grow. Others have leveraged Vygotsky's "zone of proximal development" as theoretical grounding for the creation of virtual agents, digital tools which assist children in performing tasks they understand but cannot yet perform without assistance (Marco et al., 2009).

We leverage this well-established approach by applying the *dual representation* theory of symbolic understanding (described next), and prior knowledge of its developmental trajectory, to the design of visual interfaces. By assessing children's ability to work with standard digital interface elements that employ symbolic constructs, we are able to define guidance for designing to accommodate young children's emerging abilities in this area.

2.3. The theory of dual representation

An extensive body of prior work by DeLoache and colleagues demonstrates that the ability to mentally maintain a symbol, its referent, and the mapping between them is a skill that develops

¹ We follow traditional linguistic notation where age is reported in yy;mm format (e.g., 2;6 represents 2 years and 6 months) (Baron, 1993).

gradually throughout the first years of life (DeLoache, 2004, 1995; DeLoache et al., 1997). A significant inflection point occurs between the ages of 2;6 and 3;0, when children typically acquire a stable understanding of the fact that a symbol can stand in for a referent other than itself (DeLoache, 1987). This ability to interpret an object as both an entity in its own right and a representation of something else has been termed *dual representation*, and acquisition of this skill represents a critical leap in children's cognitive development (DeLoache et al., 1997).

These classic investigations demonstrate, for example, that very young children cannot relate a scale model to an identical larger room, even after numerous explanations and demonstrations by researchers. After watching a researcher hide a large doll in a large room, children under 3 are unable to find a corresponding small doll hidden in a corresponding part of a scale model of the room, and vice versa (DeLoache et al., 1997). Though children are told in these experiments that the scale model is a representation of the large room and that everything in the large room is exactly the same as everything in the small room, this information proves insufficient to support children under 3 in maintaining a link between the two constructs (DeLoache and Marzolf, 1995). Remarkably, when children of the same age are asked to perform the same tasks, they are able to do so successfully if they are told that a “shrinking machine” has turned the large room into the small room (or, working in reverse, turned the scale model back into the large room). By telling children that the two physical spaces are one and the same, rather than two symbolically linked objects, the task becomes trivially easy. At age two-and-a-half, children are able to perform the search handily once the requirement to maintain two simultaneous mental representations of a single symbolic object is removed. These results provide strong support for the theory of dual representation, as they demonstrate that all other aspects of the task are achievable for children in this age range.

Young children's inability to link a symbol to its referent has been replicated in a variety of contexts. Prior work demonstrates that children between 2 and 4 years old struggle to use anatomically correct dolls as representations of their own bodies (DeLoache and Marzolf, 1995), an activity that requires mapping between the child's body and the symbolic doll. Likewise, Troseth and colleagues demonstrated that 2-year-olds fail to make use of information presented by video, which requires symbolic mapping between on-screen items and their real-world counterparts (Troseth and DeLoache, 1998). Studies of children's ability to understand the difference between photographs and the items they represent (DeLoache, 1991; Flavell et al., 1990), interpret maps of locations with which they are familiar (Liben and Yekel, 1996; Uttal, 2000), and acquire formal alphanumeric symbolic systems (Gentner and Loewenstein, 2002; Uttal et al., 1997) are all consistent with this theory.

We build on this existing work by examining how children's struggles with symbolic representation in the physical world translate to digital interfaces. Like the shrinking room experiments, we isolate dual representation demands in our digital tasks in order to determine the developmental trajectory of this capacity in a digital context. We demonstrate the way in which prevalent UI elements place such demands on young children and present alternative interface designs that accommodate this early childhood challenge.

2.4. Dual representation and symbol salience

Prior work in child development further demonstrates that the difficulty of dual representation is influenced by the salience of the symbol as an object in its own right (DeLoache, 1995). Enhancing a symbolic object's status makes its use as a symbolic representation

more difficult to maintain. For example, by age 3, children are able to understand that a scale model can be a representation of a larger room, but giving children in this age range an opportunity to play with the scale model (as one might play with a doll house) increases its salience as a concrete object and impedes their performance when they attempt to draw inferences about the large room based on the model (DeLoache, 2000). By comparison, setting the scale model behind a glass wall such that children can only view it at a distance decreases its salience as a concrete object and enables younger children to successfully make use of the model as a symbolic representation of the larger room.

Similarly, in a reverse-contingency, forced-choice task where children chose between a larger and smaller set of candies knowing they would receive the set they did *not* select, children in this age were more successful when symbolic rocks stood in for the actual candies (Carlson et al., 2005). That is, it was easier for children to remember that a small group of rocks represented a large group of candies than it was to remember that a small group of candies represented a large group of candies. Because candy is a meaningful object in this context, it makes a poor symbol. Rocks have no special meaning in this task and are therefore easier to treat as representations.

Based on this literature, we hypothesized that a graphical treatment of UI symbols that embellishes them with visual detail will increase their salience as objects in their own right, increase the barrier to dual representation, and increase the challenge for preschoolers. We build on this prior work by investigating both the extent to which popular apps embellish the symbols they use and by manipulating the level of embellishment and evaluating its impact on children's understanding.

2.5. Dual representation and child–computer interaction

To date, the developmental trajectory of dual representation has received little attention as a guiding principle for the design of digital interfaces for children. Research in the design of physical manipulatives to teach young children mathematics has linked the demands of dual representation to design tenets for these objects (Pouw et al., 2014), bringing this topic into the realm of design. Others have demonstrated that young children fail to transfer knowledge from video to the physical world, leading to the implication that children view interfaces as concrete objects even in situations where they are intended to be representational (Troseth, 2003a). We build on these indications that the theory of dual representation has a role to play in interface design by identifying instances in which current interfaces demand dual representation and demonstrating the challenge that these existing elements present to users.

3. Hypotheses and preliminary work

3.1. Hypotheses

Based on the child development literature reviewed above, we formed three hypotheses about the ways in which children's age-dependent capacity for symbolic representation affects their interactions with digital interfaces.

H1: Very young children will be unable to effectively use symbolic user interface elements, such as progress bars and cartoon-hand demonstrations.

H2: As children acquire the capacity for symbolic representation between the ages of 2 and 3, they will become capable of successfully applying this understanding to digital interfaces. The ability to use symbolic visual elements will increase with age in

accordance with the established developmental trajectory of dual representation.

H3: Across this age span, children will be less successful interpreting symbols when they have high salience as meaningful components of the interface. They will be more successful interpreting symbols when they have minimal detail and their significance as stand-alone objects is diminished.

3.2. Preliminary work

To select the UI elements to evaluate in this investigation, we conducted a preliminary review of 94 semi-randomly selected apps for preschoolers that are available from the iTunes app store. We first reviewed this sample to identify common elements which we anticipated would necessitate dual representation. We then coded the entire sample for the prevalence of these techniques.

All apps in our review had been given the iTunes App Store's "Kids 5 and Under" designation, indicating that they were created for a preschool audience. To our knowledge, no straightforward mechanism exists for viewing all apps in the store and selecting from them randomly, thus we selected our sample by searching for lists of popular apps, looking at recommendations from Common Sense Media, reviewing award sites such as the Children's Technology Review and the Parents' Choice Awards, and looking at the apps featured by iTunes in an attempt to find a diverse set of apps likely to have large user bases. We chose 94 unique titles created by 68 unique app developers. These spanned a variety of categories and included a mix of educational and entertainment content. Though we did not review apps from other app stores, we did examine Google Play to determine whether the apps we sampled were available from this marketplace as well. Of the apps we reviewed, 54% were also available from the Google Play store, suggesting that the design choices we encountered in our sample are likely to surface in marketplaces other than iTunes.

Each researcher independently played through 10–15 of these apps, documenting any symbolic user interface elements that he or she encountered using an open-coding technique (Hsieh and Shannon, 2005). The research team then discussed the symbols they encountered as a group to identify themes of symbolic UI elements. We then selected two interface elements common in tablet applications: progress bars (see Fig. 1) and cartoon-hand demonstrations (see Fig. 2). We chose to assess these elements, first, because of their clear conformity to the symbol-referent paradigm which is necessary to create the demand for dual representation. Second, we felt that both elements were potentially non-obvious symbols. Unlike letters, words, and numerals, which compose formal symbolic systems and require an understanding of systems of notation, the mapping between a progress

bar and a user's progress, or a cartoon-hand demonstration and the user's touch interactions, stand alone as ad hoc instances of symbolism that may be less obvious to designers.

