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An Early Investigation into Raised-Line Tactile Graphics Reading Behavior among Blind and Visually Impaired Individuals

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ABSTRACT

It has always been a challenge for blind and visually impaired (BVI) people to comprehend the information on tactile graphics materials. Despite the advancements in tactile graphic design, a comprehensive understanding of how they explore and interpret raised-line tactile graphics is still lacking. To bridge this gap, this paper introduces a fingertip tracking system employing color marker detection algorithm to investigate the cognitive process of four totally blind participants associated with the Malaysian Association for The Blind (MAB). Each participant was provided with five distinct kinds of raised-line tactile graphics for reading, and their reading activities were afterwards recorded. All participants exhibited diverse interpretations, exploration times, and difficulty perceptions, showcasing the subjective nature of cognitive processing. It is identified that the complex diagram took longer time of exploration with an average time of 141 seconds compared the simple diagram with an average time of 27.5 seconds. It shows that the complexity of the diagrams did impact participants' cognitive process. Based on the distribution and concentration of fingertip locations, every tactile graphic has salient regions that have been focused on by every participant for recognition and interpretation of the information. It was also identified that the frequently performed exploratory procedures among participants were contour following and lateral motions. However, their reading strategies were too random and lacked systematic patterns. The system aims to be an instrument for visualising the cognitive process underpinning the exploration and interpretation of tactile graphics by people with visual impairment and blindness.

Keywords: Tactile graphics; Visually impairment; Computer vision system; Exploratory procedure

INTRODUCTION

Tactile graphics serve as an essential means of conveying non-textual information to individuals who are blind or visually impaired (BVI). They are extensively utilized in STEM (Science, Technology, Engineering, and Mathematics) disciplines, as well as in the field of geography (Ducasse et al. 2018; Mukhiddinov & Kim 2021) and for illustrative purposes in children's books (Wright et al., 2008). According to Sheppard and Aldrich (2000) and Bara et al. (2018), it is necessary to transform visual-based formats such as graphs, maps, diagrams, and other sorts of drawings into tactile formats for the BVI people. It is a fact that the BVI people must rely on haptic perception, which means, utilizing their hands and fingertips to explore and engage with the raised surfaces depicted in the diagrams (Yu et al 2019). This requires the use of tactual perception, which refers to the physiological skills of the human sensory system in exploring and discriminating through the sense of touch (Gupta et al 2017). However, the limited contact area of the fingertips and the varying tactual perception abilities of BVI individuals can make the interpretation of tactile graphics difficult (Downing et al. 2003).

There are multiple methods for creating a mental image of tactile graphics, which isn't solely reliant on physically touching the materials. It's also influenced by the design of the tactile graphics (Dulin 2007; Dulin & Hatwell 2006). Additionally, the guidance and instructions provided by sighted individuals are vital for BVI individuals when they're exploring and recognizing figures within these graphics (Simonnet et al 2019). In fact, to effectively extract information from haptic scenes, BVI individuals must be trained with specific procedures and strategies for exploration. (McLinden 2004). Nevertherless, there's still uncertainty regarding how BVI individuals comprehend graphical information through touch. Conducting research in this area could be beneficial for further improvement in tactile graphic representation, offering guidelines and teaching methods for exploring graphical information, and designing accessible interfaces for touchscreens (Murai et al. 2018; Breidegard et al. 2008; Brock et al. 2012; Morash et al. 2014; Bardot et al. 2017).

To address the gap in this field of research a fingertips tracking system based on the detection of colour markers has been developed. The system can detect and register the precise location of the five colour markers placed on the participant's fingertips. It can record fingertips movement and visualize frequently touched areas when exploring tactile graphics with a single hand. The decision to employ this technique is a way forward to overcome some of the limitations faced by previous studies that relied on video recording which were time consuming and the incapability to visualize the trajectory of the exploration strategies from the fingertips' motions (Bara et al. 2018; Wijntjes et al. 2008). With this approach, the data obtained from the experiment involving four totally blind participants from Malaysian Association for The Blind (MAB) had benefited more valuable insights into their exploration behavior and strategies to comprehend graphical information through touch sensing. This paper begins with the related works that have been done by other researchers in Section 2. In Section 3, a detailed description of our proposed system is presented. We then discussed the results and performance of the system in Section 4 and finally concluded this paper with the future directions for research in this field in Section 5.

RELATED WORKS

Multiple types of research have been conducted over the past decade to investigate the perceptual and cognitive processes employed by BVI individuals in the interpretation and comprehension of tactile graphics. For example, there are studies focusing on how individuals perceive tactile graphics; the distinctions in perception between between sighted participants who are blindfolded and BVI people; techniques employed by readers to interpret braille and tactile maps; the differences in perception associated with various tactile graphic designs and more. Nevertheless, the current focus of interest lies on tactile graphic reading and exploration behaviour. Therefore, this section provides a concise summary of the techniques used in prior studies to record, classify, and analyse tactile behaviours.

Since tactile graphics reading involves touching the raised surfaces (Aldrich et al 2002; Mukhiddinov & Kim 2021), most researchers were focused on tracking hands and fingertips movements (Brock et al. 2012; Murgavel 2014; Bardot et al. 2017; Murai et al. 2018). Firstly, Brock et al. (2012) used a depth camera and multitouch screen to record touch interactions made by individuals with visual impairments (BVI) while reading tactile maps. The captured data of each finger movement were used to visualize the exploration strategies that were performed by the BVI people. Murgavel (2014) created a color-marker finger tracking system. He created a finger tracking programme that processes each frame of recorded video of BVI people reading raised-line diagrams by detecting and segmenting colour markers.

As for Bardot et al. (2017), a touch screen and RGB camera were employed to monitor the movements of hands and fingers while BVI individuals were engaged with raised-line diagrams. Colour marker detection was also employed to monitor the movement of all ten fingers of the BVI readers. Throughout their works, they discovered the salient areas that frequently touched by BVI readers on each tactile graphics. Murai et al. (2018) used two RGB cameras to record touch activities, affixed a marker to the BVI reader's index fingertip, and analysed the footage using a colour marker detection algorithm to locate the finger. Two BVI individuals have read 17 tactile graphics materials to evaluate the system. Finally, Garcia et al. (2019), used only multitouch screen technology to capture touch behaviours during tactile graphics exploration. They even designed the tactile protocol analysis along with the analysis software to interpret the multitouch data specifically for shape matching tasks.

