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Tactile Exploratory Procedures of Individuals with Blindness in Identifying Two-Dimensional Geometric Shapes

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Abstract

The objective of this pilot study was to clarify the tactile exploratory procedures (TEPs) used by adults with congenital and early-onset blindness when exploring two-dimensional cut-out geometric shapes, with particular attention to patterns of TEP use and how these varied with shape size and complexity. A total of five adults with blindness participated in the study. Each participant was presented with small and large two-dimensional geometric shapes ranging from simple to complex. Eight types of TEPs were observed in total, with some variation in their use across participants, shape sizes, and levels of shape complexity. Despite this variation, a clear overall pattern emerged, with the findings suggesting that contour following, global enclosure, and partial enclosure constitute the core TEPs for exploring two-dimensional geometric shapes.

Keywords: individuals with blindness; tactile exploratory procedures; two-dimensional shapes; simple and complex shapes

1. Introduction

Geometry is a major component of mathematics education from early childhood through secondary education, accounting for a substantial and relatively consistent proportion of mathematics content, alongside other major areas such as numbers, algebra, measurement, data, and probability (Trimurtini et al., 2022). At the same time, visual representations, including geometric figures and diagrams, play an important role in the learning of geometry (Žakelj & Klančar, 2022). In classrooms where much of this mathematical content is presented visually, it is important to ensure that students who are blind have equitable access to the same content through appropriate nonvisual means.

For students who are blind, geometric information is commonly presented through tactile graphics and manipulative materials, including embossed representations and two-dimensional cut-outs. Because tactile perception differs fundamentally from visual perception, such materials must support the sequential acquisition and integration of spatial information. Although the design and quality of tactile materials influence their comprehensibility, successful interpretation also depends on how learners actively move their hands and fingers to locate boundaries, examine distinctive features, and construct an understanding of the overall shape (Herzberg et al., 2023; Rosenblum et al., 2018; Zebehazy, 2014). Thus, accessibility cannot be understood solely as a property of the tactile representation; it also depends on the tactile exploratory strategies through which the representation is examined.

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Understanding information through touch involves complex perceptual and cognitive processes (Aldrich et al., 2003; Lederman & Klatzky, 2009). In the case of geometric information, acquiring the shape through touch requires the integration of tactile information across space and time (A. A. Kalia & Sinha, 2012). That is, whereas vision can provide relatively simultaneous access to the spatial configuration of a shape, touch is sequential. The individual must therefore actively move the hands and fingers across the shape, obtain local pieces of information over time, retain this information, and integrate it into a representation of the overall shape. Once the shape has been acquired, the individual must then interpret this information and associate it with an existing representation of an object or geometric shape.

A substantial body of research has examined how humans actively use their hands to explore and obtain information about objects. One of the foundational studies in this area was conducted by Lederman and Klatzky (1987), who identified eight typical patterns of hand and finger movements, referred to as "exploratory procedures", each associated with obtaining particular types of information about an object. These include enclosure, contour following, and lateral motion. Although Lederman and Klatzky's work focused primarily on three-dimensional objects, their classification of EPs has subsequently been used as a framework for examining tactile exploration of different types of stimuli, including tactile graphics/pictures (Bara, 2014; Vinter et al., 2012; Zhao et al., 2021), and two-dimensional cutout shapes (A. Kalia et al., 2014). In addition, a broader body of research on tactile exploration has identified several strategies associated with better tactile perception and recognition. For example, bimanual exploration has been shown to result in better performance than unimanual exploration (Morash et al., 2014; Vinter et al., 2012), while using multiple fingers rather than one or only a few fingers allows more tactile information to be acquired at once (Klatzky et al., 1993). Research has also shown that the use of Eps varies with age and developmental experience (Morrongiello et al., 1994).

Exploratory procedures should not be regarded as isolated or interchangeable hand movements. Rather, their selection is functionally related to the information that the individual seeks to obtain. As mentioned above, the work of Lederman and Klatzky (1987) demonstrated that particular tactile procedures are especially well suited to extracting specific object properties, such as exact shape, texture, weight, and volume. This functional specificity has subsequently been supported in research involving participants who were blind. In a tactile object-matching task, Withagen et al. (2012) found that both blind and sighted participants could distinguish object properties through active touch, although performance was influenced more strongly by age than by visual status. A subsequent, more detailed analysis of exploratory behavior showed that congenitally blind and sighted children and adults generally selected the same dominant exploratory procedure when examining weight, size, exact shape, and texture (Withagen et al., 2013). Nevertheless, children tended to employ more procedures than necessary, whereas repeated experience with the task increased exploratory efficiency across groups. Similarly, Argyropoulos and Chamonikolaou (2016) found that adults with blindness used different movements to obtain global and featural information from geometric shapes; for example, enclosure supported the apprehension of global shape, whereas contour following contributed to the examination and confirmation of more exact shape properties. The above findings suggest that tactile exploration is a goal-directed and adaptive process in which procedures are selected, combined, and refined according to the information sought, the characteristics of the stimulus, and the individual's tactile experience.

In addition, tactile exploration may also be organized into recurrent patterns and coordinated sequences rather than consisting of a random succession of movements. In their examination of two-dimensional tactile images, Vinter et al. (2012) found that children who

were blind or had low vision employed a broader range of procedures and used bimanual exploration more frequently than blindfolded sighted children. Among children who were blind, contour following also increased with age, suggesting that exploratory strategies may become progressively differentiated through development and tactile experience. Research using three-dimensional objects has similarly shown that employing both hands and multiple fingers can improve haptic performance by expanding the perceptual field and increasing the amount of information acquired simultaneously (Morash et al., 2014). More recent evidence indicates that congenital blindness may shape the spatial organization of exploration. For example, Leo et al. (2022) found that congenitally blind adults contacted a larger tactile area simultaneously and changed their patterns of contact more rapidly than late-blind and sighted participants, with broader simultaneous contact associated with shorter exploration time. These findings complement evidence of recurring combinations of holding, rotating, contour tracing, and fingertip examination among children with visual impairment and multiple disabilities (Papazafiri & Argyropoulos, 2023). Accordingly, the analysis of which procedures occur, how they are sequenced, and how the two hands assume complementary roles may provide a more informative account of tactile shape exploration than recognition accuracy alone.

Although previous research demonstrates the importance of exploratory procedures in tactile object and shape recognition, detailed evidence concerning the exploration of two-dimensional cut-out geometric shapes remains limited (Argyropoulos & Chamonikolaou, 2016; A. Kalia et al., 2014; Theurel et al., 2012). For instance, Argyropoulos and Chamonikolaou (2016) explored hand movements employed by individuals with visual impairment when examining and observing geometric shapes. However, their study included both two- and three- dimensional shapes made from different materials with different textures, with the aim of examining exploratory movement across these different stimulus characteristics.

