How do preverbal infants represent geometric shapes?

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Abstract

Humans' sensitivity to geometric structure begins to emerge in infancy. However, representational strategies underlying infant shape processing remain unknown. Do infants encode shapes through abstract combinations of geometric primitives, or do they rely primarily on low-level perceptual features? To address this question, we examined shape processing in 10–12-month-olds using a novel eye-tracking intruder task. Infants viewed arrays of 4 geometric shapes consisting of 3 standard and 1 deviant shape (e.g. 3 squares, 1 distorted square). Shapes varied in regularity and number of sides/angles (equilateral triangle, isosceles triangle, square, rhombus, regular pentagon). We assessed whether shape complexity influenced deviant detection, defined as the proportion of looking time to the deviant shape. Results revealed a significant effect of shape, with above-chance deviant detection only for squares. This selective success suggests that infants' geometric representations may be sensitive to particular structural properties (e.g. right angles, symmetry, parallelism), rather than reflecting a fully-fledged combinatorial system of geometric primitives.

Keywords: infant cognition; eye tracking; geometry; language of thought; compositionality

Introduction

Geometric concepts are fundamental to human cognition, supporting spatial understanding and navigation, and providing the basis for evaluating the efficiency of others' actions (e.g. Gergely & Csibra, 2003) and goal attribution (e.g. Liu et al., 2017). Geometric and spatial skills developing in childhood predict later mathematics achievement (e.g., Gunderson, et al., 2012; Verdine et al., 2014) and are associated with long-term success in STEM fields (Wai et al., 2009). Importantly, sensitivity to abstract geometric properties and spatial relations emerges in infancy (for review, Spelke, 2022), suggesting that humans may be endowed with early-developing cognitive systems for encoding geometric structures. However, it is not well understood how infants represent complex shapes. Do they represent complex shapes through combinations of geometric primitives, as preschoolers and adults (Sablé-Meyer et al., 2021)? Or, alternatively, do they rely on low-level features, similar to non-human primates (*idem*)? Our aim was to shed light on these questions by examining whether and how human infants identify distorted shapes among copies of their non-distorted counterpart, and whether this was modulated by regularity. We used a novel infant-friendly eye-tracking intruder task (Figure 1).

During the first year of life, infants begin to appreciate some key geometric properties such as angle, relative length, and symmetry. To test infants' sensitivity to angle and relative length, Dillon, Izard, & Spelke (2020) presented 7-month-olds with two streams of 2D shapes: in one stream, only area varied, whereas in the other, area varied along with an additional geometric property (e.g., relative length, angle). When orientation was kept constant, infants looked longer at the stream in which more properties varied. When orientation varied, this looking pattern was maintained only for relative length. This behavior provides evidence that, although infants are capable of extracting both angle and relative length, their representations of relative length are more robust. A similar pattern of findings was observed by Lourenco and Huttenlocher (2010, see also Lindskog et al., 2019) who habituated 4.5- to 6.5-month-olds to an isosceles triangle with a red dot in one corner (i.e. either the corner with the unique angle or one of the two corners with the same angle). At test, the dot alternated between the habituated and a novel corner. When orientation varied, infants differentiated the unique corner from those with the same angle but failed to differentiate between these latter corners. Finally, sensitivity to symmetry is evident as early as 4 months of age. Bornstein, Ferdinandsen, and Gross (1981) showed that 4-month-old infants discriminated vertically symmetrical from asymmetrical and horizontally symmetrical patterns.

What kind of representations underlie early-emerging geometric processing? Sablé-Meyer and colleagues (2021) distinguished two main mechanisms that may support geometric shape representation: feature-based processing and conceptual processing. Feature-based processing was suggested to rely on low-level features (e.g. luminance, oriented lines and edges) used by the ventral cortices to recognize objects and not specific to geometry. In contrast, conceptual processing, rooted in the Language of Thought (LoT) framework (Fodor, 1975; Quilty-Dunn et al., 2023) and its recent application to geometry (Dehaene et al., 2022, 2025), was suggested to rely on combining symbols indexing geometric primitives (e.g. right angle, parallel sides) into structured shape descriptions of different complexity.