In summary, there were three categories of approaches used which were color marker tracking, depth sensing and touch sensing which require the use of image sensor and touch screen technology. The depth sensing approach may not be a suitable approach because of its limitation to detect occluded fingers. As reported by Brock et al. (2014), this approach failed to detect closed fingers when the blind subject was reading tactile graphics. Similarly, the touch screen technique faces limitations in identifying specific touching fingers and distinguishing between genuine touch events and unintended contact, like resting the palm on the surface (Garcia et al. 2019). On the contrary, the color marker tracking method emerges as a suitable choice for this study due to its capacity for accurately detecting and capturing fingertip locations and movements (Bardot et al. 2017). Despite its inability to detect hidden or overlapped fingers during tactile graphic exploration, this method offers quicker access to valuable insights into exploration behavior.

METHODOLOGY

In this section, we proposed to develop a computer vision system using color marker detection method to investigate the cognitive processes of tactile graphics based on the fingertips' movements. This system aims to capture and track the movements of five fingertips of participants in real-time as they read and explore tactile graphics. This will enable us to analyze and visualize the complex movements and exploration strategies employed during tactile graphic interaction. In general, we utilized video processing techniques to decode the tactile activity and this technique will not disturb the participant's behaviour during the experiment (Johari et al. 2023). The breakdown of the methodology will be discussed in the following section.

PARTICIPANTS

In total, four participants from MAB volunteered to take part in this study. Four blind participants were two men and two women, aged between 31 to 44 years old (M = 39.5, SD = 5.92). The interview revealed that all participants were born blind. They attended blind schools and used tactile graphics solely in school, but not at work.

All participants shared their experience regarding methodologies for reading tactile graphics and rated their proficiency in reading tactile graphics and braille using 5-points Likert scale. The results showed that the expertise of reading tactile graphics fell between 3 to 4 points (M = 3.25, SD = 0.5) while braille reading fell between 2 to 5 points (M = 4, SD = 1.41).

Besides that, three participants (P2, P3 and P4) prefer to use both hands except one person (P1) who usually use the right hand to read tactile materials. For finger, they responded that the index finger is the dominant one. They also highlighted some methods that usually being used when read tactile graphics materials which are:

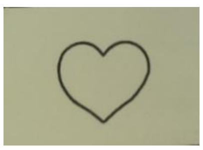
1. Touching the whole diagram.
2. Searching important labels that explain about the diagrams.
3. Differentiating the characteristics of the diagram.

EXPERIMENT DESIGN AND PROCEDURE

There were five raised line tactile graphics that have been used for the experiment. All diagrams were selected from Snodgrass and Vanderwart's (1980) 260 images which also have been used by previous and related researchers such as Bardot et al. (2017), Mazella, Albaret and Picard (2016), Picard, Albaret and Mazella (2014 and 2013) and Theurel et al. (2013). After the selection of diagram, we printed in A4 landscape format on Zytech swell paper. The raised line tactile graphics that have been printed are shown in Table 1.

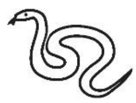
The task and instructions were given to each participant per session during the experiment. The printed tactile graphics were new to all participants. They were allowed to freely explore all five tactile graphics with only one hand and had to precisely identify each raised line graphic without time constraints. Neither feedback nor communication occurred between participants and the researcher during the experiment. The duration of reading was measured from the moment participants were given permission to read until they chose to conclude the activity upon request. Finally, every participant was asked to guess the name of the diagram regardless it was correct or incorrect. Other than that, they were asked to score their reading experience, behaviour, technique, commonly used fingers, and tactile graphic complexity rate.

TABLE 1. Experimental raised line tactile graphics

No.	Name of images	Digital Images	Tactile images printed on Zytec swell paper
1	Love		
2	Banana		

continue ...

... cont.

3	Apple		
4	Butterfly		
5	Snake		

SYSTEM DESIGN AND OVERVIEW

For this study, we have employed a computer vision system to capture and track the movements of fingertips using color marker detection method. This system was developed using MATLAB software and a webcam (Logitech C922) is attached to a stand. As shown in Figure 1, the webcam was positioned above to capture a top-down view of the participant's hand when exploring the tactile graphic. Figure 1 and Figure 2 show the view of the experimental setup and flowchart of the system respectively. Table 1 describes the flowchart of the system.

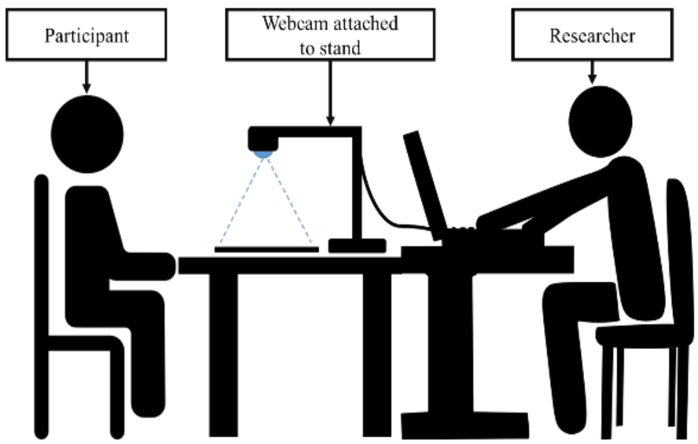


FIGURE 1. Experimental setup

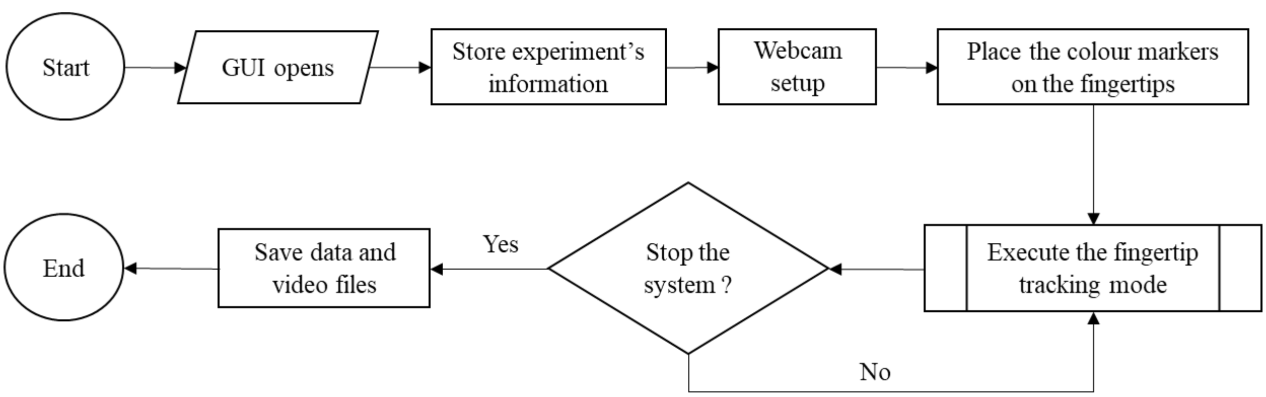


FIGURE 2. Flowchart of the system

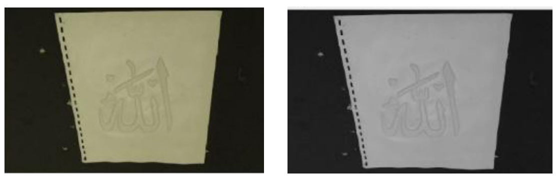
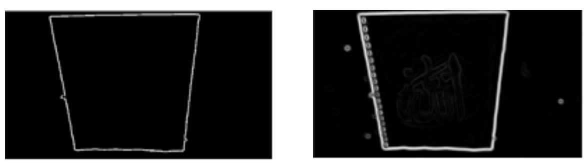
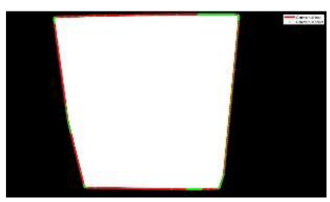
TABLE 2. Description of the system's flowchart