To the authors' knowledge, A. Kalia et al. (2014) research is one of the few studies that focused specifically on two-dimensional cut-out geometric shapes and the exploratory procedures of individuals with visual impairment. Their study compared the recognition of two-dimensional cutouts with embossed representations, taking into account differences in the exploratory procedures afforded by their physical characteristics. In particular, two-dimensional cutouts allow enclosure, an exploratory procedure considered optimal for assessing global shape, whereas the physical characteristics of embossed representations constrain the use of this procedure. Their analysis therefore focused primarily on recognition accuracy and differences between the two types of representations, rather than on a detailed examination of the exploratory hand movements employed when examining two-dimensional cutouts. Thus, less is known about the specific types of exploratory procedures employed by individuals with congenital blindness when examining two-dimensional cutout geometric shapes, how these movements are combined and sequenced, and how exploratory strategies may vary according to stimulus characteristics such as size and geometric complexity. Addressing these questions may provide a stronger empirical foundation for the systematic teaching of tactile exploration strategies to students who are blind.

The present study was conducted as a pilot investigation for a larger research project examining tactile exploratory procedures of two-dimensional cutout shapes among students who are blind in school settings. Given the limited research in this area, this initial study involved a small number of adults with congenital and early-onset blindness who had extensive experience obtaining information through touch. The pilot study was conducted to examine the feasibility of the stimuli, observation methods, and coding procedures before applying the approach to school-aged students who are blind.

The objective of this pilot study was to clarify the tactile exploratory procedures (TEPs) used by adults with congenital and early-onset blindness when exploring two-dimensional

cut-out geometric shapes, with particular attention to TEPs employed and the influence of shape characteristics on TEP use.

The research questions addressed were as follows.

RQ1. What tactile exploratory procedures (TEPs) and usage patterns are observed across individuals with blindness during the exploration of geometric shapes?

RQ2. How does geometric shape size (large vs. small) influence tactile exploratory procedure (TEP) selection and usage patterns during the exploration of geometric shapes by individuals with blindness?

RQ3. How does shape complexity (simple vs. complex) influence tactile exploratory procedure (TEP) selection and usage patterns during the exploration of geometric shapes by individuals with blindness?

2. Materials and Methods

2.1. Participants and Recruitment

Given the exploratory nature of this pilot study, participants were recruited using purposive sampling via professional networks. Specifically, teachers at one of the largest schools for the blind in Japan with established connections to individuals with blindness assisted in identifying and contacting potential participants who met the inclusion criteria. The inclusion criteria required participants to be adults (18 years of age or above) with congenital or early-onset blindness, and substantial experience in braille use. Ethical approval for the study was obtained from the Institutional Review Board of the first author prior to data collection (Approval No. TSU2025-280A).

A total of 5 participants (4 male, 1 female) participated in the study (Table 1). Participants ranged in age from their 20s to mid-50s. Most participants experienced blindness onset before the age of five, although one participant reported onset at approximately 10 years of age. All participants had used braille as their primary literacy medium from primary or lower secondary school and reported enjoying tactile exploration. Three participants reported a strong interest in mathematics and geometry, whereas the remaining two reported a moderate level of interest. With regard to occupation, three participants were engaged in mathematics-related fields, including teaching and research, one participant worked as a teacher in a non-mathematics field, and one participant was employed outside the education and research sectors.

Table 1. Participant Profiles.

Participant	Age	Gender	Interest in Math/Geometry	Occupational/Academic Field
A	50s	M	Strong	Mathematics-related
B	50s	M	Strong	Mathematics-related
C	20s	M	Moderate	Other
D	40s	F	Moderate	Education, non-mathematics
E	20s	M	Strong	Mathematics-related

2.2. Materials and Data Collected

The stimuli consisted of two sets of small and two sets of large shapes, each containing four different geometrical shapes. All shapes were constructed from 1 mm thick wood pulp-based paperboard with a smooth, paper-like surface. This material is commonly used in schools for the blind in Japan to produce two-dimensional cutouts for instructional

purposes and is familiar as a material that is comfortable to touch and explore. The material was also selected for its resistance to tearing and bending during tactile exploration. All shapes were cut using laser cutting to ensure precise, sharp edges and well-defined contours, which are critical for tactile perception by individuals with blindness.

All small shapes had a maximum dimension of 4–6 cm, which can be explored using one hand, and all large shapes had a maximum dimension of 12–16 cm, which required exploration using two hands. To determine what constituted small and large shapes, the dimensions were first selected based on the sizes of geometric shapes commonly presented in braille mathematics textbooks used in schools for the blind in Japan. The proposed sizes were then reviewed by experienced teachers at schools for the blind to ensure that they were appropriate for tactile exploration.

The shapes used included both basic geometric shapes and shapes that were combinations of basic geometric shapes, ranging from simple to complex. Shape complexity was informed by the Property-Based Shape Sequence proposed by Nurnberger-Haag and Thompson (2023), in which "simple" shapes are defined as those that are mathematically easier to define and possess simpler properties that children are prepared to learn (Nurnberger-Haag & Thompson, 2023).

Based on these criteria, shapes were classified into four levels of complexity (Table 2). Level 1 (very low complexity) included shapes with few and simple defining properties (e.g., circle, triangle). Level 2 (low-to-moderate complexity) included shapes with a greater number and moderately more difficult defining properties (e.g., square, parallelogram, sector). Level 3 (moderate-to-high complexity) included shapes with more numerous and more difficult defining properties (e.g., hexagon, octagon). Level 4 (high complexity) included shapes with the greatest number of and the most difficult defining properties (e.g., six-pointed star, Koch snowflake). The final selection of shapes and their complexity classifications were also reviewed by experienced teachers at schools for the blind.

Table 2. Types of shapes and levels of complexity.

		Types of Shapes	Complexity Level (1–4)
Small	Set 1	Right triangle	1
		Scalene triangle	1
		Square	2
		Parallelogram	2
	Set 2	Pentagon	2
		Hexagon	3
		Octagon	3
		Five-pointed star	4
Large	Set 3	Circle	1
		Semi-circle	1
		Sector	2
		Cardioid	2
	Set 4	Circle	1
		Ellipse	1
		Six-point star	4
		Koch Snowflake	4

Data collected included hand movements (left and right hands), think-aloud verbalizations, task completion time, and participant demographic and background information (i.e., age group, gender, age of blindness onset, braille use, occupation, enjoyment of tactile

exploration, and interest in mathematics and geometry). All data were recorded using a video camera, allowing for time-stamped and synchronized analysis.

2.3. Procedure

2.3.1. Positioning

Participants were seated comfortably at a table. The experimenter was positioned across from the participant, and a camera was placed at the top right-hand side of the participant to capture both hand movements and the shapes being explored. The video recordings also captured participants' concurrent verbalizations during shape exploration. For each participant, one of the two sets within each size condition was randomly selected (Set 1 or 2 for the small condition and Set 3 or 4 for the large condition).

2.3.2. Explanation and Practice

The experiment lasted approximately 60 min per participant. At the beginning of the session, participants were provided with an overview of the experiment and gave informed consent. Participants were informed that they could withdraw from the experiment at any time if they chose to do so. All instructions were provided verbally to ensure accessibility. Participants were informed that they would be presented with four different shapes and asked to explore each shape freely and report what they thought the shape was. They were also instructed to verbalize their thoughts continuously throughout the exploration.

Prior to the formal experiment, participants completed a practice trial using a cut-out shape that was not included in the main task. The purpose of the practice trial was to familiarize participants with the experiment, including tactile exploration and verbalizing their thoughts during exploration. Participants were informed that there were no correct or wrong answers and were encouraged to explore the shapes naturally while verbalizing their thoughts.