Sablé-Meyer et al. (2021) conducted a series of intruder detection experiments to examine the nature of shape representation across human adults, young children, and non-human primates (baboons). Participants were presented with arrays of six quadrilaterals of the same category, varying in regularity (e.g. from most to least regular: square, rectangle, trapezoid, rhombus, etc.). Regularity was defined by the number of a shape's geometric properties (e.g. presence of

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parallel sides, equal angles, right angles, etc). Each array included one distorted shape that served as the intruder. For example, an array could consist of five squares and one distorted square (for more details, see *Stimuli* section). Participants were instructed to detect the intruder as rapidly and accurately as possible. Adults' error rates and reaction times increased as the shape regularity decreased. For instance, error rates and reaction times were higher for parallelograms than squares. These results revealed a geometric regularity effect, with intruder detection becoming progressively more difficult for more irregular shapes. Five-year-old children displayed a similar pattern of performance. In contrast, baboons' performance did not scale with shape regularity, as more regular shapes did not consistently yield higher accuracy. These divergent patterns of responses strongly suggest that humans and baboons recruit different shape representation strategies. Namely, humans seem to set up abstract shape descriptions that directly reflect combinations of geometric properties of viewed shapes (e.g. presence/number of: parallel lines, equal lines, right angles, etc.), whereas baboons rely on low-level visual features. This interpretation was supported by computational modeling: human performance was captured by a symbolic model grounded in Euclidian geometric properties, while baboon performance was better explained by convolutional neural networks approximating the ventral pathway.

Inspired by the approach of Sablé-Meyer et al. (2021) and informed by prior research in infant cognitive development, we developed a novel infant-friendly eye-tracking intruder task (for another infant-friendly intruder task, see Lindskog et al., 2019). Our aim was to examine whether infants can discriminate geometric shapes of different regularity and shed light on underlying shape representation mechanisms. To explore whether shape representations are affected by the number of sides, we used three families of shapes: triangle, quadrilateral, pentagon (for more details on our rationale, see *Methods*). This approach differs from Sablé-Meyer and colleagues, who did not examine side number and instead focused exclusively on quadrilaterals. Infants were presented with arrays of four geometric shapes from the same category (e.g. square), with one shape altered to serve as the intruder (e.g. 3 squares, 1 distorted square). Across trials, shapes varied in complexity and regularity. An additional condition used photographs of familiar real-world objects that infants can easily differentiate (e.g. 3 ducks, 1 car) to validate the task and maintain engagement. Auditory input was limited to brief verbal encouragement (e.g. *Hi baby, you're doing great!)* and soft background music; no verbal guidance was