Block	Description
Store experiment's information	Researcher needs to choose the directory to save the information and experimental data.
Webcam setup	A window of live webcam feed will appear, and the webcam's setting can be adjusted using the TrackBar GUI.
Execute the fingertip tracking mode	The video recording will begin, and fingertips tracking will be executed.
Save data and video files	Store the experimental data and recorded video into the chosen directory.

LOCATING AND RECTIFYING TACTILE GRAPHIC

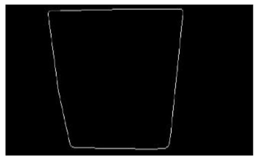
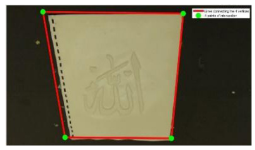
After establishing a connection with the webcam, the system proceeded to locate and adjust the webcam's perspective towards the tactile graphics. This approach aims to enhance the reliability of fingertip tracking by eliminating projective and distortions in both the background frame (tactile graphics) and the foreground frame (tactile graphics with the participant's hand). Subsequently, to distinguish the foreground from the background, we conducted the image segmentation and corner detection procedures, encompassing the subsequent steps outlined in Table 3.

TABLE 3. Identification of selected muscle and electrode placement position

Steps	Figures
Convert the image from RGB format into Grayscale format	
Blur the image to reduce image noise using Gaussian blur filter	
Convert the grayscale image to binary image and remove any small blobs to reveal the edges of tactile graphic.	
Compute convex hull function to obtain the tactile graphic region. The operation results in a binary rectangular shape which is the foreground image.	

continue ...

... cont.

Apply Sobel edge detection method to the foreground image to clear edges and vertices of the tactile graphic.	
Apply Hough transform to identify all connected lines of the foreground image.	
Find the intersection between all lines to reveal four corners of the tactile graphic.	
Image rectification to obtain flat image of tactile graphic.	

According to the procedures, the goal is to get four points that represent the tactile graphic's outline and perspective transformation dimension. After the locating and correcting process were conducted, only the flat top-dzown view of the tactile graphic will be continuously captured during the experiment as shown in Figure 3.

FIGURE 3. Top-down view during live video acquisition after the successfully locating and correcting the tactile graphic

COLOUR MARKER DETECTION AND SEGMENTATION

To capture the fingertips' movements when reading the tactile graphic, we placed five different colour markers. This approach was chosen so every finger can be tracked individually based on the colour used. To detect and segment every colour marker, we have used MATLAB's Colour Thresholder App to create every colour profile and thresholding in HSV colour model. The steps involved were as follows:

1. Convert the rectified image from RGB colour space into HSV colour space.
2. Define HSV threshold value for every colour marker in MATLAB's Colour Thresholder App.
3. Transform every segmented colour marker into binary image for morphological operation.

The result of the process is shown in Figure 4. After segmenting all colour markers, the morphological procedure begins. Every binary picture of the colour marker undergoes dilation and erosion process. The dilation expands the binary picture of colour markers, while erosion shrinks them. This technique creates a smooth, closed, and complete blob of colour markers in binary mask image as shown in Figure 5.