2.4. Data Analysis

The dataset consisted of video recordings capturing participants' hand movements and concurrent verbalizations during tactile exploration. Exploration time was measured from the video recordings. Although think-aloud verbalizations were collected during the exploration sessions, they were not analysed in the present study, because the authors wanted to focus specifically on the identification and patterns of TEPs.

The initial coding framework was developed by drawing on established classifications of haptic exploratory movements, particularly the exploratory procedure framework of Lederman and Klatzky (1987), together with subsequent work on the tactile exploration of two-dimensional patterns and geometric properties (Davidson, 1972; Vinter et al., 2012). The resulting coding framework, termed the Hand Exploration and Manipulation Protocol (HEMP), was designed to characterize participants' exploratory and manipulative hand movements during interaction with the geometric shapes. The initial protocol served as a provisional framework whose categories and operational definitions were examined against the recorded movements. During its refinement, the authors considered whether categories could be distinguished consistently and whether they adequately described exploration of the two-dimensional cut-out shapes. The initial version included 11 categories. However, three—Pressure, Static Contact, and Unsupported Holding—were not observed in the dataset and were therefore removed. The final HEMP comprised eight hand-movement categories; that is, surface sweeping, global enclosure, partial enclosure, pinch procedure, contour following, flipping/rotating, tapping, and holding (see Table 3). For each participant, the recordings were examined by shape trial, with left- and right-hand movements documented separately. The three authors produced independent observa-

tions and subsequently compared their classifications and descriptions of the exploratory sequences. Differences in category assignment, uncertain movements, and the distinction between exploratory and holding movements informed the discussions used to refine the operational definitions.

Table 3. Hand Exploration and Manipulation Protocol (HEMP).

	Hand Movement	Exploration Procedure
SS	Surface sweeping	Dynamic and usually repetitive movement of one or more fingers or of the palm over the model's surface, similar to Lateral motion
GE	Global enclosure of the shape	Dynamic moulding of the palm and/or fingers to the shape's contour
PE	Partial enclosure of local pattern	Dynamic moulding of the fingers to parts of the pattern
PP	Pinch procedure	Holding edges in a pincer grip between the thumb and one or more other fingers
CF	Contour following	Dynamic edge following using finger movements
FR	Flipping/rotating the object	Flipping or rotating the object clockwise or anticlockwise
TO	Tapping the object	Tapping the object with fingers and hear the sound it makes
HO	Holding the object	Holding the object in a fixed position (HWR for holding the object in a fixed position but allowing wrist movements such as wrist rotation)

Following the initial coding, the authors met to compare their classifications, discuss discrepancies, and refine the operational definitions where necessary. This iterative process continued until consensus was reached on the final coding. The grounding of the framework in established classifications, independent examination of the recordings, and explicit discussion of discrepant observations supported the credibility of the coding process. However, these procedures do not constitute formal validation of HEMP or a quantitative assessment of inter-rater reliability. The researchers subsequently re-examined the recordings individually to identify recurring patterns and sequences of hand movements.

3. Results

The results are organized according to the three research questions. First, we describe the tactile exploratory procedures (TEPs) and participant-specific patterns observed during exploration of small and large geometric shapes (RQ1). We then present descriptive comparisons of TEP frequencies and relative proportions across the two shape-size conditions (RQ2) and the four levels of shape complexity (RQ3). The participant-level descriptions highlight recurring combinations and distinctive exploration patterns, while the tables provide the detailed sequences and frequency distributions.

3.1. Types of TEPs Observed During Tactile Exploration (RQ1)

Eight types of TEPs were observed across the exploration trials. Contour following (CF) was a recurring component of exploration, although participants differed in the procedures used alongside it and in the length and variety of their exploratory sequences. The following subsections describe these patterns separately for small and large shapes, using the same participant order to facilitate comparison.

3.1.1. Small Shapes

Exploration of small shapes showed variation in the combinations of contour following (CF), enclosure [partial (PE) or global (GE)], surface sweeping (SS), and object manipulation (FR). Some participants frequently alternated between procedures, whereas others relied on a more restricted repertoire. Table A1 (see Appendix A.1) presents the complete sequences recorded for the left and right hands, together with exploration times. The descriptions below highlight the principal patterns for each participant.

Participant A, who was presented with the Set 2 stimuli, used contour following (CF), surface sweeping (SS), partial enclosure (PE), and global enclosure (GE) as the main exploratory procedures across the four shapes. The use of these procedures varied across shapes. When examining the five-pointed star, Participant A used contour following (CF), surface sweeping (SS), partial enclosure (PE), and global enclosure (GE), with occasional use of pinch procedure (PP) to examine salient features such as the points of the star. During exploration of the pentagon and octagon, global enclosure (GE) was used frequently, together with contour following (CF), to examine the shapes' boundaries. For the hexagon, contour following (CF), surface sweeping (SS), and enclosure procedures were used.

In terms of sequence, participant A's exploration was characterized by frequent transitions between local and global exploratory procedures. Local exploration often involved sequences combining partial enclosure (PE) and contour following (CF), whereas global exploration frequently involved global enclosure (GE) and contour following (CF). These procedures were used in combination rather than as isolated movements, with participant A moving between examination of local features and assessment of the whole shape. Overall, participant A adopted an exploration strategy that systematically combined local and global shape information across the different shapes.

Participant B, who was given the Set 1 stimuli, primarily relied on global enclosure (GE), contour following (CF), and object rotation (FR). Exploration of the square involved repeated enclosure (GE and PE) and contour following (CF) movements to assess edge regularity. For both triangular shapes, contour following (CF) was frequently combined with object rotation (FR), likely to identify angular relationships and side lengths. The parallelogram was explored through enclosure, rotation, and contour tracing. In general, participant B relied primarily on global enclosure (GE), contour following (CF), and object rotation (FR) during shape exploration.

Participant C, who was presented with the Set 2 stimuli, displayed the most diverse repertoire of TEPs across all explored shapes. While examining the hexagon, the participant repeatedly alternated between contour following (CF), global enclosure (GE), surface sweeping (SS), object rotation (FR), and tapping (TO). Similar contour-based exploration (CF) was observed for the pentagon and octagon, although these shapes also involved occasional enclosure (GE) and manipulation (FR). For the five-pointed star, rotation (FR), contour following (CF), partial enclosure (PE), and pinch procedure (PP) were used to investigate the distinctive points and overall structure.

Participant D, who was given the Set 1 stimuli, adopted a predominantly contour-following (CF) strategy. The square was explored mainly through contour tracing (CF) with occasional partial enclosure (PE), while the right triangle and parallelogram were investigated almost exclusively through repeated contour following (CF) movements. Exploration of the scalene triangle similarly relied on tracing (CF) the edges and boundaries of the shape. Compared with the other participants, participant D showed limited use of enclosure (that is, no GE and very few PE) or object manipulation (such as FR) procedures.

