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The Shape of Things: The Origin of Young Children's Knowledge of the Names and Properties of Geometric Forms

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How do toddlers learn the names of geometric forms? Previous work suggests that preschoolers have fragmentary knowledge and that defining properties are not understood until well into elementary school. The current study investigated when children first begin to understand shape names and how they apply those labels to unusual instances. We tested 25- and 30-month-old children's (N = 30 each) understanding of names for *canonical* shapes (commonly encountered instances, e.g., equilateral triangles), *noncanonical* shapes (more irregular instances, e.g., scalene triangles), and *embedded* shapes (shapes within a larger picture, e.g., triangular slices of pizza). At 25 months, children knew very few names, including those for canonical shapes. By 30 months, however, children had acquired more shape names and were beginning to apply them to some of the less typical instances of the shapes. Possible mechanisms driving this initial development of shape knowledge and implications of that development for school readiness are explored.

We are surrounded by geometric shapes—for example, rectangular pictures on the wall, circular tables, and square window panes. Infants can categorize visual stimuli like dot patterns arranged as geometric shapes (Quinn & Eimas, 1986), and even newborns can create perceptual categories for open and closed forms (Turati, Simion, & Zanon, 2003). By 3 to 4 months of age, infants are capable of extracting shapes from simple patterns (Quinn, Brown, & Streppa, 1997) and of creating classes for simple geometric forms (e.g., circle, triangle; Quinn, Slater, Brown, & Hayes, 2001). They are even capable of creating prototypical representations based on variations in shapes seen in dot patterns (Quinn, 1987). Thus, at least by 2 years of age, children appear to have the tools necessary to begin to learn shape names and accurately apply them.

During their second year, children can learn to label shapes with relatively little exposure to them (Heibeck & Markman, 1987), and they appear to know some basic shape names by age 3 years (Clements, Swaminathan, Hannibal, & Sarama, 1999). Although children are capable of creating categories of shapes prior to learning their names (e.g., Quinn, 1987), early shape concepts are not focused on the features that define the shape categories. In the

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latter part of the second year, children begin to learn words by "fast-mapping" the meaning of a new term to a specific referent based on only one or two labeling events (e.g., Carey & Bartlett, 1978; Golinkoff, Hirsh-Pasek, Bailey, & Wenger, 1992). Thus, children may quickly learn to label shapes they have encountered. However, research suggests that children's initial referents for shape names are the most common versions of those shapes (e.g., an equilateral triangle on its base; Cross, Woods, & Schweingruber, 2009; Satlow & Newcombe, 1998), and it is clear that children are not using shape categories in a mature fashion at this early age. They do not initially apply shape names to unusual variants of the shapes and seem not to understand the properties that define the shapes (e.g., that triangles have three sides and three angles; Clements & Battista, 1992; Clements et al., 1999; Fisher, Hirsh-Pasek, Newcombe, & Golinkoff, 2013; Satlow & Newcombe, 1998). To deepen their understanding of how shape terms are used, children need to move beyond canonical referents and their "standard" perceptual features to eventually encompass all members of the category based on the properties that define the shape. The cited literature suggests that creating definition-focused concepts begins with children slowly extending their labeling of canonical forms to increasingly atypical instances of shapes. Beginning to extend names to unusual instances, therefore, is a likely first step in achieving definition-focused concepts. What helps children begin to extend shape names to less canonical shape types?

One possibility is that simply hearing shape names and seeing many instances would help children begin to pick out the relevant information, although there is much debate about the degree to which language drives concept formation or vice versa (see, e.g., Gentner & Goldin-Meadow, 2003). From an education standpoint, there are a number of concerns about the extent to which children are being exposed to shapes in formal and informal settings. For example, Rudd, Lambert, Satterwhite, and Zaier (2008) found that only 1.2% of mathematics-related language referred to shapes in relatively high-quality, university-related childcare classrooms for children aged 0 to 5 years old. During 44 hrs of observation, they recorded only 26 mentions of shape names. An exploratory study we conducted using the Child Language Data Exchange System (CHILDESS) database (MacWhinney, 2000) revealed that shape names are used infrequently with young children and that the six shape names used in the current studies (circle, triangle, square, rectangle, pentagon, and star) comprised only 0.11% of all words produced by parents in everyday speech. The relatively infrequent use of shape names both in the classroom and at home would seem to present significant challenges for learning shape names.

Further, as with other lexical concepts (e.g., Carmichael & Hayes, 2001; Rakison & Oakes, 2003), varied exposure to geometric shapes of different types, their labels, and comparisons between shapes in the same and different categories is likely necessary to begin extending shape names beyond perceptually based matches (e.g., Gentner & Namy, 1999; Graham, Namy, Gentner, & Meagher, 2010; Namy & Gentner, 2002). Yet children's shape toys rarely include noncanonical shapes for parents to use to highlight these features or even invite comparison without adult input (Dempsey, Verdine, Golinkoff, & Hirsh-Pasek, 2013), and though books include more instances of unusual shapes (Resnick, Verdine, Lopez, McCaffery, & Golinkoff, 2014), they are still not ubiquitous. It is also unclear the extent to which parents actually talk about such properties even when unusual instances are present. If early education teachers are any indication, it is probably not often. For example, Sarama and Clements (2004) suggested that during the minimal time in which early education teachers talk about geometry, they fail to enrich children's shape knowledge. They tend to ask for shape identification (e.g., "What is this?" while holding up a triangle) and then simply confirm a correct response without inviting discussion to increase awareness of the properties of different shapes.