Next, we systematically evaluated the prevalence of these two interface elements across the entire sample to determine whether these emergent themes were in fact pervasive across apps. Though we did not attempt to determine whether they were the most prevalent symbols in the apps we sampled, we wanted to understand if these would be UI elements that children would be likely to encounter routinely.

To do this, each researcher first, played through each of the 10–15 apps that he or she originally examined, this time in more detail. More detailed play included reviewing menus and sampling multiple levels, exercises, and mini-games. The researcher noted any instances of visual progress tracking. "Progress tracking" was defined as visual state change that was persistent (in contrast to fleeting feedback) and reflected incremental changes toward a goal. The research team collectively found that 57% of apps presented visual tracking of users' progress, and that 57% of these progress-tracking apps (or 38% of apps total) used a symbolic tracker, such as accumulating a collection of stars after completing a series of mini-tasks or growing a garden of flowers by completing game levels. By comparison, a non-symbolic tracker maintains the user's progress through the manipulated items themselves; for example, the remaining tasks in a digital jigsaw puzzle are documented non-symbolically by the remaining pieces.

Of the apps that presented a symbolic progress tracker, 52% styled their tracker with minimal detail (such as a traditional abstract progress bar or a series of circles to represent pages in a book) while 48% embellished their tracker with visual detail. For example, in one app, each car in a Ferris wheel represents a math problem for a child to solve; in another, a series of small letters accumulates in the corner of the screen to represent the large letters a child is drawing in the center of the screen. Examples of apps with embellished (rather than abstract) progress tracking are shown in Fig. 3.

Next, we evaluated whether each app made use of a cartoon hand to demonstrate the actions the user should perform with his or her own hand. In addition to playing the apps and reviewing menus, our review also involved accessing demos and tutorials, intentionally playing incorrectly, and intentionally waiting for an extended period of time to give the app the opportunity to prompt the user in response to a lack of input. We found that 14% of apps made use of this technique. Across all 94 apps, 44% used at least one of these two symbolic techniques, incorporating either a symbolic progress tracker or a hand demonstrating gestures.

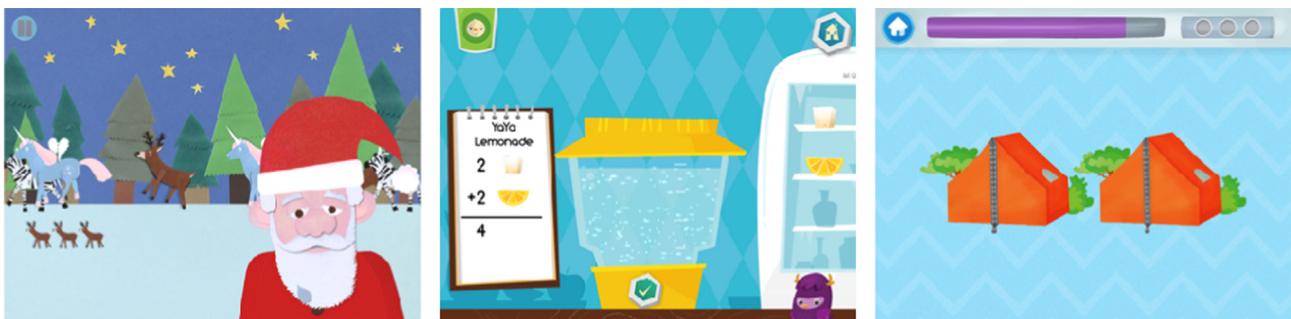


Fig. 1. Progress tracking in apps for children under 5. Left – A series of small reindeer at the bottom represent the large reindeer that the child has found on the top (screenshot from "Astropolo," © Les Trois Elles). Middle – The level of happiness expressed on a face in the top left corner tracks the number of drinks the player has blended (screenshot from "Moose Math," © Duck Duck Moose, Inc.). Right – A traditional progress bar tracks the amount of time the child spends on the task (screenshot from "Cookie Monster's Challenge," © 2014 Public Broadcasting Service).



Fig. 2. Example cartoon-hand demonstrations from apps for children under 5. Left – A hand demonstrates how to drag a crane to a matching train car (screen shot from “Thomas and Friends: Lift and Haul,” © 2015 Funny Garbage and HIT Entertainment Limited). Middle – Hands holding an iPad demonstrate how to shake the iPad to activate its accelerometer (screen shot from “Color Drops,” © Kid Baby Toddler 2013). Right – A hand demonstrates dragging one bubble to another to join them (screen shot from “Hungry Guppy” © Motion Math 2012).



Fig. 3. Symbolic progress trackers embellished with visual detail unrelated to the task. Left – The number of bubbles persistently floating on screen represents the number of puzzle pieces the player has placed successfully (screenshot from “Educational Animal Games,” © Antti Lehtinen). Middle – The number of decorative flags plotted on the landscape represent the number of mini-games the player has completed (screenshot from “TinyHands Towers 2,” © TinyHands). Right – The number of flowers blooming on the tree represent the number of shapes the player has identified (screenshot from “Leo’s Pad,” © Kidaptive, Inc.).

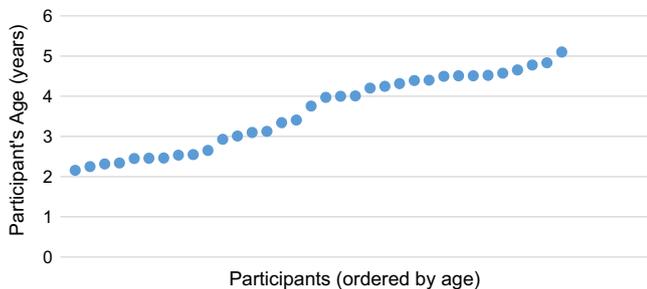


Fig. 4. All participants’ ages, ordered by age.

4. Methods

4.1. Participants and study site

We conducted this investigation at a private preschool in the city of Seattle for children between the ages of 1 and 5. School administrators sent a solicitation email to the families of all students. Parents of 41 children enrolled their child in the study. Two children under 2 were excluded due to limited language and inability to follow one-step directions. Of the remaining 39 children, 5 declined to participate when asked in person for their assent. A total of 34 children (35% male) between the ages of 2 and 5 (mean=3;7, sd=0;11) participated in this study. Fig. 4 shows the age of each participant. Our sample included four sibling pairs of different ages and one pair of identical twins.

We asked parents by email to report their child’s past experience with touchscreen technology. Of the 34 children who participated, parents of 25 (74%) responded, as shown in Table 1. All

Table 1

Participants’ prior touchscreen experience.

How often does your child use a touchscreen device?	
Never	3%
Less than once a month	6%
Less than once a week	21%
A few times a week	26%
Every day	12%
More than once a day	6%
No response	26%

parents who volunteered their child’s participation were given a \$5 gift certificate to Amazon as a token of appreciation.

4.2. Materials and procedures

We designed and implemented three tasks to assess children’s ability to navigate interfaces that require symbolic mappings. We developed all tasks for iOS using the Cocos 2D animation library (“Cocos2D-x: World’s #1 Open-Source Game Development Platform,” n.d.) and conducted the tasks on an iPad 2. Each participant completed all three tasks, and task-order was counter-balanced across participants.

All data were collected at school during the school day over a one-week period in December 2014. Data were collected during periods of free play in order to avoid disrupting structured parts of the school day, such as meals or naps. A researcher asked one child at a time if he or she would like to “be a helper” by “playing some games on a little computer.” If the child responded affirmatively, the researcher escorted him or her to a nearby office, away from

the distractions of the classroom. The researcher showed the child the iPad and asked if he or she had used one before. The researcher then supported the child in playing a warm-up app where the child could draw shapes on the iPad and pop them by tapping them. Once the child was successfully performing touch interactions with the warm-up app, the researcher moved on to the experimental procedures. All participants were able to easily navigate the warm-up exercise and were creating and “popping” shapes within a few minutes of exposure. The researcher sequentially guided the child through all tasks (described in detail below), with task-order randomly predetermined and automatically populated based on participant ID. After the child completed all tasks, the researcher thanked the child for his or her help and escorted him or her back to class. A second researcher took notes. We audio and video recorded all sessions, and each session took approximately 15 min.