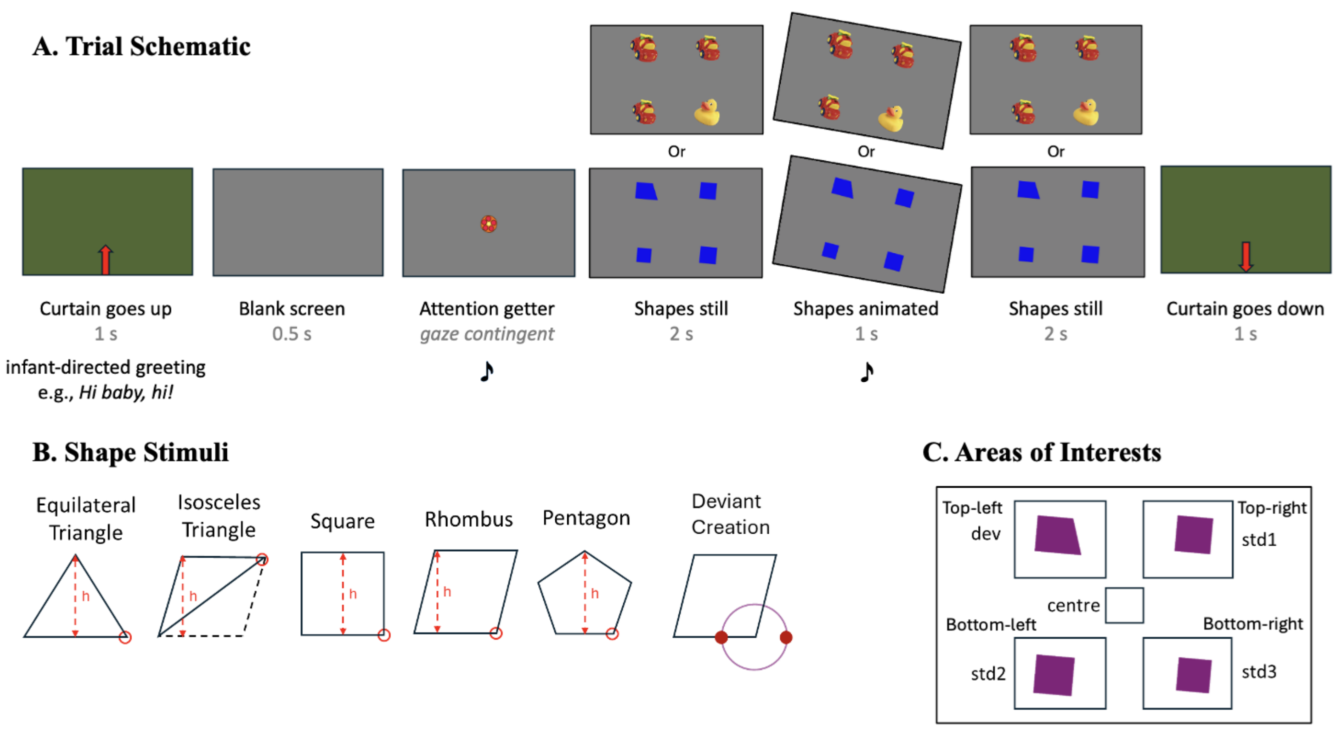

Figure 1: **Overview of task design & areas of interest used for analysis.** (**A**) Trial schematic. The bottom line depicts a sample shape trial; the top line depicts a control trial with real-world objects. (**B**) Shape stimuli used in the study. All shapes besides the isosceles triangle were matched in height. Isosceles triangles were created by bisecting the rhombus along the longer diagonal. Deviants for each shape were constructed by either lengthening or shortening the bottom right vertex by the same fixed amount (for details, see *Stimuli*). (**C**) Schematic of the areas of interest (AOIs) used to analyze infants' gaze data: there are four shape shape/object AOIs and one centre AOI corresponding to the attention getter. Note that the location of deviant (*dev*) and standard stimuli (*std1*, *std2*, *std3*) was randomized (for details, see *Randomization*).

provided. We monitored infants' looking behavior to assess whether they were able to detect intruder shapes and whether their intruder detection performance was affected by shape complexity. If infants represent shape conceptually by combining geometric primitives, similarly to adults and preschoolers, they should display a geometric regularity effect and look longer at the intruder for less complex shapes. If they do not rely on geometric properties but on low-level surface features, similarly to non-human primates, they should display a comparable level of looking at the intruder across all shapes (Figure 2A).

Methods

All materials, data, analysis code and appendix is publicly available via OSF: https://osf.io/bp6wn/overview.

Participants

Twenty-four 10-12-month-olds (mean age = 10.93 months, range: 9.77–13.5 months, female: 10) participated in the experiment. An additional 12 infants were excluded from the analysis due to insufficient valid trials (n = 8, see *Data Analysis*), a bias toward a single quadrant of the display (n = 1), or an experimenter error (n = 3). Parental consent was obtained prior to testing. The study was approved by the University of Birmingham Science, Technology, Engineering and Mathematics (STEM) ethics committee (ERN_19-0813AP4B).

Design

The intruder task consisted of four blocks (with 6 trials per block) and was administered alongside a second task (a word-mapping paradigm not reported here). Blocks from the two tasks were interleaved. The task order was fixed such that the intruder task was always presented first.