Early spatial experiences are important for spatial (e.g., Levine, Ratliff, Huttenlocher, & Cannon, 2012) and mathematical development (e.g., Mix & Cheng, 2012; Verdine, Irwin, Golinkoff, & Hirsh-Pasek, 2014). Likewise, exposure to spatial language (e.g., spatial location words like up or down, deictic terms like here or there, dimensions, shape terms, spatial orientations, etc.) elicits more spatial language production (e.g., Ferrara, Hirsh-Pasek, Newcombe, Golinkoff, & Lam, 2011) and builds later skills such as the ability to do spatial transformations and analogies (Pruden, Levine, & Huttenlocher, 2011). Playing with toys that incorporate shapes (e.g., shape sorters), labeling them, and discussing shape properties may be among the earliest spatial experiences parents provide. Regardless of the impact of such experiences on spatial skills, thanks to recent changes in preschool and kindergarten standards, shape knowledge is a vital aspect of school readiness (Common Core State Standards Initiative, 2010; Office of Head Start, 2011). For example, the Common Core Standards now emphasize geometric and spatial competencies for kindergarten mathematics instruction and state that children should be able to: a) "describe objects in the environment using names of shapes"; b) "correctly name shapes regardless of their orientations or overall size"; and c) "analyze and compare two- and three-dimensional shapes, in different sizes and orientations, using informal language to describe their similarities, differences, parts …" (Common Core State Standards Initiative, 2010, p. 12).

Understanding how and when to provide experiences with shapes is an important consideration and is essential for informing the development of curricula (Ginsburg, Lee, & Boyd, 2008). A number of factors having to do with language development, biases in how children interpret the world, and early symbolic understanding likely influence the acquisition of shape knowledge. We now explore these factors.

Factors Influencing the Acquisition of Shape Labels and Understanding of Shape Properties

Whole-object labeling and description of object properties. A challenge for learning the names of shapes is that adults often highlight nouns for concrete objects (e.g., Brown, 1973; Goldfield, 1993) and focus first on labeling whole objects (e.g., "That's a door") before describing the properties of those objects ("It's a rectangle"; e.g., Hollich, Golinkoff, & Hirsh-Pasek, 2007). When interpreting novel words, children seem to begin with the default assumption that a new word is the name for a whole object rather an object's parts or material (Hollich et al., 2007; Markman & Wachtel, 1988). In English, unlike other object properties, shape names are usually preceded by an article (e.g., "This is *a* square" compared with, "This is metal"). Articles often signal that the name that follows is an object label (Markman & Wachtel, 1988), which may obscure the specific property being highlighted, such as the rectangularity of a door. These patterns may make shape labels particularly hard to recognize as describing a property of an object.

One name for one object: Mutual exclusivity and dual representation. Another challenge occurs when adults apply names to shapes embedded in objects. Understanding that a wall clock is also a "circle" requires overriding "mutual exclusivity"—the bias that objects have but single names (Markman & Wachtel, 1988). Thus, 2-year-old children may resist new labels for already-named objects as when they disagree that a hammer is also a tool (Blewitt, Golinkoff, & Alioto, 2000), making it particularly difficult for children to learn what is being labeled by a shape term.

Applying shape names to everyday objects potentially creates another obstacle: Children must engage in "dual representation"—the process of simultaneously representing a symbol and its referent (DeLoache, 2000). Understanding that an object with a specific name and function, like a clock, can simultaneously act as a symbol for something else (i.e., a circle) requires representation of both the clock and the circle it symbolizes. At 2.5 years of age, children struggle with dual representation (e.g., DeLoache, Miller, & Rosengren, 1997; Uttal, Scudder, & DeLoache, 1997), suggesting that toddlers might have difficulty identifying shapes that are embedded within familiar objects. Accepting objects as being symbolic requires children to ignore the primary identity of the objects, which is not an easy or automatic task for 30-month-olds (Troseth, Bloom Pickard, & DeLoache, 2007).

The shape bias. Despite these challenges in learning shapes, there is one factor that may actually help with initially learning their names: the "shape bias" (Landau, Smith, & Jones, 1988, 1998). Children undergo a spurt in learning names for concrete objects at around 20 months of age, purportedly when they notice that object categories are often defined by shape rather than color or size (Gershkoff-Stowe & Smith, 2004). Big and little cups and red and blue cups, for example, are called "cup" because of their shape. The shape bias increases from 2 years to 3 years of age and into adulthood and is stronger for classifying objects labeled by an adult than when presented without a label (Landau et al., 1988). Thus, the shape bias may promote children's attention to similarities and differences in shape properties, and adult labeling of shapes may only increase that tendency.

Paradoxically, the shape bias and its strong focus on object shape, which could potentially be helpful in the initial acquisition of shape names, has the potential to be a liability for *refining* shape concepts. Too strong a focus on shape and repeated exposure to only canonical versions could cause children to resist the inclusion of valid but nonstandard versions into a shape category. Research does show that children by age 2 years, especially those with more advanced vocabularies, are able to categorize objects based on caricatures of those objects (Smith, 2003) and have some flexibility in their interpretation of shape. However, exclusive exposure to canonical versions of shapes could interrupt this flexibility by exposing children to geometric shapes with invariant properties that are not an important aspect of the shape category. Equal size angles, for example, are not a criterial property of triangles; scalene triangles have all different-sized angles. Variability in adults' shape labeling may also make the essential properties of shapes harder to extract and visual appearances harder to ignore. For instance, an adult might label a square resting on a corner as a diamond even though, by definition, they are both squares regardless of orientation.

Likely as a result of these challenges and a paucity of meaningful input, many children enter kindergarten without understanding the defining properties of many geometric forms (Clements et al., 1999; Satlow & Newcombe, 1998). This finding is particularly frustrating because of research like that of Fisher et al. (2013), who showed that guided play, used to discover the properties that define shapes, helped 4- and 5-year-olds build more definition-focused concepts. Such research indicates that preschoolers are capable of identifying shapes and learning more sophisticated information about them from *high-quality* instruction much earlier than they otherwise would without intervention.