4.2.1. Faucet task: testing symbolic representation

The purpose of this task was to assess participants' ability to interpret a progress bar as a symbolic representation of their in-app actions. We implemented two versions of a task in which the user must fill an on-screen cup with water by tapping a faucet positioned above the cup. In one version of the task (the “non-symbolic” version), the user can see into a transparent cup and can observe his or her progress directly (see Fig. 5a). In the second version (the “symbolic” version), a traditional progress bar tracks the level of water as the user fills an opaque cup (see Fig. 5b). The two versions of the interface were designed to, respectively, not require and require the user to form a symbolic mapping in order to track his or her progress. In both versions of the task, the user must make iterative progress toward a goal and detect when the goal has been achieved.

In both versions of the task, the only interactive item on the screen is the faucet. In response to a single tap from the user, the faucet handle lifts, and a short animation shows water pouring into the cup. When looking at the transparent cup, the user can see the water level rising, and it grows until it reaches the next demarcation (see Fig. 5a). When looking at the opaque cup, a progress bar at the top of the screen fills to the next demarcation (see Fig. 5b) immediately after the faucet-water animation has completed. In both cases, after a small amount of water has poured into the cup, the faucet handle then lowers and returns to the “off” position. While the animation is running, the faucet does not respond to touch input. After all animation is complete, the faucet again becomes interactive and in response to a new touch will again pour a small amount of water into the cup. In both versions of the task, the duration of the water-running animation was 2 s long.

All participants saw both the symbolic and non-symbolic version of the faucet task. Version-order was counterbalanced across participants. At the start of each version of the task, the researcher explained to the child that she wanted the child to fill the cup to the very top. She then explained that tapping the faucet one time would pour a little bit of water into the cup and that each time the child added some water the researcher would ask the child if he or she thought the cup was full or if he or she needed to add a little more. The child was then given access to touch the screen. Each time the child tapped the faucet the researcher asked him or her, “Do you think it's full, or do we need to add a little more water?” The researcher alternated between asking if the cup was full first or second in order to detect perseveration. After the child responded, the researcher followed up by asking, “How do you know?” regardless of whether the child replied affirmatively or negatively.

When the child reported that the cup was full, the researcher asked, “So do we need to add any more water?” If the child said no, the researcher went on to the next task. If the child said that more water was needed after the cup was full, the researcher allowed the child to tap the faucet again as many as 5 additional times, asking each time if the cup was full and how the child knew. If the child attempted to add water more than 5 times after the cup had been filled, the researcher informed him or her that it was time to proceed to the next game.

4.2.2. Progress-tracking task: testing the interaction between symbolic representation and visual embellishment

As prior work shows that children are less likely to interpret an object's symbolic meaning when it has high salience as a concrete object in its own right (DeLoache, 2000), we implemented a second task which assessed children's ability to interpret high- vs. low-salience symbols. We hypothesized that children would be more successful at interpreting a symbol when it had minimal visual significance than when it was embellished with visual detail and given high-salience as a standalone object.

We created four versions of a second progress-tracking task that varied along two axes (see Fig. 6): (1) non-symbolic or symbolic and (2) minimal detail or embellished detail. This yielded four distinct task versions: (1) a non-symbolic task with minimal details, (2) a non-symbolic task with embellished details, (3) a symbolic task with minimal details, and (4) a symbolic task with embellished details (see Fig. 6). Each of these is described in more details below.

(1) Non-symbolic task with embellished details (Fig. 6a)

(a) *Materials:* In this task, the child was presented with a scene in which a river is visible in the center of the screen, with two

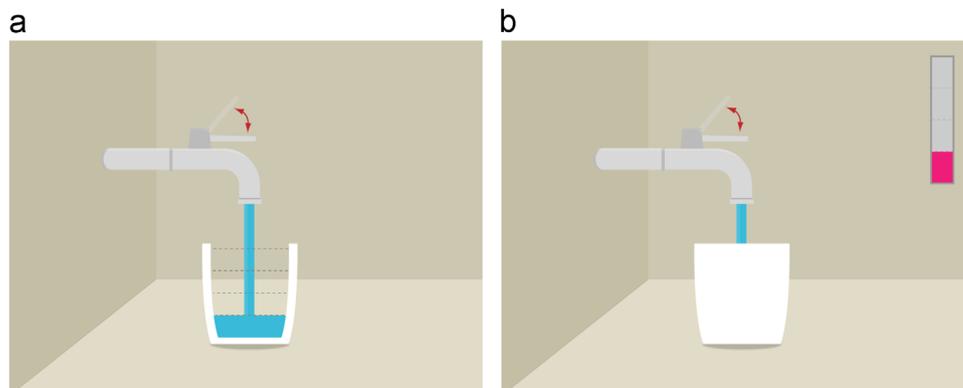


Fig. 5. (a) A transparent cup, the non-symbolic representation, fills in response to a tap on the faucet. (b) A traditional progress bar, the symbolic representation, fills in response to a tap on the faucet.

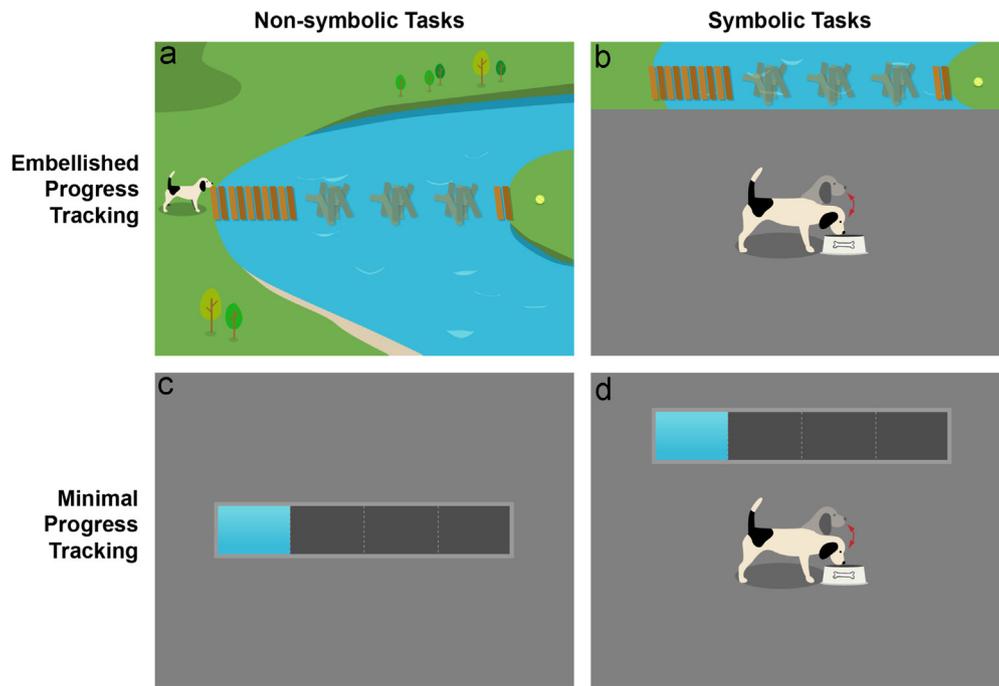


Fig. 6. (a) Non-symbolic task with embellished details: the user progresses in the task by tapping the piles of wood to construct a bridge to help canine protagonist, Luna, reach a tennis ball on the opposite side of a river. (b) Symbolic task with embellished details: the user progresses in the task by tapping Luna which causes her to eat. Each time she eats, a piece of the bridge above is constructed. (c) Non-symbolic task with minimal details: the user progresses in the task by tapping the abstract progress bar to fill it in, one segment at a time. (d) Symbolic task with minimal details: the user progresses in the task by tapping Luna which causes her to eat. Each time she eats, one segment of the abstract progress bar above is filled in.

banks on either side. On the left bank is a dog, on the right a tennis ball. Throughout the river are a series of piles of logs (between 3 and 5 piles, determined randomly when the task begins). Tapping a pile turns it into a set of planks that stretches across one section of the river. When all piles have been tapped, a complete bridge stretches from one bank to another, and the dog runs across the completed bridge to the ball.