Stimuli We used a set of five geometric shapes comprising three regular shapes and two irregular ones. The regular shapes were an *equilateral triangle*, a *square*, and a *regular pentagon*, each defined by equal side lengths and equal internal angles. The two irregular shapes were an *isosceles triangle* and a *rhombus*. All shapes were matched in height, except the isosceles triangle that was created by halving the rhombus, ensuring consistency in structural properties across irregular stimuli (Figure 1B). These shapes were selected to increase monotonically in the number of sides while varying in regularity, allowing us to examine whether infants' representations track: (i) the number of constituent edges and angles, (ii) the number of constituent edges and angles along with other geometrical properties normalized by number of sides (Figure 2A, see also *OSF Appendix Table 1: https://osf.io/bp6wn/files/4wtp3*).

Following Sablé-Meyer et al. (2021), for each geometric shape, deviants were created by manipulating a single vertex by lengthening (deviant type 1) or shortening (deviant type 2) the vertex by a constant amount corresponding to 30% of the average side length calculated across all shapes. This manipulation preserved overall shape identity while introducing a controlled and quantifiable deviation. Note also that one standard was matched in height with the deviant, while other standards were scaled to introduce variability in size. One was reduced in size (scale factor: 0.875, 0.925, or 0.975, randomly selected), and the other was enlarged (scale factor: 1.025, 1.075, or 1.125, randomly selected).

To verify that infants were able to detect intruder stimuli in this task, familiar real-life objects that infants can easily differentiate (i.e., a toy car and a rubber duck) were also included.

Trial structure On each trial, the screen was divided into four quadrants, and infants viewed arrays of four stimuli comprising three standard and one deviant version (e.g., 3 regular squares/cars and 1 distorted square/duck). For shapes, all four stimuli within a trial shared the same color fill and orientation, with rotation applied uniformly to the entire array.

Each trial followed a fixed sequence with a total duration of approximately six seconds. The sequence began with a curtain going up (1s) to reveal a blank screen (0.5 s). Then, a central gaze-contingent attention getter appeared in the centre of the screen. The infant was required to fixate on it for 0.5 s to proceed to the next event. When this criterion was met, the attention getter disappeared and four intruder stimuli were displayed on the four screen quadrants for a total of 5 s, divided into three events: initially static (2s), animated by rotating or zooming in/out (1s) and static again (2s). The trial concluded with a curtain going down (1s). Auditory input was limited to joyful background music playing quietly throughout and brief verbal encouragement delivered with infant-directed intonation (e.g., *Hi baby, hi!; You are doing a great job!; Hi baby, well done.)* presented at the beginning of each trial (see Figure 1A).

To enhance infants' engagement with the task, short cartoons (e.g. clips from *In the Night Garden*) were presented between blocks.

Randomization The following factors were randomized within-subjects: (i) location of the deviant and standard stimuli (counterbalanced across blocks such that each shape appeared equally often in all four quadrants); (ii) shape color (blue, yellow, red, green, or purple), (iii) stimulus orientation (5°, 25°, 325° or 355°; counterbalanced across trials), (iii) deviant type (bottom right vertex either lengthened or shortened). The order of presentation of stimuli within the block was randomized across subjects.

Apparatus

Infants' binocular gaze data were collected using a Tobii Pro Spectrum eye tracker with an integrated 23.8-inch-diagonal monitor (resolution: 1920 × 1080; refresh rate: 60 Hz; Tobii, Danderyd, Sweden, https://www.tobii.com/), sampling rate: 60 Hz. The sound was presented using a pair of external speakers placed behind the eye tracker screen. Custom-built scripts using PsychoPy 2021.1.3. (Peirce et al., 2019) were used for calibration, stimuli delivery and data collection.

Procedure

Data collection took place in a dimly lit quiet room. Infants were seated on their parent's lap approximately 60 cm from the eye-tracker. Parents were instructed to remain neutral and to limit interaction with their child. An infant-friendly five-point calibration was performed at the start of each session. Sessions were terminated early in cases of infant fatigue. Gaze data were recorded continuously throughout the session.

Data processing and analysis

Time window of analysis We analyzed the events when the shapes were still (Figure 1A), totaling 4 s per trial.