The Present Research

We here probe whether toddlers can identify exemplars of shapes at 25 and 30 months of age and test a substantially younger population than those in prior studies (e.g., Clements et al., 1999; Fuson & Murray, 1978). We wish to understand a) the early course of shape recognition, and b) how variations in the shapes' properties influence children's performance. Knowledge of shape names was tested in a pointing version of the intermodal preferential looking paradigm (IPLP) (Golinkoff, Ma, Song, & Hirsh-Pasek, 2013). The method is a two-forced-choice paradigm in which participants responded by pointing to the prompted shape. This paradigm minimizes task demands because it relies on language comprehension rather than production. Thus, rather than asking children to verbalize their responses (as in, e.g., the clinical interviews used in Clements et al., 1999) or to sort stimuli into categories (as in, e.g., Satlow & Newcombe, 1998), we aimed to uncover the leading edge of children's shape knowledge by using a recognition task.

Children indicated their comprehension of a shape term by simply pointing to one of two static shapes presented on a split-screen monitor (Figure 1). The stimuli included six shape types appearing in three different representations. The representations were *canonical* versions of the shape categories and two types of unusual instances of the shapes: a) *noncanonical* versions, which were selected through adults' ratings of a range of shapes to be neither canonical nor extremely atypical, and b) shapes that were *embedded* within other objects such as a circular clock or a rectangular door (see Figure 2). These representation types allowed us to see how changes to the shapes influenced children's identification of them.

Although children younger than 3 years of age might not know all the shapes, we expected that the 30-month-olds would know at least the canonical versions of those that are most popular in shape toys and shape-focused touch-screen applications—star, circle, triangle, and square (Dempsey et al., 2013). Exploratory studies (Dempsey et al., 2013; Resnick et al., 2014) suggested that *rectangle* and *pentagon* would be particularly difficult shapes for young children based on the low amount of exposure to those shapes. Prior work (e.g., Satlow & Newcombe, 1998) has also suggested that children would have

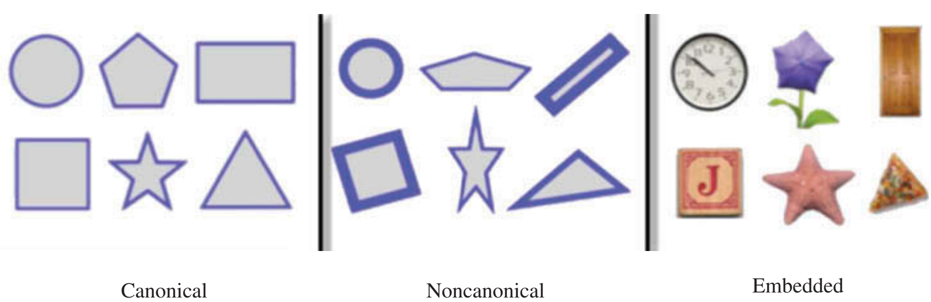


FIGURE 1 The shape types and representation categories used in the study.

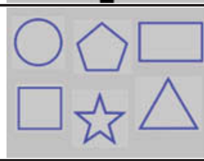
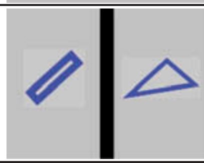
Trial	Visual Stimuli	Auditory Stimuli
Training Phase		Wow! See the tiger! See the tiger!
Familiarization Trial		Look at the square! See the triangle! Check out the pentagon! Look at the rectangle! See the circle! Check out the star!
Test Trial (Noncanonical)		Point to the rectangle!
Test Trial (Embedded)		Touch the circle!

FIGURE 2 Trial phases with examples of the image presentations and auditory prompts.

difficulty identifying *noncanonical* and *embedded* versions of the shapes. Overall, we expected the 30-month-olds would tend to be more successful than the 25-month-olds, specifically on the unusual-shape variant trials (i.e., noncanonical and embedded trials). Results first focus on the pattern of responses in each age group and then draw comparisons across ages to look at the development of shape knowledge. Finally, we determine the influence of gender and vocabulary knowledge across the full sample of children.

METHOD

Participants

Participants were recruited using a database of birth records, were predominantly White, and were from middle-class neighborhoods in a Northeast U.S. city. Thirty English-speaking children were recruited for the 25- and 30-month old groups (N = 60). The 25-month-old group consisted of 17 boys and 13 girls (M_{age} = 2;1; range = 1;11–2;4). An additional 12 children were dropped from the study (6 boys, 6 girls; M_{age} = 2;1; range = 1;11–2;3). Nine children were dropped from the study for noncompliance (less than 50% of trials completed) or questionable data due to response patterns like simultaneously pointing at both sides of the screen even on training and filler trials containing familiar objects. Two of the children had low performance on the training and familiar-object trials (incorrect on more than two of three training trials and three of four familiar-object trials), and 1 additional child was dropped for having been born premature. On the short form of the MacArthur-Bates Communicative Development Inventory (MCDI; Fenson et al., 2000) Production Scale, a word checklist filled out by children's parents, 25-month-old participants had a mean score of 67.44 (*SD* = 22.6, range = 18–100). According to Fenson et al. (2000), the 50th percentile in a 25-month-old sample for mean words on the MCDI is around 65. Note that the MCDI does not include any shape names.

The 30-month-old group included 13 boys and 17 girls (M_{age} = 2;7; range = 2;5–2;9). An additional 2 children were dropped for noncompliance. On the MCDI Production Scale, children had a mean score of 82.1 (*SD* = 17.3; range = 30–100). The 50th percentile in a 30-month-old sample for mean words on the MCDI is around 86.

Stimuli

Eighteen pairs of shapes were presented on a single computer monitor in a split-screen configuration with individual shapes occupying approximately the same volume of screen space (around 12 cm × 12 cm). Six different shapes (circle, square, triangle, rectangle, pentagon, and star) were shown in three representation types (canonical, noncanonical, and embedded; see Figure 1). A star was included in the set of shapes, despite not being a "standard" geometric form, because it commonly appears in shape toys (Dempsey et al., 2013) and other materials designed for children (e.g., storybooks) and was expected to be identifiable relatively early for most children. Shapes were always paired within the same representation category (e.g., a canonical triangle shown against a canonical rectangle). Three quasirandom trial orders were used, which also varied the pairs of shapes presented in a trial, with representation types presented and the shapes probed interspersed. The same shape could not be queried in consecutive trials and squares were never paired with rectangles.