(b) *Procedure*: The researcher showed the screen to the child and explained that the dog wants to play with her ball, but first she has to cross the bridge. The researcher further explained that each time the child tapped part of the bridge he or she would build a little bit of it. She explained that each time the child built part of the bridge, she was going to ask him or her if the bridge was all done if or if there was still more to do. Each time the child progressed in the task, the researcher asked, “Is it all done, or is there still more to do?” alternating the order of the two options to detect perseverance. Regardless of the child’s response, the researcher then followed up by asking the child, “How do you know?”

(2) Symbolic task with embellished details (Fig. 6b)

(a) *Materials*: A cartoon dog is visible in the center of the screen next to a bowl of food, and tapping the dog causes her to lower her head to the bowl and eat for 1 s, then raise her head. Above the dog is a river, two end-points of a bridge set on either bank. Throughout the river are a series of piles of logs (between 3 and 5 piles, determined randomly when the task begins). Each time the dog finishes eating, the left-most pile of logs transforms into a set of planks to form the next section of the bridge.

(b) *Procedure*: The researcher explained to the child that the dog would like to go outside and play with her ball, but that she cannot play until she has eaten all her dinner. The researcher further explained that the child could feed the dog a little bit by tapping her one time, and that each time the child fed the dog, the researcher would ask if the dog was all full or if she

needed to eat a little more. Each time the child progressed in the task, the researcher asked, “Is she all full, or is she still hungry?” alternating the order of the two options to detect perseverance. Regardless of the child’s response, the researcher then followed up by asking the child, “How do you know?”

(3) Non-symbolic task with minimal details (Fig. 6c)

(a) *Materials*: In this task, the child was presented with a scene in which a large progress bar is visible in the center of the screen, demarcated into either 3, 4, or 5 sections (with the number of sections determined randomly when the task begins). When a section of the progress bar is tapped, it animates to fill from left to right.

(b) *Procedure*: The researcher showed the screen to the child and explained that she needed the child’s help to fill up the entire shape. She further explained that the child could tap the shape to fill it up a little bit, and that each time the child filled up the shape a little more, she would ask the child if it was all full or if there was still more to do. The researcher then gave the child the chance to touch the screen. Each time the child tapped the screen the researcher would ask first, “Do we need to do more, or is it all full?” alternating the order of the two options to detect perseverance. Regardless of the child’s response, the researcher then followed up by asking the child, “How do you know?”

(4) Symbolic task with minimal details (Fig. 6d)

(a) *Materials*: A cartoon dog is visible in the center of the screen next to a bowl of food. Tapping the dog one time causes her to lower her head to the bowl and eat for 1 s, then raise her head again. Above the dog is a large minimalist progress bar demarcated into either 3, 4, or 5 sections (with the number of sections selected randomly when the task begins). Each time the dog finishes eating, the progress bar animates to fill to the next demarcation.

(b) *Procedure*: The researcher explained to the child that it was time for the dog to eat her dinner and that the child could

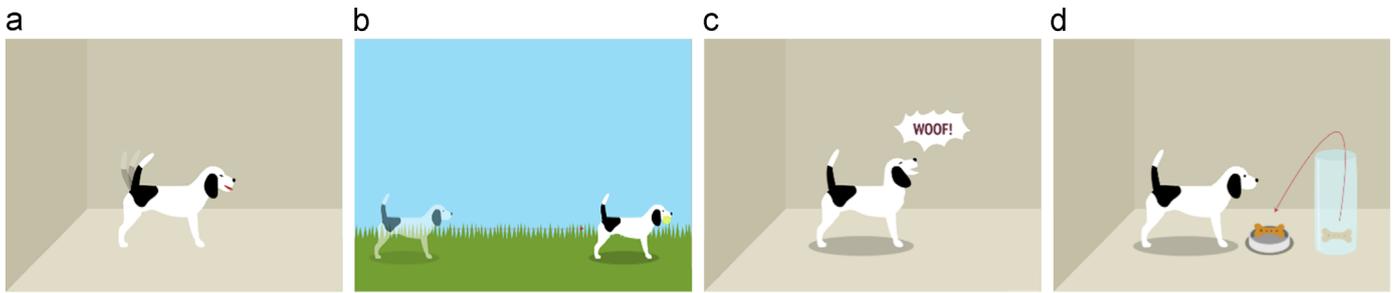


Fig. 7. Scenes. Each child saw a cartoon-hand demonstration for exactly one of four scenes. In each scene, exactly one gesture triggers a response: (a) Luna hangs out her tongue and wags her tail when double-tapped, (b) Luna runs across the screen and picks up her ball in response to a horizontal swipe, (c) Luna barks in response to shaking the iPad, and (d) a treat hops out of treat jar in response to a vertical swipe.

feed the dog a little bit by tapping her one time. The researcher further explained that each time the child fed the dog, the researcher would ask him or her whether he or she thought that the dog was full or still hungry. Each time the child progressed in the task, the researcher asked, “Is she all full, or is she still hungry?” alternating the order of the two options to detect perseveration. Regardless of the child’s response, the researcher then followed up by asking the child, “How do you know?”

To minimize learning effects, each participant saw two of the four possible tasks. He or she saw either (1) the non-symbolic-minimal task and the symbolic-embellished task or (2) the non-symbolic-embellished task and the symbolic-minimal task. In this way, each child saw exactly one symbolic task, one non-symbolic task, one minimal task, and one embellished task, without seeing any similar scenes. Task order was counter-balanced across participants.

4.2.2.1. Gesture task: testing symbolic representation in an unrelated context. Finally, to better understand whether our results are specific to progress bars or generalize to a variety of dissimilar symbolic user interface elements, we implemented a task to assess children’s ability to interpret symbols in an unrelated context. In this task, we measured children’s ability to recognize an on-screen demonstration by a cartoon hand as a symbolic representation of the child’s own hand and the touch interactions he or she should perform. We also assessed children on their ability to follow in-app instructions in three related tasks that are discussed and analyzed in a separate paper (Hiniker et al., 2015).

In this task, we implemented four scenes in which exactly one unique gesture triggers an on-screen event. The cartoon dog “Luna” from the progress-tracking task appears in each scene, and executing the correct behavior causes Luna to perform a specific action. In one scene, a horizontal swipe causes Luna to run across a field of grass and pick up a ball on the other side. In another, a vertical swipe causes a dog biscuit to hop out of a treat jar and land in Luna’s bowl. In a third scene, shaking the iPad causes Luna to bark, and in a fourth scene, double-tapping Luna causes her to stick out her tongue and wag her tail (see Fig. 7).

We specifically chose gestures that were relatively uncommon in the applications we evaluated in our initial app review to reduce the likelihood of a child already knowing to try such a gesture based on experience. We also chose gestures that would be difficult for a child to perform unintentionally before he or she had a chance to observe the prompt (e.g., we specifically did not choose a simple tap or flick gesture). We were also careful to choose gestures that would still be easy for a young child to perform once they knew what to do (e.g., we eliminated complex gestures such as tapping or dragging with two fingers (Aziz, 2013)).

Each child saw a cartoon hand demonstrate the correct gesture in exactly one of these scenes (see Fig. 8). Each participant saw a hand perform exactly one of the following gestures:

- **Double tap (Fig. 8a):** A cartoon hand with extended index finger fades into view over the dog, pauses, animates to a smaller size (to give the appearance of moving closer to the dog and farther from the user) and a pink dot appears momentarily under the tip of the finger when it has reached its smallest size (to indicate making contact with the dog). The hand animates back to its original size, and the shrinking animation is repeated to indicate a second tap. The hand again animates back to its original size and fades out of view.
- **Horizontal swipe (Fig. 8b):** A cartoon hand with extended index finger fades into view above the dog, pauses, then animates horizontally across the screen, pauses, and fades out.
- **Shake (Fig. 8c):** A cartoon image of an iPad with a scene identical to the one currently shown on the iPad fades into view. Two hands are gripping the sides of the iPad. After a pause, the image tilts repeatedly from side to side to give the appearance of the cartoon iPad shaking back and forth.
- **Vertical swipe (Fig. 8d):** A cartoon hand with extended index finger fades into view over the dog biscuit, pauses, moves to the top of the treat jar, pauses, and fades out.