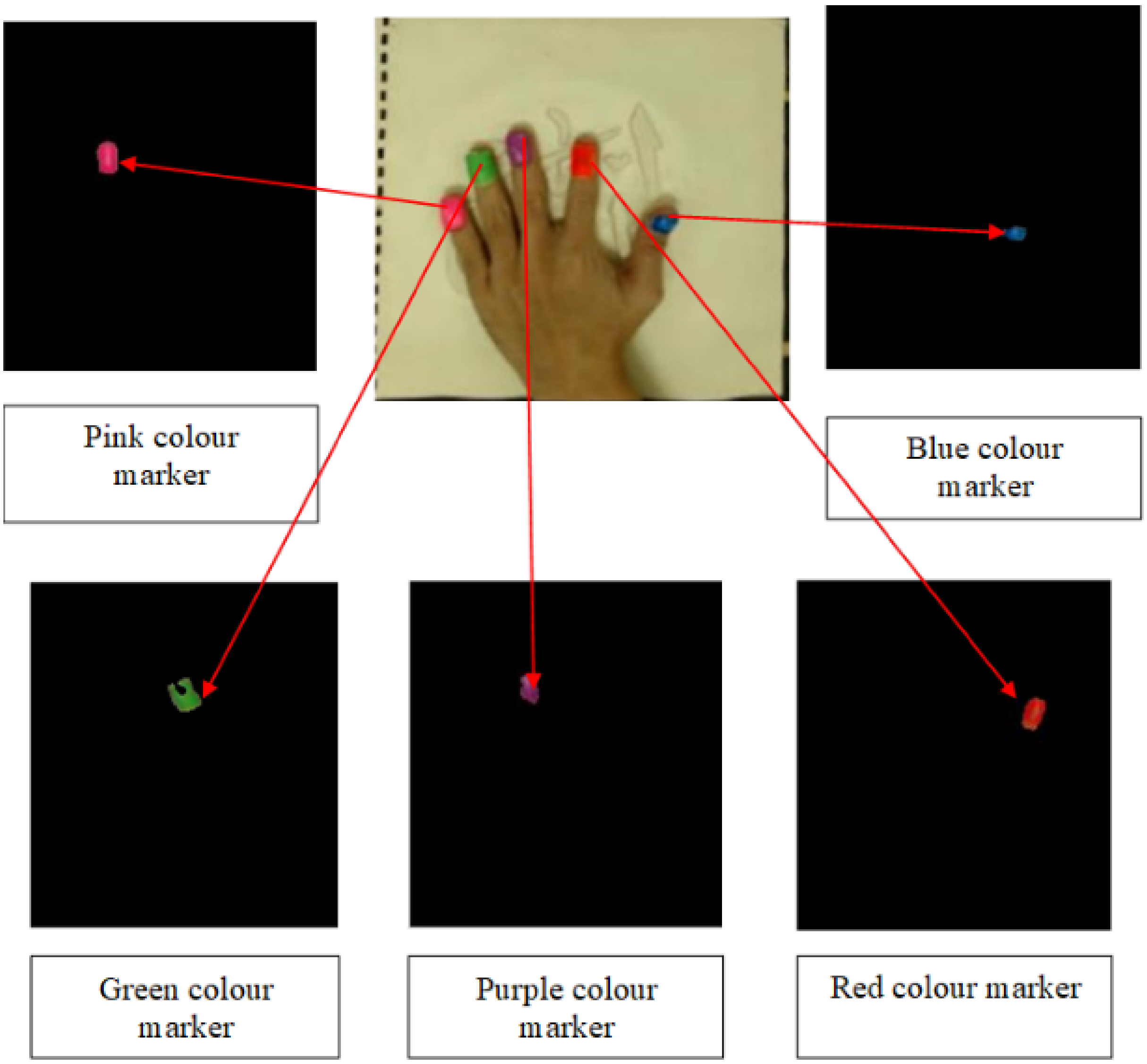


FIGURE 4. Results of colour marker detection and segmentation from the rectified tactile graphics

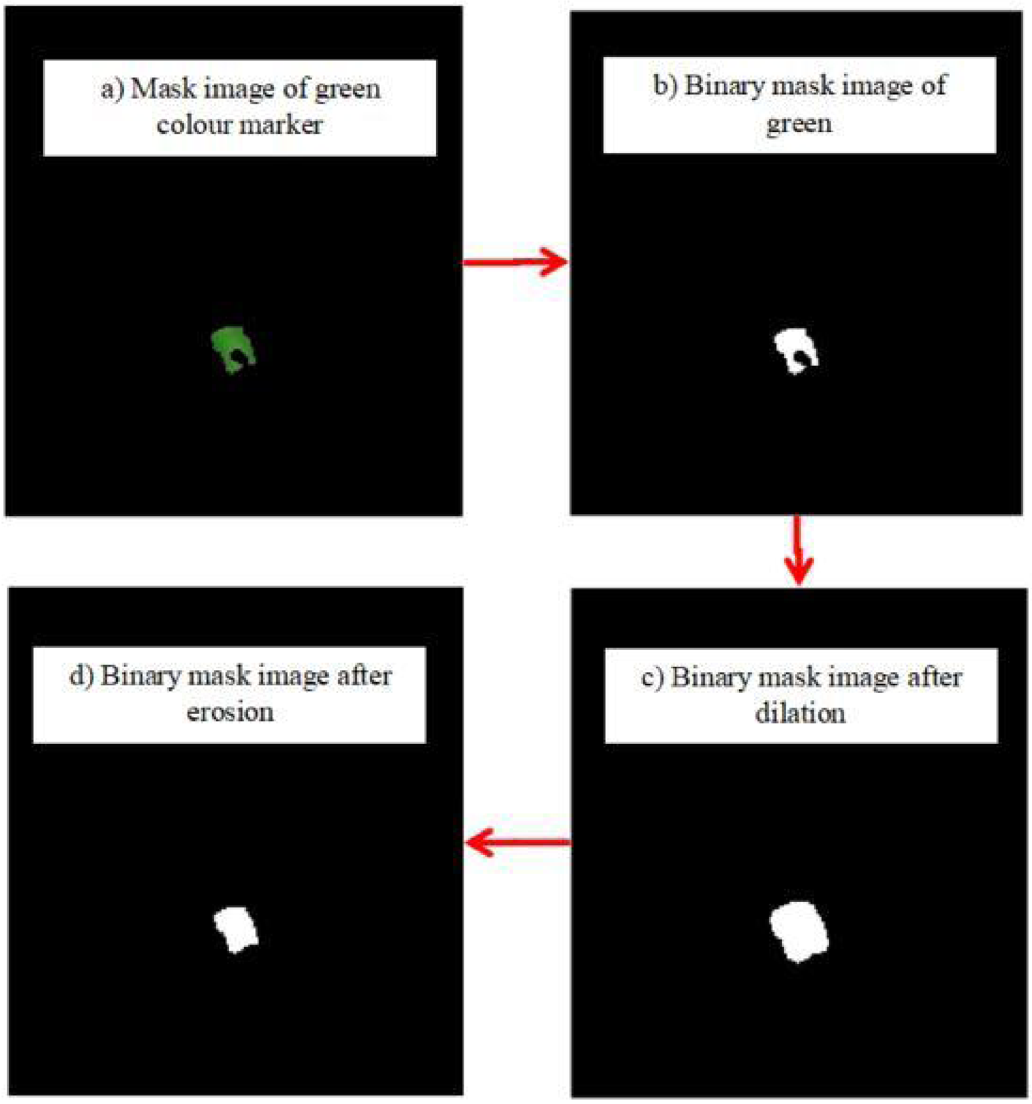


FIGURE 5. Morphological operations outcomes

VISUALIZATION OF FINGERTIP TRACKING

Finally, the trajectories of each coloured marker will be monitored and documented as x and y coordinates. The coordinates of the centroid for the white blob depicted in Figure 6 were obtained by utilising the *"regionprops()"* function within the MATLAB software. The function returns a set of measures, including area, perimeter, centroid, and other relevant quantities. By having the coordinates of the centroid of the white blob, we were able to plot and visualise the fingertips' route based on each colour marker as depicted in Figure 7.

As of now, the system can detect and tracking the positions of each colour marker placed on the fingertip over the entire duration. In addition to its primary functionality, the system has the capability to visually represent the trajectory and movements executed by the readers by plotting the x and y coordinates of each individual fingertip. However, the system is limited to detect and track five fingertips on a single hand. By utilizing color marker detection, the system offers a non-intrusive and efficient method for capturing and tracking fingertip movements, providing valuable insights into the cognitive processes involved in tactile graphic exploration. This approach addresses the limitations of traditional video recording methods, which often struggled to accurately capture and analyze the intricate movements of the fingertips when interacting with tactile graphics.