Areas of interest and gaze coordinates Five areas of interest (AOIs) were defined to analyse infants' looking behaviour (see Figure 1C): the four screen quadrants (top-left, top-right, bottom-left, bottom-right), and the central region (corresponding to the attention getter).

The gaze coordinates were calculated by averaging left and right eye coordinates. When data from only one eye were available, the corresponding single-eye coordinate was used as the gaze estimate for that sample. Samples for which data from both eyes were unavailable were marked invalid. Gaze coordinates were mapped onto AOIs and classified as deviant (*dev*), standard 1 (*std1*), standard 2 (*std2*), standard 3 (*std3*), or center if they fell within the corresponding spatial boundaries.

Inclusion criteria Gaze samples were considered valid if they were registered on-screen, and invalid if they were registered offscreen or gaze coordinates were not recorded. Events were considered valid if their duration was within ±5 samples (i.e. ± 0.08 s) of the expected 120-sample (i.e. 2 s) duration. A trial was considered valid only if (1) both events during which the shapes were static were valid, (2) at least 50% of the samples were valid, (3) at least one fixation (i.e., ≥300 ms, or ≥18 consecutive valid samples) was recorded within any AOI during the time window of interest. To be included in the final sample, participants had to (1) provide at least one valid trial per condition (i.e. for each of the 6 different stimuli: object, equilateral triangle, isosceles triangle, square, rhombus, pentagon), (2) display no overall bias towards looking at one quadrant, (3) had no more than 2 trials with invalid events.

Main measure: proportion of looking at the deviant Our main measure was the *proportion of looking time at the deviant shape* (PLTD); it was computed by dividing the total number of samples recorded in the deviant AOI by the total number of samples recorded across the four shape AOIs (deviant, standard1, standard2, standard3): PLTD = *n(deviant) / (n(deviant + standard1 + standard2 +standard3).* PLTD was computed for each trial and