The researcher began the task procedures by explaining that Luna can do tricks and that the child can figure out how to make her do these tricks. The researcher pressed a discrete button on the top-left corner of the screen to initiate the symbolic hand demonstration as the child watched. The researcher then asked, “What should we do?” and then gave the child the opportunity to experiment with the device.

Participants were not trained in any way or told what types of gestures to perform. At no point did the researcher suggest what to do (other than triggering the appropriate prompt). Participants only knew what gesture to perform by interpreting the prompt, performing trial-and-error, or possibly drawing on prior experience with other applications.

If the child asked the researcher for assistance, said that he or she was unsure what to do, or stopped experimenting, the researcher asked the child if he or she would like to try anything else. After the second time the child stopped experimenting with the iPad, the researcher asked the child if he or she was ready to move on to the next scene. If, at any point, the child performed a gesture successfully, the researcher praised the child and asked first, “How did you make that happen?” If the child described what he or she did (even if it was not an accurate description), the researcher then asked, “How did you know how to do that?”

4.3. Data analysis

For each subtask, we coded whether or not the child understood the message being expressed by the interface. In the two faucet subtasks, we evaluated whether each child understood when the cup was full. We coded a child as understanding

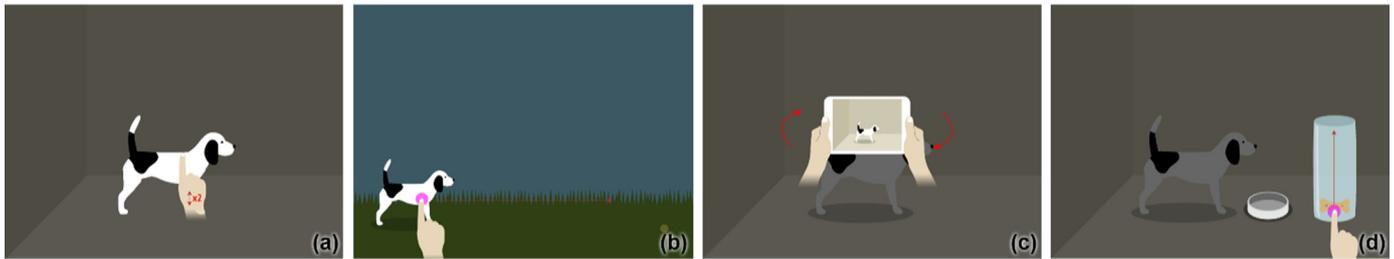


Fig. 8. Hand-prompts indicating that a user should perform: (a) double tap, (b) horizontal swipe, (c) shake, and (d) vertical swipe. Red arrows are annotations to show on-screen animation and were not visible to users. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

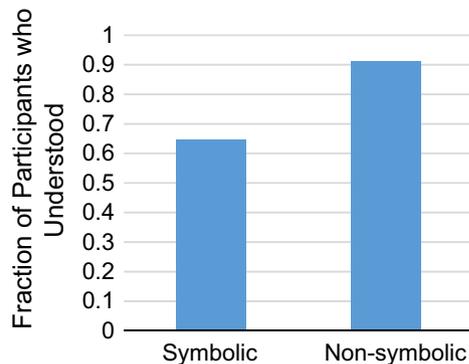


Fig. 9. Fraction of participants who understood the symbolic and non-symbolic versions of the faucet task.

whether the cup was full if he or she stopped adding water to the cup exactly after the correct number of taps without hesitation. Many of these children were able to answer the follow-up question of “How do you know [that it’s full]?” but some said things like “because it is” or “I just know.” In all cases where a child did not express certainty, he or she stopped at an incorrect point and did not answer the follow-up question of “How do you know?” In these instances, children most often continued adding water after the cup was full, but in three instances a child stopped early, saying the cup was full but was unable to explain why.

In the symbolic progress-tracking subtasks, we evaluated whether the child understood when Luna had had enough to eat. We coded a child as understanding a symbolic task if he or she repeatedly told us that Luna was still hungry while the progress tracker (either an abstract progress bar or a bridge) was partially filled and then told us that Luna was full as soon as the progress bar (or bridge) became completely filled. Participants who were coded as not understanding either did not answer the question of whether Luna was full or answered incorrectly or inconsistently (saying things like, “She’s full because she eats raw dog biscuits,” at a point when the progress tracker was only partially filled). These responses showed no relation to the progress tracker. Many of the children who answered correctly were also able to answer the follow up question of “How do you know?” when progress was tracked by the abstract progress bar. For example, they often pointed to the progress bar and said things like “because that’s full.” None of our participants were able to articulate the symbol-referent relationship when progress was tracked by the visually embellished bridge.

In the non-symbolic progress-tracking subtasks, we similarly coded whether the child understood when the task was complete based on whether he or she consistently responded correctly to our questions of “Is it [the bridge] all done or is there more to do?” or “Is it [the abstract tracker] all full or do we need to do more?” If the child responded that more was needed each time until the task

was complete and then told us that it was all done (or full), we marked the child as understanding.

In the gesture task, we evaluated whether the child understood that he or she should attempt to copy the actions of the cartoon hand. For each subtask, we again coded understanding as either 0 (did not understand) or 1 (did understand), using the same criteria.

Coding was performed via video analysis of session recordings. Two researchers each coded half of the data, spot-checking each other’s codes for agreement. A third researcher formally assessed interrater reliability by independently coding a randomly selected 20% of all data. Cohen’s κ was 0.842. Disagreements were discussed until consensus was reached.

5. Results

5.1. Faucet task

We documented whether each child understood the symbolic and non-symbolic versions of the faucet task (each recorded as “yes” or “no”). Because of our dichotomous dependent variable, we used a related-samples exact McNemar’s test to compare within-subjects’ understanding based on whether the task was symbolic, where the only observable changes were to the progress bar, or non-symbolic, where the child could see the water filling the cup directly. The proportion of children who understood increased from 0.65 on the symbolic task to 0.91 on the non-symbolic task, a highly significant difference ($\chi^2(1)=7.11, p=.004$). Fig. 9 shows the fraction of children who understood how to track their progress on each subtask.

As we hypothesized that children would be able to perform the symbolic version of the task only after acquiring the age-driven capacity for dual representation, we also examined the effect of age on performance. We created a repeated-measures binomial logistic regression model to assess the effect of level of symbolism (“symbolic” or “non-symbolic”) on understanding (“yes” or “no”) with age as a covariate. Because we hypothesized that our dichotomous coding of children’s understanding likely represents a hidden Gaussian, we used a probit link function. In this model, a Wald chi-square test again revealed a significant main effect of level of symbolism ($\chi^2(1)=6.612, p=.010$) as well as a significant main effect of age ($\chi^2(1)=15.192, p<.001$). It further revealed a significant interaction between age and level of symbolism ($\chi^2(1)=5.123, p=.024$). As predicted, very young children were unable to perform the symbolic task and made enormous performance gains between the ages of two-and-a-half and three-and-a-half. In contrast, even the youngest children were relatively successful in performing the non-symbolic version of the task. These task-dependent differences as a function of age are illustrated in Fig. 10.

5.2. Progress-tracking task

In the progress-tracking task, we measured how children's ability to understand user interface elements that were and were not symbolic changed when these elements were and were not embellished with visual detail. To determine the combined effects of symbolism and embellishment on children's understanding, we created a binomial logistic regression model with level of symbolism ("symbolic" or "non-symbolic") and level of embellishment ("embellished" or "minimal") as predictors of our dichotomous response variable, understanding ("yes" or "no"). We used a generalized estimating equation to account for the fact that each subject performed two different trials (and thus observations were not independent). To control for age-dependent differences, we included age as a covariate in the model. Because we hypothesized that our dichotomous coding of children's understanding likely represents a hidden Gaussian, we again used a probit link function.