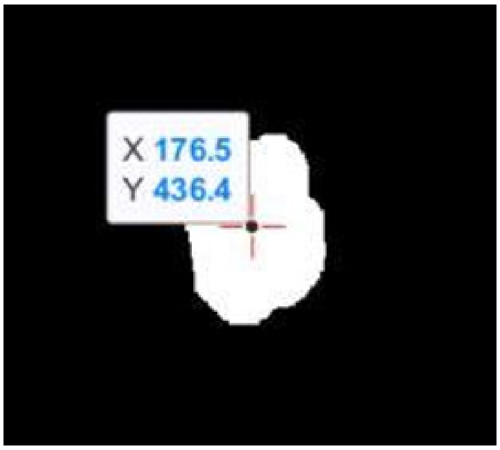


FIGURE 6. Centroid of the white blob in *x* and *y* coordinate

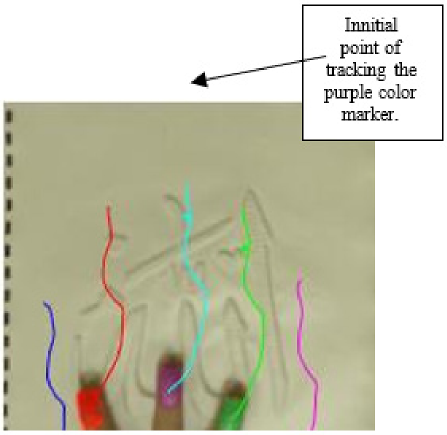


FIGURE 7. Fingertips tracking visualization. The lines plotted shows the path of movement made by the hand on the tactile graphics. This visualization can be useful to understand the cognitive processes of tactile graphics

RESULTS AND DISCUSSION

DURATION OF TACTILE GRAPHIC READING AND PARTICIPANTS' FEEDBACK

The results of each participant while interpreting each diagram in Table 1 are presented in Table 4 to Table 8. We have collected the time taken for each participant to guess the presented diagram, the diagram's name given by the participant, and the rate of difficulty to read the diagram using Likert scale. The participants were also required to share their reading experience and reported the frequently used fingers. Meanwhile Figure 8 to Figure 10 illustrate the data gathered for average reading time, frequently used fingers and difficulty's rate which corresponded to the tabulated data.

Based on the tabulated data and figures, there are interesting insight that can be discussed from various perspectives. Firstly, every participant showed varying degrees of consistency in naming the diagram. For example, the snake outline diagram was the most correctly named due to their familiarity with the shape. Meanwhile, some participants provided diverse or incorrect names such as half moon for the banana diagram because of its shape similarity. This shows that, every participant had subjective interpretations for every diagram. In term of the participant's achievements, participant P4 had successfully named all diagrams correctly and quicker reading time compared to rest. This might show that the capability of the participant to interpret the diagram.

The bar graph in Figure 8 represents the average time taken to read every diagram according to Table 4 to Table 8. It shows that the participants took a longer time to discover apple diagram with an average time at 141 seconds to read. The primary cause was due from their lack of clarity regarding the leaf component of the apple. Even though, the average time required to trace the love shape was the shortest with only 27.5 seconds, only participants P1 and P4 were able to provide the accurate response, while participants P2 and P3 exhibited difficulty in identifying the shape due to their unfamiliarity with the love shape presented in an outline manner. Here, longer reading times, might suggest higher complexity in interpreting those specific diagrams for certain participants. But shorter reading times did not always align with perceiving diagrams as easier since there were some participants that incorrectly name the diagram.

Other than that, Figure 9 presents a bar graph illustrating the rate of difficulty associated with reading each diagram that have been rated using the 5-points Likert scale. The results potray that, the apple diagram was the most difficult shape to interpret compared to the snake diagram as the easiest. This shows that, the complexity of the diagram did impact the participants cognitive process, which can be reflected by the average reading time for each diagram. Finally, all participants reported that they frequently used the index finger (Figure 10) when exploring the diagram. As a result, this research has focused on index finger behaviour and tactile picture comprehension for the next part of the discussion.

Overall, all participants exhibited diverse interpretations, response times, and difficulty perceptions, showcasing the subjective nature of tactile graphics interpretation. Plus, there isn't a straightforward correlation between reading time, accurate naming, and perception difficulty, suggesting a complex relationship between these factors.

TABLE 4. Every participant's love diagram reading result

LOVE DIAGRAM			
Participants (S)	Reading time (s)	Name of the diagram given by the participants	Rate of the difficulty *(Likert scale)*
P1	20	Love	5
P2	58	No answer or guess given	3
P3	25	No answer or guess given	3
P4	8	Love	4

Likert scale: 1 = Very Difficult | 2 = Difficult | 3 =Neutral | 4 = Easy | 5 =Very Easy

TABLE 5. Every participant's result when reading the banana diagram

BANANA DIAGRAM			
Participants (S)	Reading time (s)	Name of the diagram given by the participants	Rate of the difficulty *(Likert scale)*
P1	32	Banana	4
P2	60	Banana	4
P3	25	Banana	5
P4	144	Half moon, Banana	3

Likert scale: 1 = Very Difficult | 2 = Difficult | 3 =Neutral | 4 = Easy | 5 =Very Easy

TABLE 6. Every participant's result when reading the apple diagram

APPLE DIAGRAM			
Participants (S)	Reading time (s)	Name of the diagram given by the participants	Rate of the difficulty *(Likert scale)*
P1	380	Pomegranate, Guava	3
P2	109	Pineapple. Pear	3
P3	45	No answer	2
P4	30	Apple	4

Likert scale: 1 = Very Difficult | 2 = Difficult | 3 =Neutral | 4 = Easy | 5 =Very Easy

TABLE 7. Every participant's result when reading the butterfly diagram

BUTTERFLY DIAGRAM			
Participants (S)	Reading time (s)	Name of the diagram given by the participants	Rate of the difficulty *(Likert scale)*
P1	25	Butterfly	5
P2	51	Butterfly	3
P3	32	No answer	2
P4	146	Butterfly	2
Likert scale: 1 = Very Difficult | 2 = Difficult | 3 =Neutral | 4 = Easy | 5 =Very Easy			

TABLE 8. Every participant's result when reading the snake diagram

SNAKE DIAGRAM			
Participants (S)	Reading time (s)	Name of the diagram given by the participants	Rate of the difficulty *(Likert scale)*
P1	66	Snake	4
P2	22	Snake	5
P3	22	Snake	5
P4	76	Snake	3

Likert scale: 1 = Very Difficult | 2 = Difficult | 3 =Neutral | 4 = Easy | 5 =Very Easy