Participant E, who was also given the Set 1 stimuli, primarily used contour following (CF), partial enclosure (PE), and object manipulation (FR). The square and parallelogram

were primarily explored through combinations of contour following (CF) and partial enclosure (PE), accompanied by brief rotation (FR) movements that facilitated rapid assessment of their overall shape. In contrast, exploration of the right-angled and scalene triangles relied mainly on contour following (CF), rotation (FR), and pinch procedure (PP), enabling the participant to identify salient geometric features, such as edges and vertices, with minimal exploratory actions. Overall, participant E employed fewer exploratory movements and considerably shorter exploration sequences than the other participants, spending a total 64 s exploring all four shapes, whereas participants D and B dedicated 153 s and 102 s respectively for the same shapes.

Overall, contour following recurred across participants, but its combinations with other procedures differed. Participant A frequently alternated between enclosure and contour following, Participant B combined these procedures with rotation, and Participant C used a varied repertoire that included tapping. Participant D relied mainly on contour following and holding, whereas Participant E used short sequences incorporating contour following, enclosure, rotation, and pinching. These findings show variation in how participants combined procedures during small-shape exploration.

3.1.2. Large Shapes

Contour following (CF) also recurred during exploration of large shapes, alongside partial enclosure (PE), holding, and rotation (HO & FR). Participant differences were evident in both the composition of the TEPs and length of the sequences. Table A2 (see Appendix A.2) presents the complete hand-specific sequences and exploration times. The following descriptions summarize the main sequences of TEPs observed while each participant explored large geometric shapes.

Participant A, who was presented with the Set 4 stimuli, explored the shapes using a combination of contour following (CF), partial enclosure (PE), global enclosure (GE), and object manipulation (HO, FR, PP). Exploration of the circle was dominated by repeated contour-following (CF) movements interspersed with global enclosure (GE) and rotation (FR). The ellipse was explored primarily through partial enclosure (PE) and object holding (HO), followed by contour following (CF) and rotation (FR). For the snowflake and six-pointed star, participant A alternated between contour following (CF) and partial enclosure (PE), occasionally employing pinch procedure (PP) and rotation (FR). Overall, Participant A adopted a systematic exploration strategy that integrated global exploration, frequently involving global enclosure (GE) and contour following (CF) with detailed local exploration, involving partial enclosure (PE), contour following (CF), and pinch procedure (PP).

Participant B, who was presented with the Set 3 stimuli, adopted a concise exploration strategy characterized by relatively short exploration sequences, and shorter exploration times than the other participants. For example, Participant B explored the circle in 10 s, compared with 23–49 s for the other participants (M = 30.75 s). The circle and semicircle were explored mainly through contour following (CF) combined with global (GE) and partial enclosure (PE), whereas the sector relied more heavily on rotation (FR) and enclosure procedures, including both global (GE) and partial (PE). The cardioid was examined almost exclusively through contour following (CF) with minimal manipulation.

Participant C, who was also presented with Set 3 stimuli, demonstrated the broadest repertoire of tactile exploratory procedures across all large shapes and dedicated a relatively great amount of time to exploration and manipulation (127 s in total). Exploration of the cardioid involved frequent alternation between contour following (CF), partial enclosure (PE), surface sweeping (SS), tapping (TO), and pinch procedure (PP). Similar combinations of contour following (CF), rotation (FR), enclosure procedures (PE and GE), and tapping (TO) were observed during exploration of the sector, semicircle, and circle. Compared with

the other participants, Participant C employed the most diverse and extensive sequences of exploratory procedures, with frequent tapping (TO) and flipping/rotating (FR) of the object occurring across the different shapes.

Participant D, who was presented with Set 3 stimuli, relied predominantly on contour following (CF) throughout exploration of the shapes. The circle and cardioid were examined mainly through repeated contour tracing (CF) with occasional partial (PE) or global enclosure (GE). Exploration of the sector and semicircle similarly involved repeated contour-following movements (CF), supported by object holding and limited enclosure procedures. Compared with the other participants, Participant D showed relatively little object manipulation, relying primarily on repeated tracing (CF) of the object boundaries, often while holding (HO) the object.

Participant E, who was given the Set 4 stimuli, adopted an exploration strategy that varied according to shape complexity. The ellipse and circle were explored through short sequences combining contour following (CF) with partial (PE) or global enclosure (GE) and flipping/rotating (FR). In contrast, the six-pointed star and snowflake elicited considerably longer and more varied exploration sequences involving repeated contour following (CF), partial enclosure (PE), pinch procedure (PP), rotation (FR), and occasional global enclosure (GE). Compared with the simpler curved shapes, these more geometrically complex stimuli involved substantially longer exploration times (66 s and 90 s, respectively) and a wider range of tactile exploratory procedures.

Overall, large-shape exploration retained contour following as a recurring procedure while showing distinct participant patterns. Participants A and E repeatedly combined contour following (CF) and partial enclosure (PE) when exploring the complex shapes. Participant B used comparatively short sequences, Participant C frequently incorporated tapping (TO) and rotation (FR), and Participant D relied mainly on contour following (CF) and holding (HO). Several participant characteristics therefore recurred across the two size conditions, although the procedures and sequence lengths also varied with the particular stimuli explored.

3.2. Influence of Shape Size on TEP Use and Usage Patterns (RQ2)

To investigate the influence of shape size on TEPs, the frequency of each TEP across all participants was calculated and compared between the small- and large- shapes. For each size condition, TEP occurrences were pooled across all geometric shapes, regardless of shape complexity.

Table 4 presents the frequencies and relative percentages of the eight tactile exploratory procedures recorded during the exploration of small and large geometric shapes. A total of 297 TEP occurrences were recorded for small shapes and 257 for large shapes. Contour Following (CF) was the most frequently recorded procedure in both conditions, accounting for similar proportions of all procedures used with small and large shapes (30.6% and 31.5%, respectively). These percentages revealed something particularly interesting and useful. Although contour following (CF) occurred more often in absolute terms for small shapes, its proportional use was similar across the two conditions—30.6% and 31.5%. Flipping/rotating (FR), pinch procedure (PP), and holding (HO) were also proportionally similar across two conditions. The clearest proportional differences remain in surface sweeping (SS), global enclosure (GE), partial enclosure (PE), and tapping (TO). More specifically, the largest proportional differences between the two size conditions were observed for surface sweeping (SS) and partial enclosure (PE). Surface sweeping (SS) represented 9.4% of the procedures recorded for small shapes but only 2.3% of those recorded for large shapes, a difference of 7.1 percentage points. Conversely, partial enclosure (PE) accounted for 17.1% of the procedures used with large shapes, compared with 10.4% for small shapes,

a difference of 6.7 percentage points. Global enclosure (GE) also represented a larger proportion of the procedures recorded for small shapes than for large shapes (12.1% vs. 7.8%), whereas tapping the object (TO) represented a larger proportion for large shapes than for small shapes (5.1% vs. 2.0%).

Table 4. Frequency and percentage of tactile exploratory procedures (TEPs) by shape size (large vs. small).