The noncanonical stimuli were intended to be neither typical (canonical) nor highly atypical. Therefore, to select the noncanonical forms, nine variations of each of the candidate shapes were generated by varying vertex angles (where permissible), side lengths, orientation relative to horizontal, and line weights. Of these, 5 of each shape (30 in total) were selected to span a range from nearly canonical to strongly atypical. On an online survey site, 73 adults rated the shapes on a 7-point Likert scale from less to more typical following Meints, Plunkett, Harris, and Dimmock (2002). Noncanonical shape forms were then selected from their ratings such that the shape used scored nearest the average for that shape category out of the 5 candidates. Certain forms such as the circle and square, by definition, had to retain specific properties that made the noncanonical shapes more similar to the canonical versions. In these instances, thicker lines or rotations were used to create the noncanonical versions. Although nominally different, adult ratings did indicate that they viewed these shapes as less canonical; therefore, these shapes were used rather than omitting specific shapes from the noncanonical shape category. The noncanonical shapes were those that scored average rather than the extremely atypical shapes because prior work indicated that, at these young ages, using highly atypical shapes would likely result in children performing at floor across all shape types (e.g., Satlow & Newcombe, 1998).

The embedded shape forms were selected from photographs of objects with outlines that corresponded to the six canonical shapes under study and for which we expected most children would know the names. There are some minor inconsistencies in the extent to which the shapes map onto canonical versions. For example, pizzas typically have a rounded edge (although the stimulus has three straight edges) and are therefore not technically triangles. However, pizza is commonly used in children's books to teach triangles (oftentimes even including a rounded edge). The flower also has a stem and the sides are not *perfectly* straight. One reason for the inconsistencies within the embedded shape category is that the underlying objects were intended to be familiar objects for which children know the common names and would easily recognize, which limits the available options.

The ultimate goal of incorporating the unusual noncanonical and embedded instances in this study was to see when children begin to extend shape names to shapes that are not perceptual matches to canonical instances. In all cases, the shapes within a representation type are unlikely to be confused for one another if the participants understand the shape names. For example, if given only two choices, a slice of pizza or a child's block, and a prompt to point to the triangle, the block could not possibly be justified as a better answer. In selecting stimuli, it was important that the shapes be viewed as significantly different from the canonical shapes but still easily recognizable to adults and older children as obvious representatives of the shape categories. All of the chosen stimuli meet this criterion.

Procedure

Participants sat in a chair centered about 72 inches (183 cm) away from the screen. The presentation of stimuli was done using slides in a PowerPoint presentation. Prompts instructing the child to point at specific shapes were given verbally by an experimenter sitting next to the child. The experimenter recorded the child's responses as they were given. Only a child's first response was tallied. A secondary coder watched the procedure and independently coded the responses. Any discrepancies were discussed immediately after the procedure and a single set of responses were agreed upon for scoring. Discrepancies were typically a result of the main coder missing the child's initial point or recording data in the wrong spot while also trying to run the experiment efficiently, rather than true disagreements. In the rare cases where disagreements did occur and were not immediately resolved, the child was given credit for a correct response. The study began with a training phase consisting of three items that asked children to point to one of two familiar filler trial images. This phase was to acquaint children with the requirement that they point to only the prompted image and allowed the experimenter to correct behaviors that may disguise the child's intended answer, like simultaneously pointing at both images. A familiarization slide followed the training phase. This slide depicted the six canonical shapes while the experimenter named the shapes and was intended to reduce any novelty response to the canonical stimuli or the auditory shape names. Then the 18 test trials were presented. Four additional familiar-object filler trials (e.g., including a tiger or a cupcake) were interspersed among the test trials. These filler trials allowed children to experience some success on the task and provided trials on which the child could be praised for correct answers. Despite adding trials to the task, piloting showed that these trials helped retain children's attention throughout the procedure, especially for 25-month-olds. On test trials, 1 point was awarded for each correctly identified shape for a total of 18 possible points.

RESULTS

The dependent variable is accuracy in pointing, and therefore, the data are binary when considering individual shapes within the representation types. Therefore, a number of nonparametric approaches are taken to analyze this data set when possible. Parametric statistics are used in some instances where detection of interactions across groups is an important aspect of the analysis, because a nonparametric equivalent for a repeated-measures analysis of variance (ANOVA) incorporating multiple group comparisons is not readily available. In these instances, the analyses only analyze data collapsed across shape or representation categories so that the underlying data are at least nominal and not binary.

Analyses Across the 25- and 30-Month-Old Groups

Are there effects of age on shape knowledge across the two samples? A Mann-Whitney *U* Test was used on the overall scores from the shape identification test as the omnibus statistical test for differences between the 25- and 30-month-old groups. This test was significant ($U = 188.5$, $p < .001$, rank-biserial $r = .58$), with the 30-month-old group ($M_{\text{rank}} = 39.22$) outperforming the 25-month-old group ($M_{\text{rank}} = 21.78$). Due to this significant omnibus effect,

TABLE 1
Mann-Whitney *U* Results Comparing 25- and 30-Month-Old Group Performance Overall and Within the Representation and Shape Types

		25-Month-Old Rank†	*30-Month-Old Rank*†	*U*	*p*	*Rank-Biserial* ††
Overall Scores		21.78	39.22	188.5	< .001*	.58
Rep Type	Canonical	22.82	38.18	219.5	< .001*	.51
	Noncanonical	24.77	36.23	278.0	.009	.38
	Embedded	24.77	36.23	278.0	.009	38
Shape Type	Star	24.70	36.30	276.0	.001*	.39
	Circle	23.97	37.03	254.0	.002*	.44
	Triangle	26.37	34.63	326.0	.051	.28
	Square	25.58	35.42	302.5	.018	.33
	Rectangle	28.33	32.67	385.0	.309	.14
	Pentagon	27.05	33.95	346.5	.106	.23