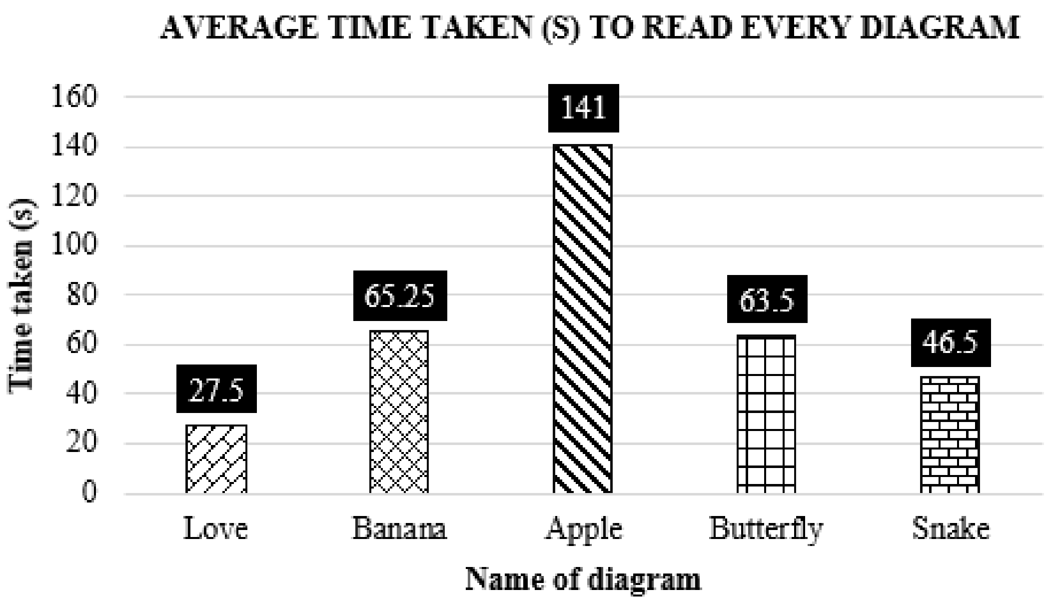


FIGURE 8. The average time taken (s) to read every diagram

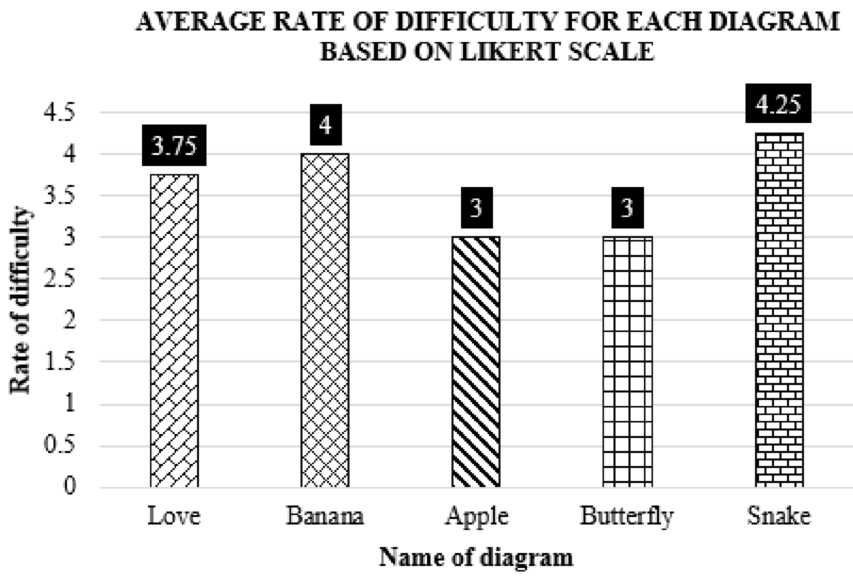


FIGURE 9. The average rate of difficulty to read every diagram based on Likert scale

(Likert scale: 1 = Very Difficult | 2 = Difficult | 3 =Neutral | 4 = Easy | 5 =Very Easy)

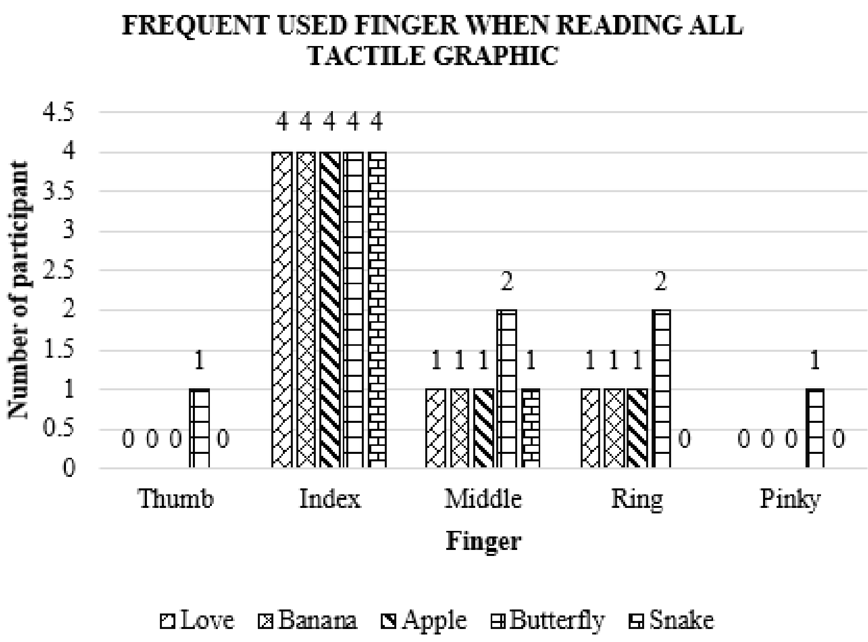


FIGURE 10. The frequently used fingers responded by the participants based on different diagram. The number 0 to 4 indicate how many participants used the respective finger

DISTRIBUTION AND CONCENTRATION OF FINGERTIP LOCATIONS ON TACTILE GRAPHICS

The second part's objective is to visually represent the distribution of fingertip locations and to identify prominent areas of focus exhibited by participants during the reading and exploration task. Hence, in order to facilitate a comprehensible visual examination, a two-dimensional heat map depicting the spatial distribution has been created, accompanied by marginal histograms. However, it is worth noting that the index finger was selected as the primary finger for result presenting due to its prevalence among all participants, as illustrated in Figure 10. The findings of the distribution and concentration of the index fingertip's coordinates on each tactile image, along with marginal histograms, are depicted in Figure 12.

The inclusion of a marginal histogram serves the objective of visually representing the marginal distribution of the coordinates of the fingertip in relation to the x and y axes. Kernel density plots were utilized to create each axis marginal histograms. As a result, a smooth curve on each axis has been created to represent fingertip coordinate distribution and density over the read diagram. In addition, the marginal histogram can be utilised to identify participants' salient regions when reading tactile images by referring to the curve peak. Figure 11 shows this section's data visualisation and presentation approaches. Figure 12(a) reveals that participant fingertip coordinates are excessively random. According to the marginal histogram, each participant may focus on two corners of the love diagram. Two-dimensional heat map visualisation demonstrates only P2's fingertip coordinate distribution density is highest at the love diagram's two corners.