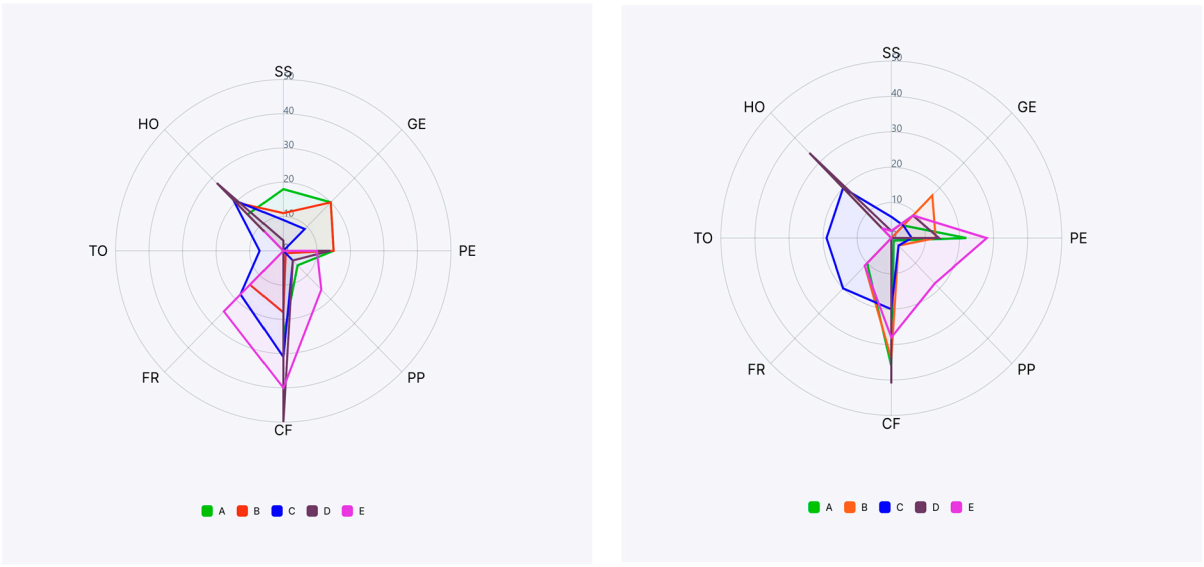
Tactile Exploratory Procedure (TEP)	Small Shapes (4–6 cm), *n* (%)	Large Shapes (12–16 cm), *n* (%)
Surface sweeping (SS)	28 (9.4)	6 (2.3)
Global enclosure (GE)	36 (12.1)	20 (7.8)
Partial enclosure (PE)	31 (10.4)	44 (17.1)
Pinch procedure (PP)	17 (5.7)	13 (5.1)
Contour following (CF)	91 (30.6)	81 (31.5)
Flipping/rotating (FR)	34 (11.4)	30 (11.7)
Tapping the object (TO)	6 (2.0)	13 (5.1)
Holding the object (HO)	54 (18.2)	50 (19.5)
Total	297 (100)	257 (100)

Note. Values are *n* (%), where *n* denotes recorded TEP occurrences pooled across participants, shape trials, and both hands within each size condition. Percentages may not sum to 100 because of rounding.

The proportional use of the remaining procedures was relatively similar across the two conditions. Pinch procedure (PP) accounted for 5.7% of the procedures used with small shapes and 5.1% of those used with large shapes. Similarly, flipping/rotating (FR) represented 11.4% and 11.7%, respectively, while holding (HO) accounted for 18.2% of the procedures used with small shapes and 19.5% of those used with large shapes. Thus, the descriptive comparison showed minimal proportional differences for contour following (CF), pinch procedure (PP), flipping/rotating (FR), and holding (HO), whereas more pronounced differences were observed for surface sweeping (SS), global enclosure (GE), partial enclosure (PE), and tapping (TO).

To facilitate comparison of TEP use between small and large shapes, radar charts were generated for each participant. The radar charts provide a visual representation of the frequency with which each TEP was employed by the participants, illustrating the relative contribution of individual exploratory procedures and enabling comparisons of exploration profiles across size. In specific, Figures 1 and 2 complement the frequency distributions in Table 4 by illustrating the relative contribution of each procedure to the exploration profiles. Figure 1 presents the individual participant profiles for small shapes (Figure 1a) and large shapes (Figure 1b), illustrating differences in the relative use of TEPs within each size condition. Figure 2 compares the pooled percentage distributions for the two size conditions. The TEP profile for small shapes (i.e., Figure 1a) is characterized by its highest point at contour following (CF), followed by holding (HO), while global enclosure (GE), flipping/rotating (FR), partial enclosure (PE), and surface sweeping (SS) occupy intermediate positions. Lower values are displayed for pinch procedure (PP) and tapping (TO). Figure 1b presents the corresponding TEP profile for large geometric shapes. As in Figure 1a, the highest point occurs at contour following (CF), followed by holding (HO); however, partial enclosure (PE) is more prominent in this profile. Surface sweeping (SS) has the lowest position, while global enclosure (GE), flipping/rotating (FR), pinch procedure (PP), and tapping (TO) occupy intermediate or lower positions in the chart.

Finally, Figure 2 puts together the two profiles to facilitate direct comparison between the size conditions. The profiles overlap closely for contour following (CF), flipping/rotating (FR), pinch procedure (PP), and holding (HO), whereas greater separation is visible for surface sweeping (SS), global enclosure (GE), partial enclosure (PE), and tapping (TO). Surface sweeping (SS) and global enclosure (GE) occupy higher positions in the small-shape profile, while partial enclosure (PE) and tapping (TO) occupy higher positions in the large-shape profile.



(**a**) (**b**)

Figure 1. Distribution of tactile exploratory procedures (TEPs) recorded for: (**a**) small geometrical shapes and (**b**) large geometrical shapes. Note. Each line represents one participant (A–E). Radial values are percentages of that participant's TEP occurrences within the relevant size condition, pooled across the four shape trials and both hands. SS = surface sweeping; GE = global enclosure; PE = partial enclosure; PP = pinch procedure; CF = contour following; FR = flipping/rotating; TO = tapping the object; HO = holding the object.

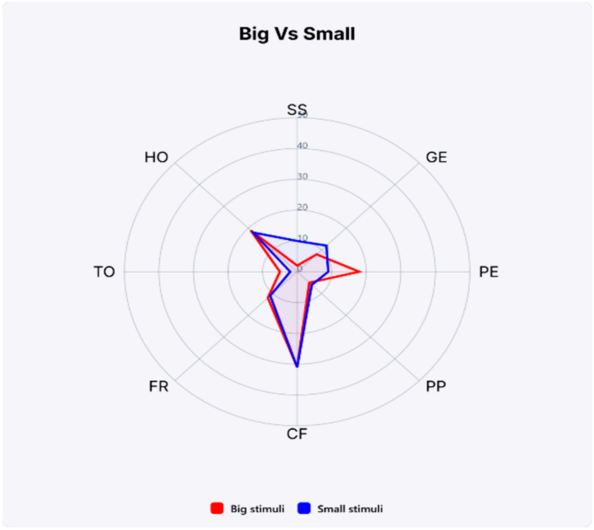


Figure 2. Comparison of pooled TEP distributions for small and large shapes.

Overall, the proportional prominence of contour following (CF) was stable across the size conditions. The clearest differences were the greater representation of surface

sweeping (SS) in small-shape exploration and partial enclosure (PE) in large-shape exploration. Smaller differences were observed for global enclosure (GE) and tapping (TO), while pinch procedure (PP), flipping/rotating (FR), and holding (HO) showed relatively similar proportions.