*Statistically significant after Bonferroni adjustment for multiple comparisons ($p < .005$) calculated by alpha divided by the number of comparisons (.05/10). †Ranks are assigned for the Mann-Whitney *U* Test to participants based on their performance across the shapes in the given analysis in comparison with the entire pool of participants (total $N = 60$; possible ranks = 1–60 for each participant). These columns indicate the average assigned rank of the individuals within each of the given age groups. ††Rank-biserial correlations are a measure of effect size for the Mann-Whitney *U* Test; the correlation is the difference between the proportion of pairs that support the hypothesis minus the proportion that do not (Kerby, 2014).

further Mann-Whitney *U* Tests were conducted to compare performance on the individual representation and shape types. The groups differed significantly, after Bonferroni correction for multiple comparisons ($p < .005$ for an $\alpha = .05$) on the canonical representation type and the star and circle (Table 1). The noncanonical and embedded representations and the square were also marginally significant. That is, their *p* values would be considered significant at traditional alpha levels as standalone analyses without Bonferroni adjustment ($p = .009$, .009, and .018, respectively).

Is there more improvement on specific representation or shape types from 25 to 30 months of age? Two repeated-measures ANOVAs were run specifically to determine if there were any interactions across age collapsing across representation (3 Representations × 2 Age Groups) or shape (6 Shapes × 2 Age Groups) categories. If there were interactions, it would mean that specific shapes or representation categories were more difficult for a specific age as compared with the other. The analyses comported with the Mann-Whitney *U* Tests, indicating an

TABLE 2
Number of Participants Pointing to Probed Shape Targets (T) and to Nontargets (NT) and Two-Tailed Binomial Test Results Comparing Pointing Accuracy to Chance Performance

		Canonical		*Noncanonical*		*Embedded*	
		T:NT		*T:NT*		*T:NT*	
25-month-olds	Star	21:	8*	25:	4**	22:	6**
(N = 30)	Circle	24:	6**	20:	7*	12:	17
	Triangle	21:	8*	15:	14	18:	12
	Square	16:	14	23:	7**	20:	8*
	Rectangle	17:	12	13:	17	17:	12
	Pentagon	21:	8*	18:	10	14:	13
30-month-olds	Star	29:	1**	29:	1**	29:	1**
(N = 30)	Circle	27:	2**	27:	3**	22:	8*
	Triangle	26:	4**	25:	5**	19:	11
	Square	25:	5**	26:	4**	23:	7**
	Rectangle	21:	8*	17:	13	16:	14
	Pentagon	25:	5**	19:	10	24:	6**

*$p < .05$. **$p < .01$.

overall effect of age in the data, but the interactions between representation or shape category and age were not significant. Because these interactions were not significant, the analyses are not reported in detail. Nonetheless, the absence of significant interactions provides some evidence that growth in shape knowledge from 25 to 30 months of age is relatively consistent across shape and representation types, a conclusion supported by visual inspection of the differences in performance across age reported in Tables 2 and 3 and Figures 3 and 4.

TABLE 3
Average Performance on the Representation Types With One-Sample *T* Test Statistics Comparing Results to Chance (0.50)

		25-Month-Olds				30-Month-Olds				
		M	*SD*	*t(29)*	*Cohen's d*	*M*	*SD*	*t(29)*	*Cohen's d*	*M Difference Between Ages*
Rep Type	Canonical	0.68	0.21	4.73**	1.76	0.85	0.22	8.53**	3.17	.17†
	Noncanonical	0.65	0.22	3.84**	1.43	0.80	0.18	8.97**	3.33	.15
	Embedded	0.60	0.22	2.43*	0.90	0.74	0.18	7.80**	2.90	.14
Shape Type	Star	0.78	0.27	5.74**	2.13	0.97	0.10	25.13**	9.33	.19†
	Circle	0.64	0.27	2.94**	1.09	0.85	0.20	9.71**	3.61	.21†
	Triangle	0.62	0.33	1.97	0.73	0.78	0.27	5.69**	2.11	.16
	Square	0.67	0.27	3.47**	1.29	0.82	0.24	7.25**	2.69	.15
	Rectangle	0.53	0.28	0.54	0.20	0.61	0.26	2.19*	0.81	.08
	Pentagon	0.63	0.32	2.20*	0.82	0.76	0.31	4.45**	1.65	.13

*Significantly different from chance (0.5) at the $p < .05$ level. **$p < .01$. †Age groups are significantly different according to Bonferroni-adjusted Mann-Whitney *U* Tests (Table 1).

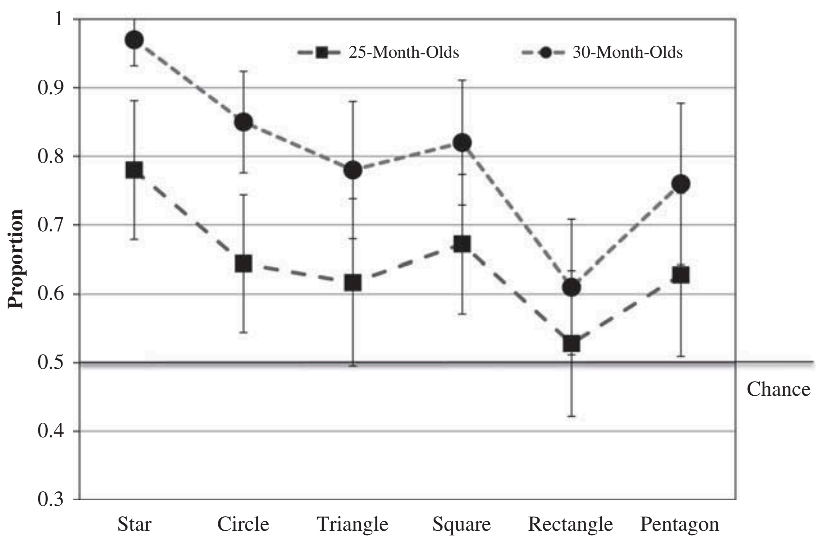


FIGURE 3 Graph showing proportion of correct trials by shape type for the 25- and 30-month-old groups with 95% confidence intervals.