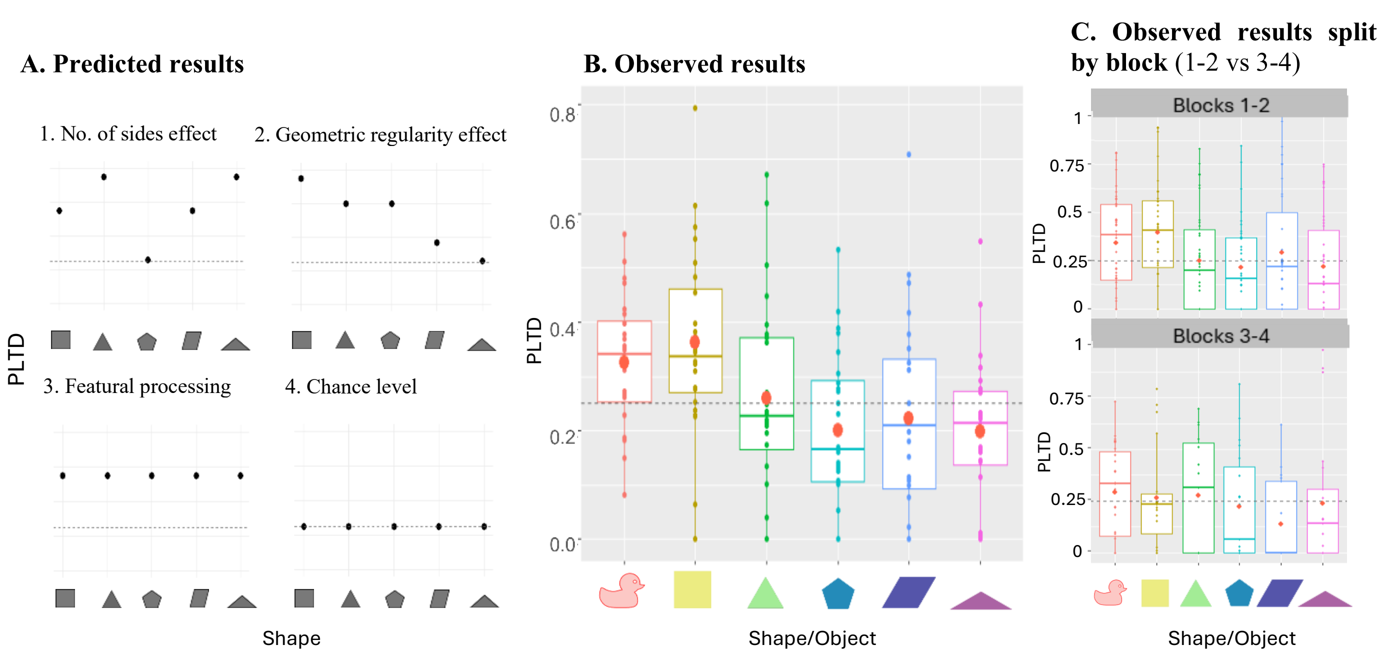

Figure 2: Predicted (**A**) and observed (**B & C**) results split by shape. Our main measure was the proportion of looking at the deviant (*PLTD,* see *Data processing and analysis).* The dotted line represents the chance level (0.25). **(A.1)** Predicted results if performance were influenced solely by the number of sides. **(A.2)** Predicted results if performance were influenced by shape regularity (see also *OSF Appendix Table 1:* https://osf.io/bp6wn/files/4wtp3). **(A.3)** Predicted results under a purely feature-based account (as observed in baboons). **(A.4)** Chance-level performance.

averaged within subjects for each shape type. Then, group-level means were computed by averaging across participants. Using proportions rather than dwell times accounted for individual differences in overall looking times. PLTD ranged from 0 to 1 and was compared to chance (0.25), with values above 0.25 indicating longer looking at the deviant shape and values below 0.25 indicating longer looking at the standard shapes.

Results

Attendance On average infants contributed 14.25 valid trials (*SD* = 3.81, range: 8 to 22). Descriptively, the number of contributed trials decreased across blocks (Block 1: *M* = 4.96; Block 2: *M* = 4.21; Block 3: *M* = 3.55; Block 4: *M* = 2.59). Infants contributed a comparable mean number of trials across the six stimulus types (object: *M* = 2.75; equilateral triangle: *M* = 2.08; isosceles triangle: *M* = 2.46; square: *M* = 2.75; rhombus: *M* = 2.46; pentagon: *M* = 2.17).

On average, infants attended the screen 90.7% of the time during valid trials (*SD* = 5.1%, range = 81.2% to 99.1%). Screen attendance showed a gradual decline across blocks (Block 1: *M* = 93.9%, *SD* = 5.6%; Block 2: *M* = 90.7%, *SD* = 7.5%; Block 3: *M* = 90.1%, *SD* = 7.2%; Block 4: *M* = 85.9%, *SD* = 12.7%). Infants appeared to attend to the screen for longer during object (*M* = 96.7%, *SD* = 4.6%) than shape trials (equilateral triangle: *M* = 89.5%, *SD* = 8.1%; isosceles triangle: *M* = 87.1%, *SD* = 9.8%; square: *M* = 90.2%, *SD* = 9.1%; rhombus: *M* = 89.3%, *SD* = 9.9%; pentagon: *M* = 90.1%, *SD* = 7.3%).

Preliminary sanity checks Overall, no systematic low-level gaze biases were observed. Looking times did not differ across screen quadrants, stimulus size, or color.

Main analysis (proportion of looking time at the deviant, PLTD) Our primary focus was to investigate if and how shape mitigates performance in the intruder task. Figure 2B shows the average PLTD values across shapes (object: *M* = 0.33, *SD* = 0.12; equilateral triangle: *M* = 0.26, *SD* = 0.18; isosceles triangle: *M* = 0.20, *SD* = 0.14; square: *M* = 0.36, *SD* = 0.17; rhombus: *M* = 0.22, *SD* = 0.18; pentagon: *M* = 0.20 *SD* = 0.15).