3.3. Influence of Shape Complexity on TEP Use and Pattern Use (RQ3)

The complexity comparison examines how the relative distribution of TEPs differed across the four complexity levels. Table 5 demonstrates how shape complexity influenced the selection and combination of TEPs. Table 5 presents these distributions, while Figure 3 provides a visual comparison. The main distinction concerns the highest-complexity level, where partial enclosure and pinch procedure were more prominent than at the other levels. Across all four levels of complexity, contour following (CF) remained one of the most predominant exploratory procedures, indicating its central role in extracting shape information regardless of stimulus complexity. However, the relative use of the remaining TEPs varied according to the geometric characteristics of the objects. For simple and moderately complex shapes, participants frequently combined contour following with global enclosure (GE), holding (HO), and flipping/rotating (FR). As complexity increased, exploration strategies shifted towards greater use of partial enclosure (PE) and pinch procedure (PP). This trend was most evident for the highly complex shapes (five-pointed star, six-pointed star, and snowflake), where partial enclosure (PE) showed the highest frequency (29 occurrences) and pinch procedure (PP) increased markedly (17 occurrences), while the use of global enclosure (GE) and holding (HO) declined substantially. In contrast, surface sweeping (SS) and tapping (TO) did not exhibit a consistent relationship with object complexity, occurring only sporadically across the four complexity levels.

Table 5. Frequency and percentage of tactile exploratory procedures (TEPs) across different levels of shape complexity.

TEP	Level 1 *n* (%)	Level 2 *n* (%)	Level 3 *n* (%)	Level 4 *n* (%)
SS	3 (3.0%)	7 (7.0%)	14 (14.0%)	5 (5.0%)
GE	12 (12.0%)	11 (11.0%)	12 (12.0%)	4 (4.0%)
PE	7 (7.0%)	14 (14.0%)	5 (5.0%)	29 (29.0%)
PP	4 (4.0%)	2 (2.0%)	0 (0.0%)	17 (17.0%)
CF	34 (34.0%)	29 (29.0%)	33 (33.0%)	27 (27.0%)
FR	16 (16.0%)	11 (11.0%)	9 (9.0%)	8 (8.0%)
TO	2 (2.0%)	5 (5.0%)	7 (7.0%)	0 (0.0%)
HO	22 (22.0%)	21 (21.0%)	20 (20.0%)	10 (10.0%)

Note. Values represent the percentage of all recorded TEPs occurrences within each complexity level. SS = Surface Sweeping; GE = Global Enclosure; PE = Partial Enclosure; PP = Pinch Procedure; CF = Contour Following; FR = Flipping/Rotating; TO = Tapping the Object; HO = Holding the Object.

Overall, contour following (CF) remained prominent across complexity levels, but the Level 4 distribution was distinguished by greater proportional representation of partial enclosure (PE) and pinch procedure (PP) and lower representation of global enclosure (GE) and holding (HO). These findings indicate variation in the combinations of procedures associated with shape complexity, particularly for the most complex stimuli, rather than a uniform progression across all four levels.

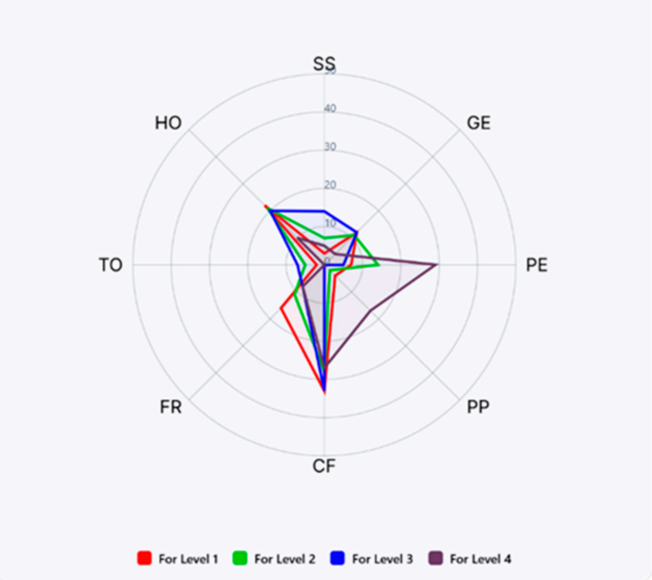


Figure 3. Relative distribution of tactile exploratory procedures across four levels of shape complexity. Note. Each line represents a complexity level. Radial values are percentages of all TEP occurrences within that level, pooled across participants, shape sizes, trials, and both hands, as re-ported in Table 5. Level 3 includes small shapes only. SS = surface sweeping; GE = global enclosure; PE = partial enclosure; PP = pinch procedure; CF = contour following; FR = flip-ping/rotating; TO = tapping the object; HO = holding the object.

To facilitate comparison of TEP distributions across levels of shape complexity (Table 5), frequencies are expressed as percentages of all TEP occurrences within each complexity level and visualized in the radar chart presented in Figure 3. Contour following (CF) accounted for the largest proportion of TEPs at Levels 1–3 (34%, 29%, and 33%, respectively), whereas at Level 4, partial enclosure (PE) (29%) and contour following (CF) (27%) were similarly prominent, followed by pinch procedure (PP) (17%). Partial enclosure (PE) varied considerably across complexity levels, accounting for 7% of TEPs at Level 1, 14% at Level 2, 5% at Level 3, and 29% at Level 4. Similarly, pinch procedure (PP) increased from relatively low or absent values at Levels 1–3 (4%, 2%, and 0%, respectively) to 17% at Level 4. Surface sweeping (SS) was most prominent at Level 3 (14%), compared with 3–7% at the other levels. Global enclosure (GE) remained relatively stable across Levels 1–3 (11–12%) but decreased to 4% at Level 4, while holding (HO) followed a similar pattern, accounting for 20–22% at Levels 1–3 and 10% at Level 4. Flipping/rotating (FR) showed its highest proportion at Level 1 (16%) and lower proportions at Levels 2–4 (11%, 9%, and 8%, respectively). Tapping (TO) remained relatively infrequent across all levels (0–7%) and was absent at Level 4. Overall, the profiles indicate the continued prominence of contour following (CF) alongside descriptive variation in the relative use of the other procedures.

In total, the distributions reported in Table 5 are visualized in Figure 3 to facilitate comparison of the overall TEP profiles across complexity levels. While Levels 1–3 show broadly comparable profiles, Level 4 presents a more distinct pattern, particularly in the greater relative prominence of partial enclosure (PE) and pinch procedure (PP) and the lower representation of global enclosure (GE) and holding (HO).

4. Discussion

The objective of this pilot study was to clarify the TEPs used by adults with congenital and early-onset blindness when exploring two-dimensional cut-out geometric shapes. Eight types of TEPs were observed in total: surface sweeping (SS), global enclosure (GE), partial

enclosure (PE), pinch procedure (PP), contour following (CF), flipping and rotating (FR), tapping (TO), and holding (HO). TEPs are associated with the extraction of specific object properties, and their use depends on the information being sought, such as shape, volume, or weight (Lederman & Klatzky, 1987; Withagen et al., 2013). Unlike previous studies involving the exploration of objects with multiple properties, such as shape, material, weight, and texture, the present study focused specifically on the exploration of shape, using two-dimensional cut-outs made from the same material. Hence, it is highly likely that the absence of certain TEPs, such as pressure and static contact, which are associated with the extraction of information about other object properties, reflects the specific nature of the task employed in this study.