Response Patterns to Shapes in the 25-Month-Old Participants

Do 25-month-old children reliably point to the target shapes? Binomial tests against chance (0.50) showed that 25-months-olds were only capable of identifying 8 of the 18 shapes

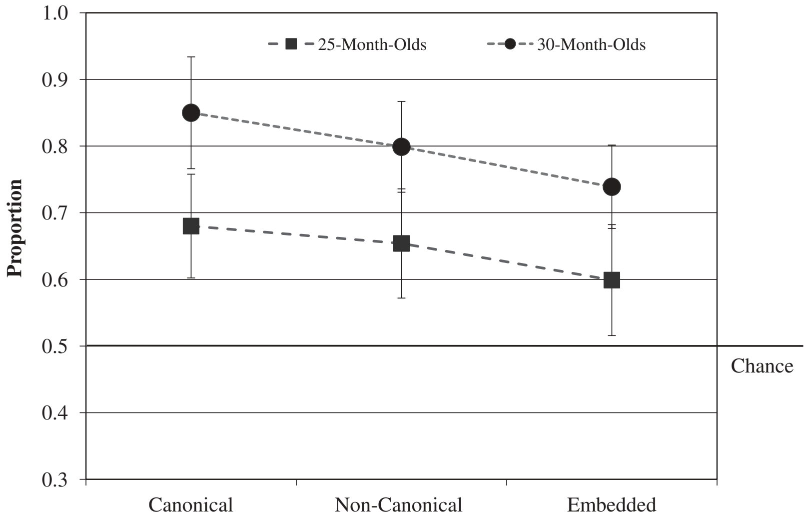


FIGURE 4 Graph showing proportion of correct trials by shape type for the 25- and 30-month-old groups with 95% confidence intervals.

significantly above chance (see Table 2) and the versions of the star accounted for 3 of those 8 shapes. *T* tests against chance collapsed across shape and across representation types (Table 3) show that children knew a number of the shape categories and representation types above chance, but performance was closer to the floor (50%) than the ceiling (100%) for every shape except the star. Across representations, children did not know triangles or rectangles above chance.

Do 25-month-old children know specific shape and representation types better than others? The average scores for pointing to a target shape collapsed across all representations and shapes for each age are presented in Figures 3 and 4 and Table 3. Two Friedman tests were conducted, one for the six shape categories and one for the three representation types, to determine whether performance differed depending on the categories displayed. The Friedman test for the shape categories was marginal, $\chi^2(5, N = 30) = 10.74$, $p = .057$, Kendall's $W = .072$ (mean ranks, star = 4.25, circle = 3.38, triangle = 3.42, square = 3.60, rectangle = 2.87, and pentagon = 3.48). Due to the marginal omnibus effect, follow-up Wilcoxon tests were performed and showed a pattern of the star exceeding the other shapes (with the exception of the square). However, using Bonferroni correction for 15 multiple comparisons requires a *p* value of less than .003 for an $\alpha = .05$. Only the comparison between the star and rectangle was below that cutoff ($p = .002$). The Friedman test comparing representation types was not significant, $\chi^2(3, N = 30) = 1.96$, $p = .375$, Kendall's $W = .033$.

Are these low levels of shape knowledge a good representation of what 25-month-olds know about shapes? As a group, the 25-month-olds were nearly perfect on the 4 familiar-object trials interspersed among the other 18 trials (99.2% correct) and none of the participants had fewer than three out of four correct. However, a relatively large number of 25-month-olds ($N = 9$) were not analyzed because of noncompliance and they did not finish more than half of the trials. Most failures to complete the task appeared to be attributable to frustration due to a lack of knowledge about shapes rather than an inability to do the task or understand what was being asked given that children tended to do well on the familiar-object training trials. Thus, if anything, our data for the 25-month-olds may be a slight overestimate of what performance would be for a sample representing a wider socioeconomic range.

Response Patterns to Shapes in the 30-Month-Old Participants

Do 30-month-old children reliably point to the target shapes? Binomial tests against chance (0.50) showed that most individual shapes within the three representation types were significantly above chance performance (see Table 2). The only exceptions were the embedded triangle, the noncanonical and embedded rectangles, and the noncanonical pentagon. *T* tests against chance collapsed across shape and across representation types (Table 3) show that, on average, participants knew the names of most shape and representation types.

Do 30-month-old children know specific shape and representation types better than others? As with the 25-month-olds, two Friedman tests were conducted, one for the six shape categories and one for the three representation types, to determine whether performance differed depending on the categories displayed. Unlike the 25-month-olds, the Friedman test for the shape categories was strongly significant, $\chi^2(5, N = 30) = 33.64$, $p < .001$, Kendall's $W = .224$ (mean ranks, star = 4.60, circle = 3.80, triangle = 3.32, square = 3.63, rectangle = 2.40, and pentagon = 3.25). Follow-up Wilcoxon tests using Bonferroni correction for multiple comparisons ($p < .003$ for an $\alpha = .05$) showed that performance on the star exceeded performance on the triangle, square, rectangle, and pentagon and that performance on the square and circle both exceeded performance on the rectangle. The Friedman test comparing representation types, again unlike the 25-month-old group, was also significant, $\chi^2(3, N = 30) = 10.67$, $p = .005$, Kendall's $W = .178$ (mean ranks, canonical = 2.33, noncanonical = 2.00, embedded = 1.67). The follow-up Wilcoxon test showed that performance on canonical trials was significantly higher than performance on the embedded trials ($p = .021$), with performance on noncanonical shapes falling in between and not significantly different from the canonical or embedded representation types.