By looking at the marginal histogram peak, Figure 12(b)'s banana diagram's top and bottom are important salient part. P2 and P4 showed highest fingertip's coordinate distribution and density at those regions compared to P1 and P4. In Figure 12(c), all four participants concentrated on the apple schematic leaf based on the marginal histogram peak and heat map intensity. that all participants find the apple diagram leaf most challenging to read and identify. Next is Figure 12(d) which is the butterfly diagram. The marginal histogram shows that the butterfly's head is the peak highest. Comparison of heat map visualisation showed that, P2 and P4 had the largest coordinate distribution intensity compared to P1 and P3.

Finally, in Figure 12(e), all participants' fingertip coordinates are excessively random. The marginal histogram shows no major peak point where fingertip coordinate density and distribution are maximum. Additionally, the heat map visualisation did not highlight many P1, P2, and P3 salient locations. Except for P4, which has high coordinate density and intensity at the snake's head. Both methods are used to visualise fingertip coordinate data distribution and concentration on each diagram. These will help participants identify key regions when reading and exploring tactile visuals, clarifying how they perceive each diagram.

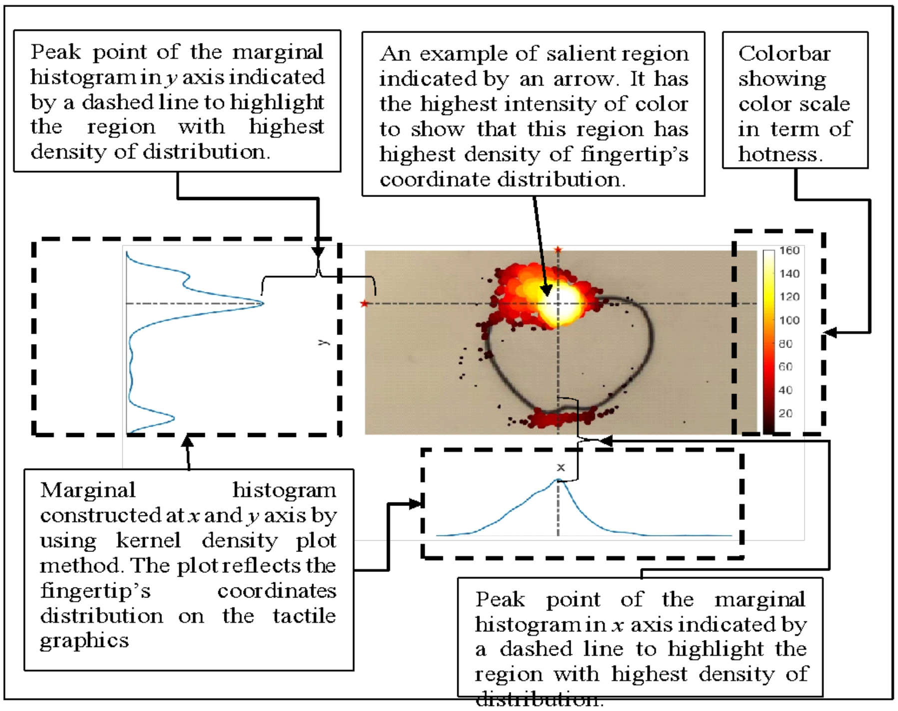
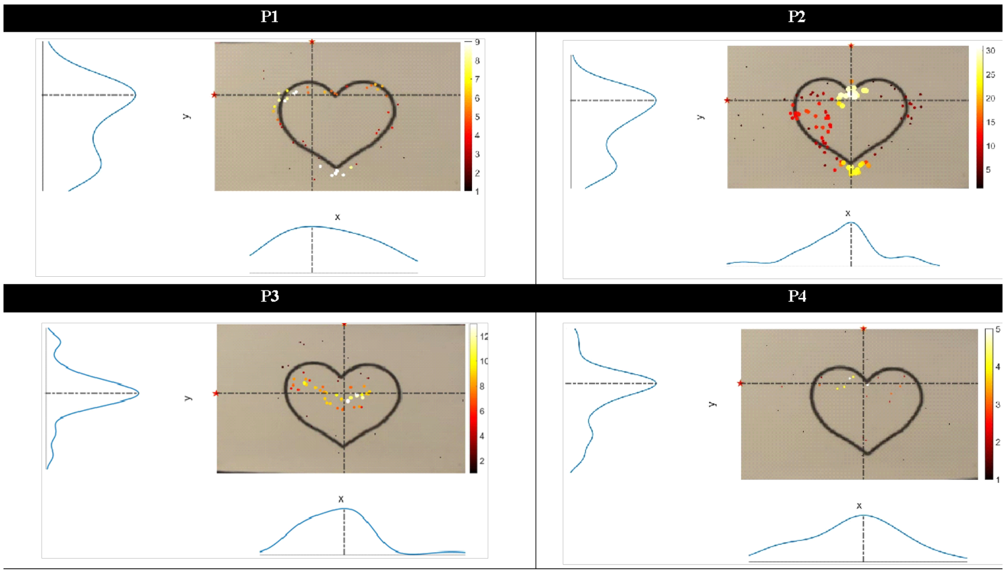
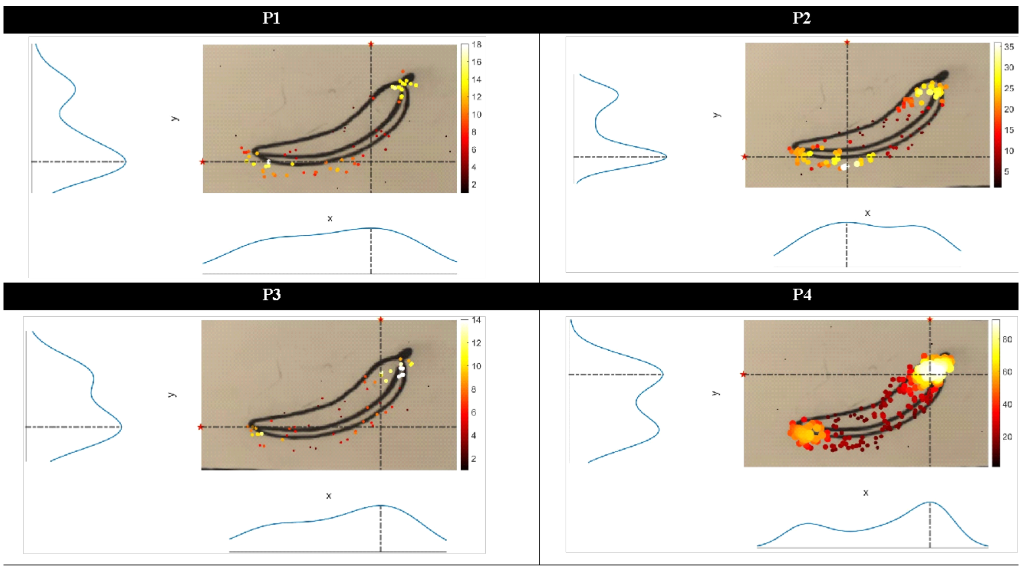