In this model, a Wald chi-square test revealed a significant main effect of level of symbolism ($\chi^2(1)=21.649$, $p < .001$) on children's ability to understand the progress tracker, demonstrating that children were significantly more successful with non-symbolic versions of the progress-tracking task (in which they directly tapped a progress bar to fill it up or directly tapped piles of logs to build a bridge) than symbolic versions (in which they fed a dog to achieve these same effects indirectly). There was no significant main effect of level of embellishment ($\chi^2(1)=2.622$, $p=.105$).

This model further revealed a significant interaction between level of symbolism and level of embellishment ($\chi^2(1)=4.310$, $p=.038$). Pairwise comparisons between task types (see Table 2) revealed that embellishment had no effect on children's understanding of non-symbolic tasks, but it significantly impaired their ability to understand symbolic ones. Thus, while the addition of thematic visual detail to objects for children to manipulate directly had no effect on their comprehension, the addition of visual detail to symbols was a significant impediment. The fraction of participants who understood each of the four subtasks is shown in Fig. 11.

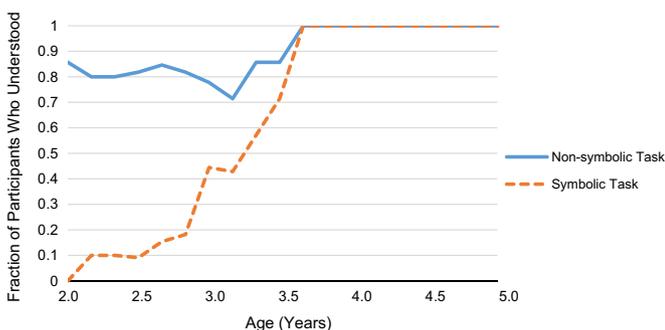


Fig. 10. Fraction of participants who understood the faucet task by task-type at each age. For smoothing, each data point represents a sliding window of 6 months on either side of the target age.

Table 2

Pairwise comparisons between each unique pair of progress-tracking subtasks.

Condition 1	Condition 2	Mean difference	SE	df	p	95% CI	
Non-symbolic minimal	Symbolic minimal	-.18	.135	1	.192	-.44	.09
	Non-symbolic embellished	.06	.097	1	.543	-.13	.25
	Symbolic embellished	-.71	.111	1	<.001	-.92	-.49
Symbolic minimal	Non-symbolic embellished	.24	.103	1	.022	.03	.44
	Symbolic embellished	-.53	.144	1	<.001	-.81	-.25
Non-symbolic embellished	Symbolic embellished	-.76	.109	1	<.001	-.98	-.55

We also examined the relationship between task performance and age by running point-biserial correlations to examine the relationship between each version of the task and age (see Table 3). We applied a Bonferroni correction to all correlations.

Across all ages, children understood the non-symbolic task with embellished details. Performance improved with age on all other tasks (see Fig. 12), but this age-dependent growth was only significant when children worked with the minimal symbol. Across all ages, children were relatively successful in performing the minimal, non-symbolic task, and relatively unsuccessful in performing the symbolic task with embellished details.

5.3. Gesture task

Finally, we examined children's ability to recognize an on-screen cartoon hand as a symbol of the user's hand. Across all participants, 50% of children successfully interpreted the hand as a symbol. A Fisher's exact test revealed no significant difference in understanding based on the type of gesture the child was prompted to perform (double tap, horizontal swipe, shaking, or vertical swipe) (Likelihood ratio=3.478, $p=.324$). We again examined the relationship between performance and age, and a point-biserial correlation revealed a highly significant association between these two measures ($r=.644$, $p < .001$). Fig. 13 shows performance on all four of the symbolic tasks plotted together.

5.4. Relationship to prior touchscreen experience

We examined the relationship between all subtasks (the symbolic and non-symbolic versions of the faucet task, the symbolic and non-symbolic versions of the progress-tracking task, and the gesture task) and parents' reports of children's prior touchscreen experience. Point-biserial correlations revealed no relationship between past experience and any of these measures (all r s < .29, all p s > .17).

6. Discussion

6.1. Dual representation and digital interfaces in early childhood

Through multiple angles, our results consistently show that, in early childhood, performing on-screen tasks that require dual representation is more difficult than performing equivalent tasks without such demands. In two unrelated experiments, children were more successful in tracking their progress when it was documented directly by the items they manipulated than when it was documented by a symbolic tracker. By leaving all components of the interface – touch interactions, graphical assets, animation, instructions from the researcher, and others – identical across tasks, we isolated a single symbolic user interface element and manipulated only its level of symbolism.

We found that the performance gap between symbolic and non-symbolic versions of these elements disappeared with age: while two-year-olds were only capable of performing the

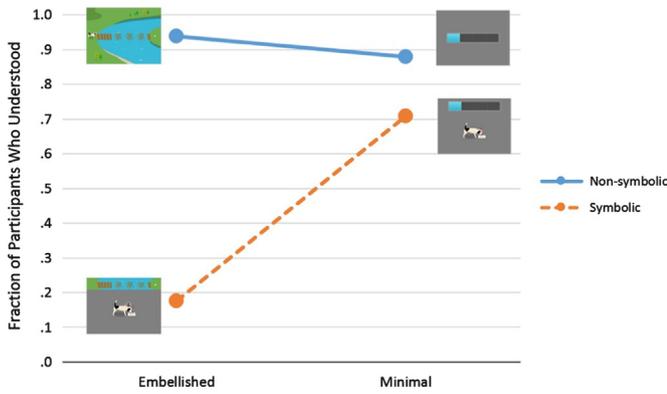


Fig. 11. Fraction of participants who understood each of the four progress-tracking tasks.

Table 3

Correlations between performance on variations of the progress-tracking task and age.

	Age		
	N	r	p
Non-symbolic minimal	17	.427	.087
Non-symbolic embellished	17	.412	.101
Symbolic minimal	17	.646	.005 ^a
Symbolic embellished	17	.496	.043

^a Significant after applying Bonferroni correction.

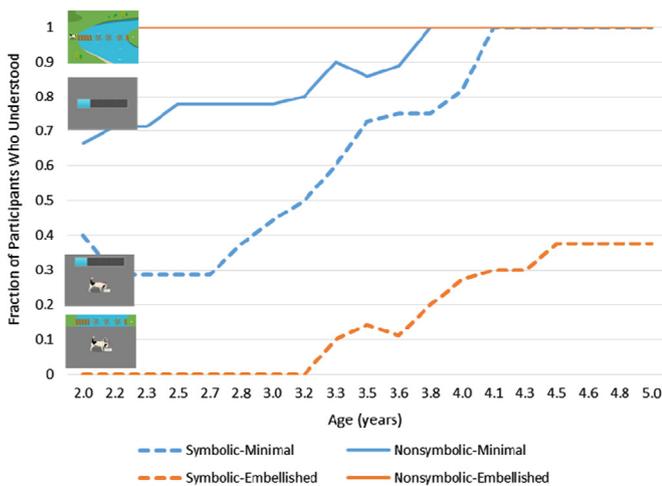


Fig. 12. Performance across all four progress-tracking tasks, by age. Children performed better on the non-symbolic tasks (solid lines) than the symbolic tasks (dotted lines). For smoothing, each data point represents a sliding window of 6 months on either side of the target age.

non-symbolic versions of our tasks, by age 4, children were equally successful in the symbolic and non-symbolic variants, and dual-representation demands no longer presented a barrier. Thus, symbolic representations in user interfaces do not deterministically add complexity for all preschoolers but instead appear to be problematic specifically for younger children who have yet to acquire the capacity for mapping symbols to their referents. We saw this same pattern of results when we asked children to interpret demonstrations by a cartoon hand as representations of their own hands and actions. Again, two-year-olds were unable to interpret the on-screen hand as a representation of their own

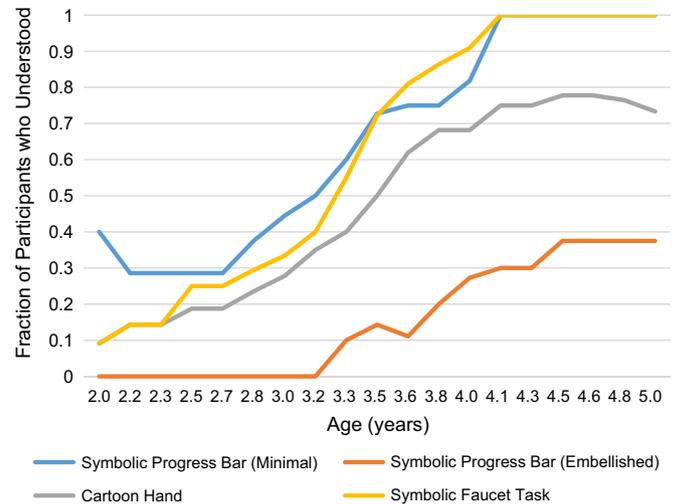


Fig. 13. Participants' understanding of symbols in unrelated contexts. Each line represents performance by age on one of our four symbolic tasks.

hand, but by age 4, children typically made this association instantly and spontaneously.