Analyses With Other Variables That Potentially Influence Shape Knowledge

Is there a relationship between gender and shape knowledge? A Mann-Whitney *U* Test on the full sample showed a significant effect of gender on overall accuracy in identifying shapes ($U = 314.5$, $p = .044$, rank-biserial $r = .30$), with girls ($M_{\text{proportion correct}} = 0.764$; $M_{\text{rank}} = 39.22$) outperforming boys ($M_{\text{proportion correct}} = 0.680$; $M_{\text{rank}} = 21.78$). However, there were proportionally more girls in the older age group, so follow-up analyses were done on the age groups individually. The effect of gender was not significant when age groups were analyzed separately, likely due to the smaller sample sizes of individual groups; the rank-biserial correlations from these tests indicated that the effect size was smaller in the 25-month-olds (rank-biserial $r = .15$) but similar to the full data set in the 30-month-olds (rank-biserial r = .31). A correlation between gender and overall pointing accuracy was significant (r = .205, p = .045) but only marginal after controlling for age in months (r = .193, p = .061). Thus, these analyses suggest a small female advantage in shape identification at 30 months.

Are language skills measured with the MCDI related to shape knowledge? Given the different response profiles in each age group, Spearman correlations were conducted separately on overall accuracy by age. In the 25-month-old group, MCDI scores were not correlated with overall performance or performance on any of the shape or representation types. In the 30-month-old group, however, MCDI scores were correlated with overall accuracy (r = .44, p = .020) and performance on the canonical (r = .47, p = .011) and noncanonical shapes (r = .38, p = .044) but not with the embedded shapes (r = .25, p = .21). The only individual shapes that were significantly correlated with MCDI scores in the 30-month-olds were circles (r = .43, p = .021) and pentagons (r = .40, p = .036).

In light of the positive correlations for the 30-month-olds between MCDI scores and shape knowledge, and what appears to be a slight advantage in shape identification for girls, it is worth noting that girls did not have an advantage on the MCDI regardless of age. A Mann-Whitney U Test on the full group (U = 306.5, p = .228, rank-biserial r = .19), Mann-Whitney U Tests on the individual age groups (rank-biserial r = .21 and .06 for the 25- and 30-month-olds, respectively), and correlations (r = .059, p = .579; partial r controlling for age in months = .025, p = .812) were all not statistically significant. If anything, based on the rank-biserial correlations from the Mann-Whitney U Tests, MCDI scores for boys and girls were more similar at 30 months old, the age at which there was a slight gender effect for shape identification. These analyses suggest that any appearance of an advantage in shape identification for girls does not stem from girls having better language skills.

GENERAL DISCUSSION

These two studies sought to determine when children begin to acquire shape knowledge and at what point they begin to extend shape names to unusual instances. Our findings suggest that most 25-month-old children do not yet know the names of most shapes, which also limits our ability to observe differences between shape categories or representation types. The 25-month-old group did exceed chance on some of the shapes (primarily the star and circle and more of the canonical shapes). This apparently low level of performance is not due to participants being unable to complete the task when they know the objects on the screen; 25-month-olds were nearly perfect on the familiar-objects trials. A strength of the pointing version of the IPLP for this age group is the ease with which they can respond and the limited cognitive load produced by only two response options. Much prior research has shown that this paradigm works well for young children (Golinkoff et al., 2013). However, the children could use an “A, not-A” inductive reasoning strategy to succeed on trials. That is, when an unfamiliar shape is paired with a familiar shape, they could induce that the unfamiliar shape was being requested (e.g., Hirsh-Pasek & Golinkoff, 1996). Considering how easy the paradigm makes it for children to reveal their burgeoning knowledge, that the sample was largely a middle- to high-socioeconomic-status sample, and that a relatively large number of low performers were dropped from the study, if anything, these data probably represent an overestimate of 25-month-olds' ability to identify shapes.

However, the time between 25 and 30 months of age, during which lexical acquisition is rapidly increasing (Hoff, 2013), appears to also be a period of strong growth in learning shape names. At 25 months, toddlers knew relatively little about shapes, including canonical types, and were just beginning to show some signs of shape knowledge. By 30 months, children knew the names of many of the shapes and performed better than chance on all three representation types and particularly well on the canonical versions with which they were likely most familiar. Language skills were a factor in determining shape knowledge in the 30-month-old group, which is perhaps not surprising given the inevitable overlap in learning shape words and learning words in general. The potential relationship between MCDI scores and shape identification at 25 months old seems likely to have been attenuated by the poor performance of children in shape identification at 25 months. Gender was perhaps a minor factor in shape identification for the 30-month-olds, with girls showing a marginal advantage in identifying shapes. Girls did not have any vestiges of a similar advantage in MCDI scores; general language skills do not explain why girls may have a slight advantage in shape naming.

Despite the limited input they receive from adults (Rudd et al., 2008), children appear to have begun in earnest their learning of shape names and properties by 30 months. Perhaps this fact is due to the appearance of the shape bias (Landau, Smith, & Jones, 1992) that turns children's attention to the shapes of concrete objects, and perhaps it is due to children's ability to fast-map new words (Carey & Bartlett, 1978; Golinkoff et al., 1992). But there may be a threshold for input needed to support children's extension of shape names to less canonical instances. The rectangle and pentagon were talked about least in our exploratory study of the CHILDES transcripts, and although not conclusive, these shapes were among the most difficult in this study.