Although eight types of TEPs were identified, their use was not uniform. Rather, certain TEPs were more prominent than others across participants and shape conditions. Despite some variation in the types and relative frequency of TEPs employed, a clear overall pattern emerged: contour following (CF), global enclosure (GE), and partial enclosure (PE) were the predominant TEPs across participants and shape conditions. These findings suggest that contour following, global enclosure, and partial enclosure may constitute the core TEPs involved in the exploration of two-dimensional geometric shapes.

A closer examination of TEP use across the two size conditions further showed systematic differences in how these TEPs were employed. Certain TEPs were used by all participants: contour following (CF), global enclosure (GE), and surface sweeping (SS) for small shapes, and contour following (CF) and partial enclosure (PE) for large shapes. Contour following is known to be both optimal and necessary for obtaining precise shape information, whereas enclosure movements (i.e., GE and PE) are known to be optimal for obtaining global shape information (A. Kalia et al., 2014; Lederman & Klatzky, 1987). The findings of the present study were consistent with these established functions. Global enclosure (GE) was more frequently observed for small shapes, possibly because participants could apprehend a greater proportion of the shape within a single hand. In contrast, larger shapes elicited greater use of partial enclosure (PE), possibly because the entire shape could not be comfortably enclosed within one hand, requiring participants to examine separate regions sequentially.

Shape complexity was also associated with differences in TEP use. As complexity increased, TEP use shifted toward greater use of contour following (CF), together with partial enclosure (PE) and pinch procedure (PP), while global enclosure (GE) and holding (HO) declined. Lederman and Klatzky (1987) explained that certain TEPs can be executed simultaneously with other TEPs, whereas others cannot. They further suggested that when exploring objects with multiple or complex properties, individuals may preferentially employ TEPs that can be executed simultaneously, allowing them to obtain different types of information through coordinated exploratory movements. TEP such as contour following is considered as one of the procedures that can be co-executed with other TEPs. Based on this perspective, the present findings suggest that as shape complexity increased, participants may have increasingly relied on TEPs that could be combined with other exploratory procedures.

In addition to the predominant TEPs, several other procedures were observed less frequently, including surface sweeping (SS), holding (HO), flipping and rotating (FR), pinch procedure (PP), and tapping (TO). While surface sweeping and pinch procedure have been reported in previous studies of tactile exploration (Bara, 2014; Vinter et al., 2012), flipping/rotating (FR) and tapping (TO) were additionally identified in the present study as distinct exploration patterns. Flipping/rotating (FR) occurred mainly when participants repositioned the object, while holding (HO) was observed when one hand held the object as the other performed a dynamic TEP, such as contour following (CF). Surface sweeping

(SS) was observed when participants explored distinctive shape features, particularly sharp angles and protruding points. Tapping (TO) was observed in only one participant. Taken together, holding (HO) and flipping/rotating (FR) appeared to assist the execution of other TEPs, whereas surface sweeping (SS) and pinch procedure (PP) appeared to provide additional exploration of specific shape features; tapping (TO) may represent an individual exploration pattern. Although Lederman and Klatzky (1987) identified a set of distinct TEPs, Withagen et al. (2013), in their study of object exploration, observed additional hand movements that could not readily be classified within these established TEPs and described them as "actions." According to Withagen et al. (2013), actions are additional hand movements performed to obtain more specific information about the object or stimulus itself (p. 1461), which they compare to what Klatzky and Lederman describe as a "quick glance." From this perspective, some of the exploratory movements observed in the present study may be understood as such additional "actions," or quick-glance-type movements, occurring during tactile exploration of two-dimensional cutout geometric shapes.

Taken together, these findings highlight an important methodological contribution of the present study: the level of detail with which tactile exploratory behavior was examined. Rather than documenting only whether particular TEPs occurred, the analysis considered the movements of the left and right hands separately, the sequences and combinations in which TEPs were employed, their frequency of occurrence, and their relative contribution to the overall exploratory profile. This multilayered approach made it possible not only to identify the repertoire of TEPs used during two-dimensional shape exploration, but also to distinguish their relative prominence and to examine how this prominence changed according to stimulus characteristics. The frequency and proportional analyses, complemented by the radar-chart representations, revealed patterns that would be less apparent from the presence or absence of individual procedures alone, including the stability of some TEPs across conditions and the increasing prominence of others as shape characteristics changed. Thus, the present analysis extends the study of tactile exploratory procedures from the identification of discrete hand movements toward a more differentiated characterization of how individual TEPs contribute to an overall tactile exploration profile. This may represent a useful methodological direction for future research examining the organization, coordination, and potential efficiency of tactile exploration. The findings of the present study, despite its pilot character, extend previous research on the functional specificity of exploratory procedures (Lederman & Klatzky, 1987; Withagen et al., 2013) by documenting how adults with blindness combine these procedures when exploring two-dimensional geometric cut-outs. The recurring use of contour following, alongside variation in enclosure and manipulation, suggests priorities for investigating explicit instruction, which can be formulated by contour following for tracing boundaries, global enclosure for apprehending smaller shapes, and partial enclosure and pinching for examining local features of complex shapes. Teachers could model these procedures and support their flexible combination, while producers of accessible materials could provide clearly defined contours, distinguishable local features, and sufficient space for hand movements (Herzberg et al., 2023; Rosenblum et al., 2018). Building on these findings, future research could extend this approach to children with congenital and early-onset blindness to examine how TEP use, including their combinations and sequences, relates to the accuracy and efficiency of shape recognition. Such research could, in turn, contribute to the development of curricula and instructional approaches that support tactile exploration skills among students with visual impairments in school settings.

5. Limitations

As a pilot study involving a small number of participants, the findings should be interpreted with caution. Furthermore, all participants expressed moderate to strong interest in mathematics/geometry, with three working or studying in mathematics-related fields, which may limit the transferability of the findings to a broader population. Several limitations related to the study design and analysis should also be noted. Because this was an exploratory study, and to minimize potential learning effects, the number of shapes at the same complexity level presented to each participant differed. In addition, although efforts were made to balance shape size across complexity levels, some differences in the distribution remained, with Complexity Level 3 consisting only of small shapes. The analysis of TEP use was descriptive, and no inferential statistical analyses were conducted. Although repeated video review and discussion continued until full coding consensus was reached, agreement before reconciliation was not formally quantified, limiting the evidence for the reproducibility of coding using HEMP.

Given these limitations, observed differences in TEP use between large and small shapes and between simple and complex shapes should be interpreted cautiously. Future research should include participants with more diverse backgrounds and levels of interest in mathematics and explore alternative stimulus designs that allow shape complexity and size to be examined more systematically while minimizing potential learning effects.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review of Institute of Human Sciences, University of Tsukuba (TSU2025-280A, with approval granted on 18 February 2026).

Informed Consent Statement: Informed consent was obtained from all participants involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author, subject to privacy and ethical restrictions.