6.2. Embellishment in symbolic interfaces

Our results also reveal that, across this age range, embellished symbols are more challenging than minimal ones. This finding may be unintuitive for many, given that 48% of all symbolic progress trackers in the apps for preschoolers we reviewed as preliminary work were embellished with visual details that gave these symbols high salience as stand-alone objects. We found trees that flowered as children successfully completed tasks, a set of tiny passengers that populated the top of the screen as cartoon characters climbed aboard a train at the bottom, and tiny pictures showing a child performing various tasks that accumulated as the user completed different in-app activities.

While adding visual detail to connect a symbol to the greater theme of an application may instinctively sound as if it will scaffold children's understanding, our results document that the exact opposite is true: adding such details gives the symbol greater relevance as a concrete object and diminishes children's understanding. Embellishment increases dual-representation demands and increases the age at which these symbols become accessible. This phenomenon is at odds with current practices, even among highly regarded, award-winning educational apps, where symbols are routinely imbued with concrete, thematic detail. Our results suggest that designers targeting children anywhere in this age range should revisit the way user progress is tracked, the way touch interactions are prompted, and more generally examine their interfaces for presence of formal and informal symbols.

Prior work shows both that symbols become easier to understand as their salience is decreased (DeLoache, 2000) and that symbols become easier to understand as they become more superficially similar to their referents (DeLoache et al., 1999). Thus, dual representation theory predicts that interface symbols can be manipulated along either of these axes in order to reduce the age at which children can successfully interpret them. It also predicts that the most opaque symbols will be those which are both embellished and unrelated to their referents, a prediction confirmed by our results. Though this may appear, on reflection, to be an intuitive choice, our app review revealed that even the most distinguished children's apps routinely employ embellished symbols unrelated to their referents.

6.3. Implications for designing with symbols for preschoolers

That demos and progress bars both come with dual representation demands reflects the diversity of ways in which symbols can be incorporated into interfaces. When we think of “symbols” and the barriers they present to young children, it is easy to think exclusively of symbolic systems with formal notation, such as numbers or written words (Uttal et al., 1997). But accommodating the potential inability to read, write, and interpret numerals does not necessarily remove all symbolic demands. Interface symbolism requires only a link between one object and another, and it is possible to use any kind of informal object as a stand-in for something else.

Our results show that designers will best serve young users if they think broadly about all of the ways in which the interfaces they craft incorporate symbolism. Sliders, switches, maps, timers, rewards, avatars, physical accompaniments, and state-tracking of any kind all have the potential to introduce dual representation demands. Our app review of the two symbolic elements we tested with children – progress bars and hand demos – suggests that elements with the potential to act as symbols are pervasive and apps frequently use these interface components in symbolic ways. Our results indicate that the struggles our participants encountered are likely to generalize to a variety of interface components that child users routinely encounter. We propose a series of design principles for creating interfaces for young children that account for their emergent capacity for dual representation. Each of these is described in detail below.

1. *Maintain object-continuity in interfaces for children under 4:* In the early preschool years, symbolic interfaces of any kind are likely to be entirely inaccessible to users. DeLoache's shrinking room experiments suggest that one way in which designers can support these users is by creating the illusion that the symbol and its referent are in fact the same item, such as visually transforming mainline UI elements into peripheral representations to track progress. For example, below we present two possible techniques for creating trackers that conceptually mimic the shrinking machine. In the first example (Fig. 14), an app which expects children to trace one shape at a time and rewards successes with stars at the top of screen is redesigned to shrink each successfully traced shape into a smaller version of itself and move it to the edge of the screen as a permanent artifact documenting incremental progress. In this way, the visual transformation allows each item to serve as its own progress tracker, and symbolic stars are replaced with non-symbolic instances of the items of interest themselves.

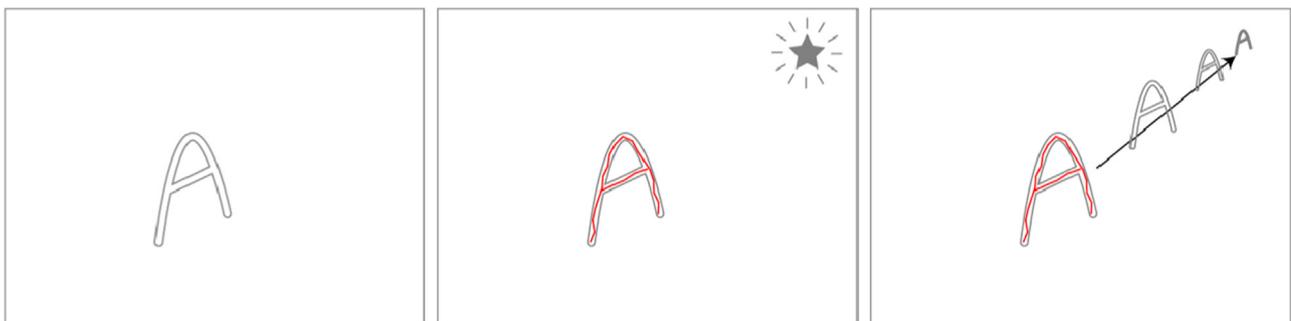


Fig. 14. Schematic designs for examples of symbolic and non-symbolic mechanisms for tracking progress. Left – an app presents a child with a letter-tracing task. Middle – in a symbolic design, the child's progress is tracked with a series of stars; he or she accumulates one star for successfully tracing the letter 'A.' Right – in a non-symbolic design, the child's progress is tracked with the letters he or she traces; he or she accumulates the letter 'A' itself, and after it is successfully traced, it shrinks down and moves to corner of the screen.

In a second example (Fig. 15), a sidebar with icons representing all of the passengers currently aboard a train (a feature of one popular app from our review) is redesigned so that open windows on the side of the train show profile views of the passengers. This allows the user to track the passengers directly and demands only that the user connect the visual of the passenger entering through the door of the train car to the profile view that appears in the window. Because this creates the illusion that the two visuals are a single entity, our results suggest that 2-year-olds would be able to perform this mapping without instruction. In contrast, our results suggest that they would be unable to perform a mapping between a passenger entering through the train door and an icon of his or her face at the top of the screen.

In both of these hypothetical apps, the redesigned interface employs a representation which collapses a progress tracker and the items it represents into a single entity, just as the shrinking machine creates the illusion that a scale model and the larger room it represents are a single physical space. Our results indicate that symbolic progress tracking is inappropriate for children under 3, but that visual effects that allow UI content of interest to double as a tracker will enable very young children to follow their own progress as they work toward a goal.

2. *Remove visual embellishment from symbols:* As children begin to acquire the capacity for dual representation between the ages of 2-and-a-half and 3-and-a-half, they also gain an emergent ability to apply this skill to the interfaces they navigate. Thus, with appropriate design choices, it is possible for app developers to create symbolic interfaces that 3- to 4-year-olds can use successfully. Further, because cumulative exposure to symbols speeds children's acquisition of this critical skill (Marzolf and DeLoache, 1994; Troseth, 2003b), creating opportunities for 3-year-olds to perform simple symbol-referent mappings provides valuable educational experiences for these users. Thus, despite the fact that children's capacity for dual representation is still developing, apps can provide value to this user group by selecting symbolic elements with care, rather than avoiding them altogether.