For the 30-month-olds, embedded shapes were particularly challenging (74% correct), despite the fact that the shapes mostly had properties similar to the canonical forms (85% correct). Perhaps the need to simultaneously represent an object as one thing (e.g., a door) and a symbol for another thing (e.g., a rectangle) poses a dual-representation problem (DeLoache et al., 1997). Note that classroom manipulatives and drawings designed to teach shapes often use common objects (Uttal et al., 1997). Such materials may create confusion about the properties being labeled, particularly when *novel* shape names are applied to *familiar* objects by adults.

Despite the performance decrement of the 30-month-olds on the embedded representations, earlier studies of shape names and their properties suggested that these children would not be as competent as they appeared. After all, Fisher et al. (2013) and Satlow and Newcombe (1998) reported that children struggled with correctly categorizing atypical shape variants at least until age 4 years. So why were children successful on some of the noncanonical and embedded shapes at 30 months old in the present study? Task differences may account for the discrepancy. First, our paradigm allowed children to use an inductive reasoning strategy; if they knew one of the shapes pictured, they could use that knowledge to infer that the other shape was being requested. Second, our task asked children to point to one of two visible shapes; by contrast, Fisher et al. and Satlow and Newcombe required children to make a *judgment* about whether a single visible shape was a valid or nonvalid member of a shape category. In our task, children might have used visual similarity between our unusual shapes and their representations of more familiar canonical instances to infer the names. However, this strategy would not work in a judgment task like those used previously because they also included nonvalid instances (e.g., triangles missing parts of their sides or angles), which had a resemblance to the canonical shapes but were not actually valid versions of those shapes. Third, Fisher et al. and Satlow and Newcombe used *atypical* shapes (more extreme differences in side length) in comparison with the *noncanonical* shapes used here. Thus, although the 30-month-old children appear to be extending their shape categories to include some noncanonical and embedded instances, more stringent tests on older children have suggested that the acquisition of definition-focused shape category knowledge takes many years.

Educational Implications

What do the present results suggest about how to support children in learning about geometric forms? Increasing the *quantity* of geometric input would likely have a positive impact as children would encounter these shapes more often. Modifications to *how* these topics are taught (Sarama & Clements, 2004) may also assist young children in this domain. When children were taught using guided play (Hirsh-Pasek, Golinkoff, Berk, & Singer, 2009) as opposed to didactic instruction, they were dramatically better in transferring their shape knowledge to atypical shapes not previously seen (Fisher et al., 2013).

The types of shapes used in toys and other educational materials may also matter. When there are varied instances of a category, research tells us that adults use labels and statements of inclusion (e.g., “An aardvark is a kind of animal”; Shipley, Kuhn, & Madden, 1983) that prompt children to form wider categories (e.g., Waxman, 1990). Groups of objects also elicit superordinate terms marking objects as members of larger classes (Liu, Golinkoff, & Sak, 2001; Shipley et al., 2008). Thus, if materials for young children included many varied shapes, parents and teachers might use language that highlights shape similarities and differences (e.g., “These are both triangles because they have three sides”). They might also be more likely to signal the existence of wider categories (e.g., “This weird one is a *kind of* triangle”). Yet popular shape-sorter toys and touch-screen apps typically contain only one iconic version of each shape category (Dempsey et al., 2013). Furthermore, designing shape materials requiring goal-directed adult involvement (e.g., Ferrara et al., 2011) might result in significantly more exposure to language about geometric forms at younger ages.

These findings and the literature suggest at least three specific practices that early educators and parents can follow when it comes specifically to teaching shapes. First, for toddlers, it may be best to avoid using familiar objects to teach shapes. It requires that children ignore the existing labels they have for those objects and may require dual representation. Second, if and when adults do use everyday objects to teach shape names, they should do more than simply point out shapes (i.e., “Look, a circle”). They should invoke the familiar object’s name (i.e., “Look that clock is also a circle”). Finally, because comparison appears to lead children to refine categories and our data indicate that children can begin to extend shape names to unusual instances by 2.5 years old, parents, teachers, and toy companies should work to offer a greater breadth of shape types and emphasize the similarities and differences between the shape categories.

Limitations

One limitation is this study's sample of children from middle-class socioeconomic backgrounds. Verdine, Golinkoff, et al. (2014) reported that preschoolers' nonverbal spatial assembly and mathematics skills were already significantly delayed by age 3 years for children from lower socioeconomic-status households. Some of this gap is likely attributable to lags in language development (e.g., Hart & Risley, 2003), and it would be important for potential interventions to know how socioeconomic status influences the acquisition of geometric shape terms and knowledge of shape properties.

Another limitation is the number of trials and variety of stimuli we could effectively use given the ages tested. Although there may be some concerns about the extent to which certain noncanonical and embedded shape categories are "unusual," we think it is important to point out that shapes were always presented in pairs from the same representation category, children had as long to respond as needed, and they rarely refused to respond. Therefore, children were consistently selecting between two shapes on the basis of the properties in front of them and their understanding of what the probed shape names meant. It should also be noted that children's books and other materials very often use objects that are not *perfect* representations of shape categories. In this way, our embedded stimuli are actually quite representative of how these shapes may be encountered in a classroom or in the home and present a challenge similar to what children may face in using objects as symbols for shapes.

Conclusions

This article explored the *origins* of children's knowledge of shape names and how they begin to extend those names to unusual instances. Three main conclusions can be drawn. First, from 25 to 30 months of age, children go from showing little understanding of the names and properties of most shapes to identifying the canonical forms of all six shapes tested. Second, children's shape concepts are likely still quite fragile at 30 months of age given that they could not identify all the shapes shown in all representation types and struggle when pressed in other paradigms. Third, the embedded shapes were harder than the canonical shapes for 30-month-olds to identify, suggesting that beginning with these in instruction (Cross et al., 2009) may create confusion. With an increasing emphasis on geometry in the Common Core Standards for mathematics, promoting an early understanding of geometric shapes has become a crucial aspect of preparing young children for school. This work provides new information about when and how children learn about geometric forms.

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