A repeated-measures ANOVA with condition as a within-subject factor (object vs equilateral triangle vs isosceles triangle vs square vs rhombus vs pentagon) revealed a significant main effect, $F(5, 115) = 4.17$, $p = 0.002$, ges = 0.14, indicating that PLTD differed significantly across conditions. This effect remained significant when the object condition was excluded from the analysis, $F(4, 92) = 3.76$, $p = 0.007$, ges = 0.12, confirming that it was not driven solely by performance in the object trials.

To examine performance relative to chance (0.25), one-sample two-tailed *t* tests were conducted for each condition. PLTD was significantly above chance for objects, $t(23) = 3.03$, $p = 0.006$, $d = 0.62$, 95% CI [0.27, 0.38], and for squares, $t(23) = 3.17$, $p = 0.004$, $d = 0.63$, 95% CI [0.29, 0.43]. No other shape condition differed significantly from chance; all other *p*s > 0.07.

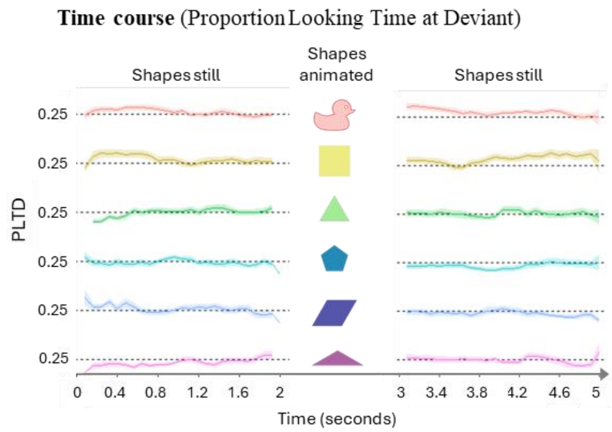

Figure 3: Time course of PLTD throughout the trial. Dotted lines indicate chance level (0.25).

Pairwise comparisons further showed that PLTD was significantly higher for squares than for isosceles triangles, $p = 0.014$, rhombi, $p = 0.025$, and pentagons, $p = 0.038$, after applying a Bonferroni correction for multiple comparisons. No significant differences were observed between squares and equilateral triangles or between squares and objects, *p*s > 0.350.

Figure 2C suggests that these results may have been driven primarily by infants' performance in blocks 1-2. In blocks 3–4, average PLTD appears to decline across both squares and objects, approaching chance.

Figure 3 illustrates the temporal dynamics of PLTD responses across the trial. Descriptively, PTLD appeared above chance only in the object and square conditions. This response was fast and sustained over the trial time. PLTD responses to other shapes remained around chance level over the trial time, suggesting that prolonged exposure did not facilitate finding the intruder.

Discussion

Our aim was to examine infants' ability to distinguish between geometric shapes and to explore the underlying shape processing mechanisms using a novel intruder task. The key finding is that shape regularity influenced infants' ability to find a deviant shape among standard ones. Infants succeeded at detecting deviant shapes in the square condition, as indexed by longer looking time to the deviant over standard shapes. However, they failed to do so in the other shape conditions. They also looked longer at the deviant stimulus in the real-world object trials, thereby validating our main measure and task, as they preferentially attended to obvious outlier stimuli in the absence of any explicit instructions or training.

This pattern of results does not perfectly align with any of the predicted outcomes. If infants relied purely on low-level feature-based processing, as observed in non-human primates (Sablé-Meyer et al., 2021), their performance should not have varied across geometric shapes. Conversely, if infants represented shapes through abstract combinations of geometric primitives, similarly to children and adults, they should have displayed a graded geometric regularity effect, with superior intruder detection for simpler and more regular shapes. Instead, infants showed reliable deviant detection specifically for squares, but not for other regular shapes such as equilateral triangles or pentagons. This selective success suggests that infants' geometric representations may not yet be fully abstract or systematically structured around combinations of geometric primitives. Rather, their performance may reflect sensitivity to a subset of particularly salient geometric properties (e.g. right angle, equal side length, parallelism) that in the current dataset were maximally instantiated in squares. Overall, preverbal infants' shape processing may reflect an early and still limited stage in the development of structured conceptual geometric representations.