We show here that removing embellishment – in particular, embellishment that is unrelated to the target that the symbol represents – is one highly effective means of supporting children who have a limited capacity for forming symbolic mappings. All of our 4- and 5-year-old participants completed the symbolic faucet task successfully. However, the embellishment that is common in children's applications was an enormous barrier for this same subset of our participant pool. App designers targeting children in this age range can expect them to reliably link minimal, readily apparent symbols to their referents and should feel comfortable incorporating standard

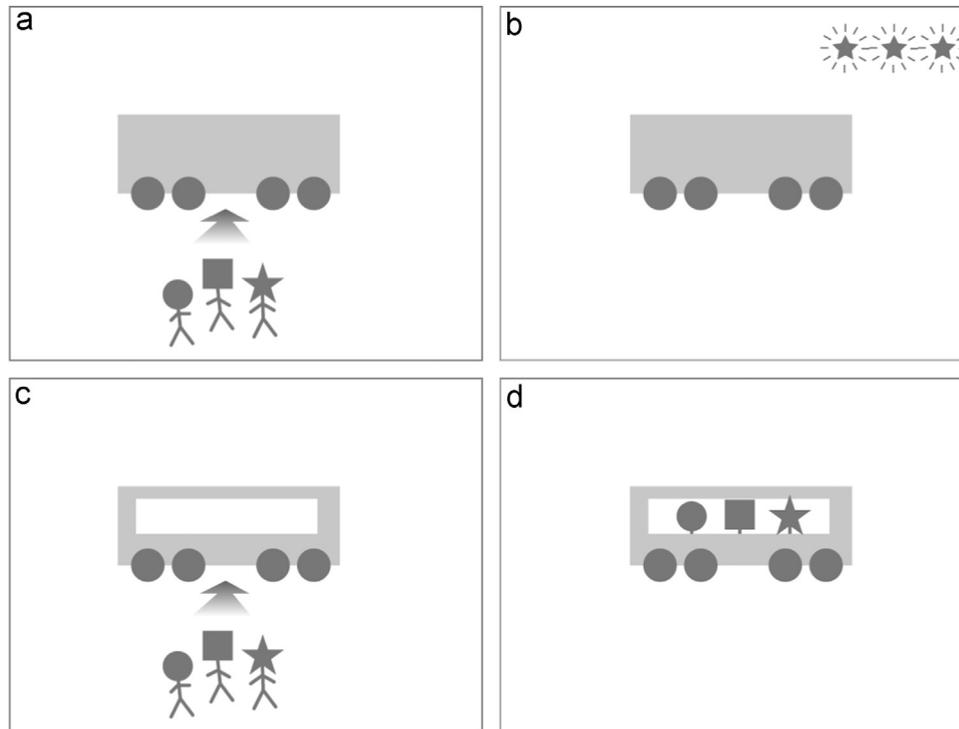


Fig. 15. Schematic designs for examples of symbolic and non-symbolic progress tracking: (a) before and (b) after pictures show a scene where a child helps passengers board a train. Each passenger he or she collects is represented by a symbolic star (similar to an example from our app review). (c) Before and (d) after pictures show a scene where a child again helps passengers board a train; this time their on-board status is represented non-symbolically and the user can see them through the window.

progress bars into their interfaces. However, they should avoid the temptation to decorate these progress bars with playful imagery unrelated to their referent which, in giving the symbol a life of its own, diminishes its symbolic status.

3. *Call attention to the link between a symbol and its referent:* In contrast to embellishment, design choices that downplay a symbol's significance as a standalone object and increase its salience as a representation make a symbol more accessible. Highlighting the link between the symbol and its referent or providing an explicit statement pointing out this relation (e.g., "Move your hand just like this one!") can also scaffold dual representation for these early symbol users (DeLoache, 1989). Explicit statements explaining that the link is intentional, and that an agent created this mapping (e.g., "I'll add a star each time you finish tracing a letter!") support 3-year-olds in noticing symbols they would otherwise miss (DeLoache, 2011).
4. *Maintain visual similarity between symbol and referent:* Prior work shows that young children become increasingly more likely to identify a symbol–referent relationship as the symbol becomes more like the object it stands in for (DeLoache et al., 1999). Thus, designers can support children by using symbols that look like their referents.

Though we derived these principles based on our investigations with two specific types of UI symbols – progress trackers and hand demonstrations – they are applicable to many different interface elements, and designers should look to these guidelines when creating any kind of symbol in an interface for young children. For example, while an adult user can easily interpret that a thought bubble over a character's head represents an idea inside the character's mind, a 2-year-old will be unable to form this mapping. While an older child may have no trouble understanding that sand

passing through an hourglass indicates that an app is doing work in the background and will soon become responsive, a young child will struggle to hold this relationship in her mind. Designers should maintain continuity between referent and symbol, avoid symbol embellishment, call attention to the link between symbol and referent, and make the symbol and referent visually similar in these and every instance of informal, on-screen symbolism.

6.4. Limitations and future work

With the exception of presenting minimal symbols instead of embellished ones, this investigation did not assess design solutions to scaffold children's understanding of symbols, and there is an opportunity for future work to create and evaluate novel solutions to this design challenge. Future work also remains to assess the extent of symbolism in interfaces for children. An in-depth review of app interfaces could systematically define a catalog of common symbolic elements (beyond the two identified here) and map these to design alternatives.

Additionally, we tested manufactured interfaces at a single point in time and did not explore children's experiences in more natural contexts with existing apps. While this was an intentional choice which enabled us to test participants' responses to carefully controlled manipulations, it calls for future work to examine children's experience in the wild through this lens. Exploring young children's interactions with apps which require symbolic representation would illuminate whether children are able to work around this challenge before they have acquired the capacity for dual representation. This would also provide designers with a better understanding of children's responses to symbols they do not understand or do not know to interpret as symbols. It remains to be seen whether children ignore such elements, imbue them with their own meaning, assume they serve a purpose they do not actually fulfill, or react in some other manner.

Further, our study included only 34 children, and only 11 of these children were between the ages of 2 and 3, the period where we saw this skill emerge. Future work expanding this investigation to a larger population would help generalize our findings and more precisely pinpoint children's acquisition of dual representation in digital contexts. Relatedly, we conducted this investigation without consideration of cognitive ability or neurodiversity. Children with autism spectrum disorders or other conditions with idiosyncratic patterns of cognitive development could demonstrate an alternative developmental trajectory with respect to their acquisition of dual representation. Further work remains to assess how a neurodiverse population interprets the types of user interface elements presented here and how this interpretation changes as a function of age.

Finally, in this study, we did not measure children's capacity for dual representation in non-digital contexts. As no easily administered instrument for dual representation currently exists, and standard assessments like the shrinking-room task were out of scope for our research team, we were unable to capture a standardized measure of children's ability to perform symbolic mappings more generally. We used comparison of symbolic abilities across disparate user interface elements to mitigate this limitation.

7. Conclusions

Though preschoolers spend a large fraction of their time with digital media (*Zero to eight: Children's media use in America 2013, 2013*) and more apps are made for this age range than any other, our results provide further evidence that not all design paradigms created for adults are effective for this user group. Through careful manipulation of isolated user interface elements, we demonstrate here that the theory of dual representation extends to children's interactions with digital interfaces and that children's gradual acquisition of the ability to map between a symbol and its referent interferes with their ability to use many standard interface components. The common practice of enlivening all user interface elements in children's apps exacerbates this difficulty, making symbols more salient and depressing their symbolic status.

By looking to the theory of dual representation for design inspiration, we see that minimizing such embellishment, increasing the similarity between symbol and referent, highlighting the symbolic link, explaining that this link is intentional, and, above all, replacing symbols with direct representations for children under 3, can make children more successful app users. Our results further indicate that the interface elements that come with symbolic demands are visually and functionally diverse, are pervasive in today's popular apps, and are informal, such that they may not necessarily be thought of as "symbolic" by app creators. Identifying and redesigning these wide-ranging, non-obvious symbols is a complex task, but it is also one that promises to deliver great value to technology's youngest consumers.

Acknowledgments

We would like to thank Daniella Kim and Chris Peloquin for their assistance with study design and data collection. We would also like to thank the Seattle preschool where we conducted this research and all of our participants and their families. The Institutional Review Board at the University of Washington approved this research.

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