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Abbreviations

The following abbreviations are used in this manuscript:

TEP	Tactile Exploratory Procedure
HEMP	Hand Exploration and Manipulation Protocol
SS	Surface Sweeping
GE	Global Enclosure
PE	Partial Enclosure
PP	Pinch Procedure
CF	Contour Following
FR	Flipping/Rotating
TO	Tapping the object
HO	Holding the object

Appendix A

Appendix A.1

Table A1. Hand-specific tactile exploratory procedure (TEP) sequences and exploration times for small size shapes.

Participants & Set of Shapes	Stimuli Explored	Exploration Time (s)	Sequence of TEPs Explored by Left (LH) and Right Hand (RH)
A Set 2	Five-pointed star	45	LH: HO, CF, SS, CF, SS, PE, GE, PE, PP, GE, CF, PE, PP, PE RH: HO, CF, SS, CF, SS, PE, PP, PP, HO, PE, PP, PE
	Pentagon	46	LH: HO, SS, GE, GE, HO, CF, GE, SS, GE, GE, CF RH: HO, SS, GE, PE, CF, CF, GE, SS, SS, GE, CF
	Octagon	44	LH: HO, GE, GE, HO, SS, GE, CF, CF, HO, CF RH: HO, GE, PE, CF, SS, CF, CF, CF, PE
	Hexagon	37	LH: HO, CF, SS, GE, PE, HO, PE RH: GE, CF, SS, CF, CF, SS
B Set 1	Square	20	LH: HO, PE, HO, GE, HO, PE, HO, PE, GE RH: HO, SS, GE, CF, SS, CF, FR, CF, PP, PE
	Scalene triangle	20	LH: HO, GE, CF, FR, CF, GE, PE, HO RH: HO, GE, CF, SS, FR, SS, CF, GE, FR
	Right-angled triangle	15	LH: GE, FR, CF, FR, GE, HO RH: GE, FR, CF, FR, SS, HO
	Parallelogram	47	LH: PE, GE, PE, HO, SS, CF RH: HO, GE, FR, PE, PE, SS, CF
C Set 2	Hexagon	70	LH: FR, CF, CF, GE, TO, SS, FR, TO, CF, SS, TO, TO, HO, FR, CF, CF, SS RH: FR, HO, HO, GE, HO, TO, TO, HO, CF, CF, FR, HO, GE, CF, GE, HO
	Pentagon	55	LH: CF, CF, FR, CF, CF, CF, CF, HO, GE, HO, CF RH: HO, HO, FR, HO, HO, FR, FR, GE, CF
	Octagon	64	LH: CF, CF, CF, SS, CF, GE, CF, SS, CF RH: HO, FR, HO, CF, FR, CF, HO
	Five-pointed star	58	LH: FR, FR, CF, CF, SS RH: HO, FR, FR, PE, GE, PP, PP, PP
D Set 1	Square	39	LH: HO, CF, PE, HO RH: PE, HO, PE, CF
	Right angled triangle	42	LH: HO, CF, CF, CF RH: PP, HO, CF, CF, PE
	Parallelogram	30	LH: HO, CF, CF, CF, CF RH: HO, CF, PE, SS, CF
	Scalene triangle	42	LH: PP, HO, CF, HO, HO RH: CF, CF, CF, CF
E Set 1	Square	15	LH: FR, PE, CF RH: FR, PE, CF
	Parallelogram	7	LH: PE, CF, FR, CF RH: PE, CF, FR, CF
	Right angled triangle	15	LH: HO, CF, CF, FR, HO, CF RH: CF, PP, CF, FR, PP, CF
	Scalene triangle	27	LH: HO, PP, FR, CF, FR, PP RH: PP, CF, FR, CF, FR, PP

Note. LH = left hand; RH = right hand. Codes show the recorded sequence for each hand. Exploration time is reported in seconds for the whole shape trial. SS = surface sweeping; GE = global enclosure; PE = partial enclosure; PP = pinch procedure; CF = contour following; FR = flip-ping/rotating; TO = tapping the object; HO = holding the object.

Appendix A.2

Table A2. Hand-specific tactile exploratory procedure (TEP) sequences and exploration times for large size shapes.

Participants & Set of Shapes	Stimuli Explored	Exploration Time (s)	Sequence of TEPs Explored by Left (LH) and Right Hand (RH)
A Set 4	Circle	49	LH: CF, CF, HO, GE, CF, CF, HO, FR, FR RH: CF, CF, CF, GE, CF, CF, FR, FR, CF
	Ellipse	20	LH: HO, PE, HO, PE, FR, HO, CF, HO RH: HO, PE, GE, PE, FR, CF, HO
	Snowflake	35	LH: HO, PE, CF, FR, CF, PE, PE, CF RH: HO, PE, CF, FR, CF, PE, PE, CF
	Six-pointed star	20	LH: HO, PE, CF, HO, PE, CF, HO RH: HO, PE, CF, CF, PE, CF, PE, PP
B Set 3	Circle	10	LH: PE, CF, CF, HO RH: PE, CF, CF, GE
	Semi-circle	7	LH: CF, HO, GE RH: FR, CF, GE
	Sector	10	LH: FR, PE, GE, HO RH: FR, PE, GE, PP
	Cardioid	12	LH: CF, CF, HO, CF RH: HO, HO, CF
C Set 3	Cardioid	44	LH: FR, CF, PE, PE, TO, TO, SS, CF, TO, PP, PP, TO, SS, TO, TO, HO, CF, CF RH: FR, HO, GE, TO, HO, CF, CF
	Sector	31	LH: HO, PE, FR, HO, SS, TO RH: FR, CF, FR, TO, FR, FR, HO
	Semi-circle	24	LH: CF, FR, TO, CF RH: HO, HO, GE, HO, FR, PE
	Circle	28	LH: CF, SS, FR, FR, TO, HO, GE RH: HO, HO, FR, FR, CF, CF, HO, TO, TO
D Set 3	Circle	23	LH: HO, CF, HO RH: GE, CF, GE, SS, GE
	Cardioid	27	LH: HO, CF, PE, CF RH: CF, PE, PE, CF
	Sector	34	LH: CF, HO, CF, GE, HO, HO, PE, HO, HO RH: HO, CF, CF, CF, CF
	Semi-circle	25	LH: HO, HO, HO, CF, PE, CF, HO, HO RH: CF, CF, CF, HO, CF, PE
E Set 4	Ellipse	10	LH: CF, PE, HO RH: CF, PE
	Circle	23	LH: GE, FR, CF, GE RH: GE, FR, CF, FR
	Six-pointed star	66	LH: PE, PE, CF, PE, CF, PE, CF, HO, PP, PP RH: PE, SS, PP, CF, PE, CF, PP, CF, PE, PP, CF, PP, PE, FR, GE, FR
	Snowflake	90	LH: PE, CF, PE, CF, PP, CF, GE RH: PE, CF, PE, CF, PE, CF, PP, PP, CF, FR

Note. LH = left hand; RH = right hand. Codes show the recorded sequence for each hand. Exploration time is reported in seconds for the whole shape trial. SS = surface sweeping; GE = global enclosure; PE = partial enclosure; PP = pinch procedure; CF = contour following; FR = flip-ping/rotating; TO = tapping the object; HO = holding the object.

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