Our results raise important questions about the language of thought proposed to characterize geometric cognition in humans (Dehaene et al., 2025). What geometric primitives are infants equipped with? How are these primitives composed into structured descriptions of increasing complexity? How are new primitives acquired over developmental time? Does the construction of fully structured geometric representations depend on the acquisition of external symbolic systems, such as natural language or formal mathematical notation? A central challenge for future research is to chart the developmental trajectory of geometric primitives and their combinatorial growth into the structured systems characteristic of mature human geometry. Comparing quadrilaterals such as squares, rectangles, trapezoids, and rhombi would make it possible to disentangle the relative salience of right angles, symmetry, parallelism, and side equality within a controlled class of shapes. Such a design would also enable more direct comparison with Sablé-Meyer et al.'s (2021) quadrilateral-based paradigm. We are currently pursuing this line of work to more precisely characterize the primitives and combinatorial operations available early in development.

Although "triangle" is among the first shape names acquired (around 25 months; Verdine et al., 2016), infants in the present study appeared to struggle to visually analyze this shape. Why might this be the case? One reason infants may have struggled to detect the intruder in the triangle trials could be related to the symmetry processing. Squares possess four axes of symmetry, point symmetry and rotational symmetry of order 4, whilst equilateral triangles possess only three axes of symmetry, no point symmetry and rotational symmetry of order 3 (*OSF Appendix Table 2: https://osf.io/bp6wn/files/4wtp3*). In adults, symmetry influences shape processing (e.g. Feldman, 2007; Kayaert & Wagemans, 2009). If similar principles operate in infancy, shapes with greater symmetry may be encoded more robustly. Supporting this view, Bornstein et al. (1981) found that by 4 months of age, infants process vertically symmetrical shapes more efficiently than asymmetrical ones (see also Fisher et al., 1981). The square's multiple symmetry axes may have afforded a more stable structural representation across minor orientation changes.

Another possible explanation for infants' success in the square condition, but not in the equilateral triangle condition, concerns the type of angles defining each shape. In many Western urban environments, right angles are pervasive in architecture, furniture, and everyday objects, potentially rendering rectilinear structures especially familiar even early in life (Roberson et al., 2002). Greater exposure to orthogonal structures may enhance sensitivity to deviations from right angles, thereby facilitating intruder detection in square trials. Although Sablé-Meyer et al. (2021) addressed environmental exposure in adults by including participants from non-carpentered backgrounds, environmental regularities may play a more pronounced role in infancy, when visual experience is still accumulating.

Further, unlike in Sablé-Meyer et al. (2021), shapes in the current task were not rotated relative to each other. As a result, parallel sides aligned across shapes. An orientation-detection mechanism would spot deviants more easily in shapes with more parallel sides. This would explain the square's results but predict identical performance for square and rhombus, which does not match our data.

Future research could also replicate the current intruder task in adults. If adults similarly show greater difficulty with equilateral triangles than squares, it would suggest that complexity does not scale with the number of sides and/or that adults may weigh certain primitives (e.g. parallelism, right angles) higher than others. Conversely, if adult performance worsens with the increasing number of sides, it will indicate a developmental change in representational structure.

This line of work may be of interest for early childhood education and the design of learning materials. Infants' ability to detect deviants among squares, but not other geometric forms, suggests that early shape learning may benefit from an initial focus on simpler, highly regular shapes. This aligns with educational frameworks that introduce shapes like squares and circles before more complex polygons (Clements & Sarama, 2007). Understanding that young children may respond more readily to symmetry and right angles could help inform how geometric concepts are introduced in books, toys, and early teaching strategies, ultimately supporting the development of mathematical reasoning from infancy.

To conclude, the present study introduced an eye-tracking intruder task as a promising method for probing the nature of early geometric representations and showed that infants' performance in this task is selectively influenced by shape. Infants reliably detected deviants only in the square condition and in the object control condition. This behavior is in line with the idea that a combinatorial system for shape representation may be under construction during infancy and calls for future work to characterize it. It also opens the possibility of probing more fine grand theories of geometric shape representation with eye-tracking.

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