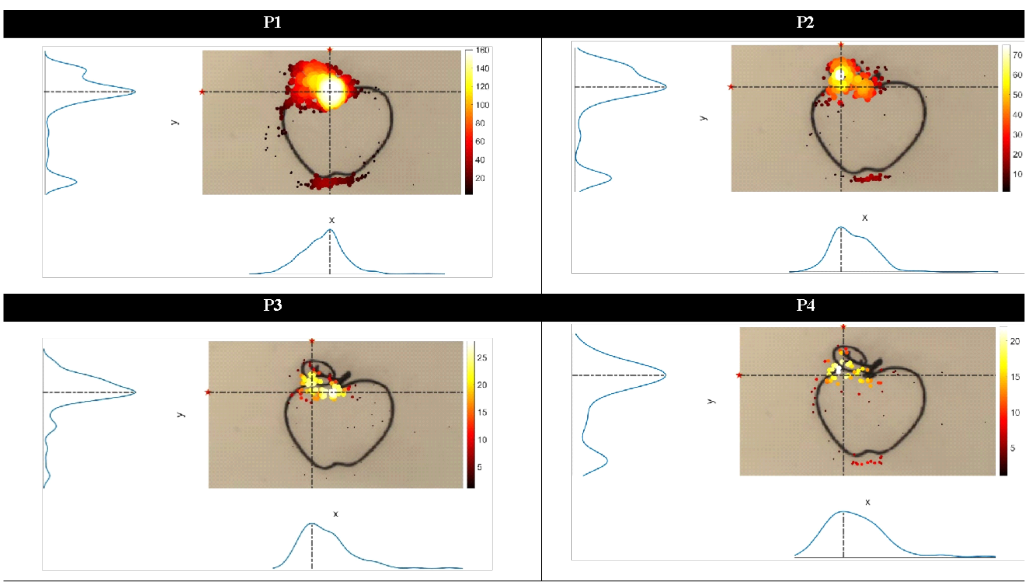
FIGURE 11. Two-dimensional heat map spatial distribution with marginal histogram illustration of data visualisation and display.



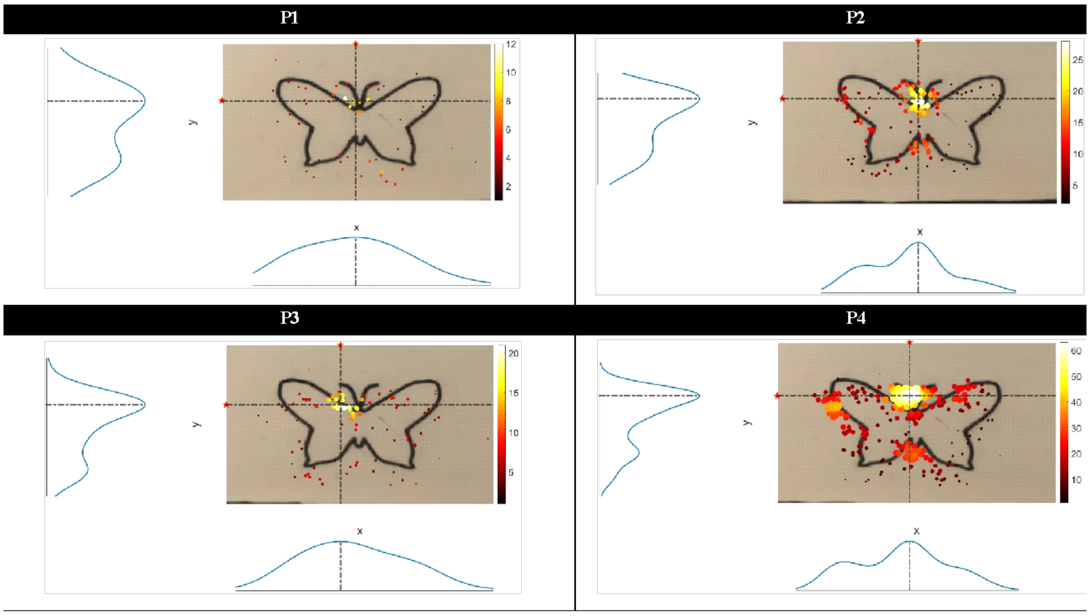
(a)



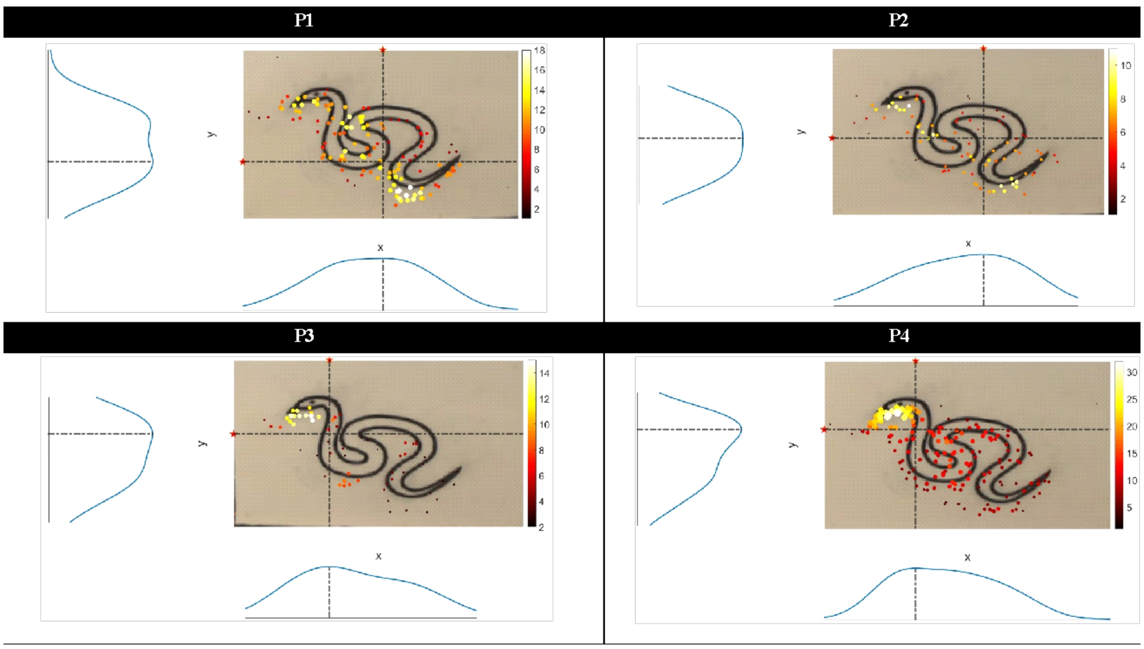
(b)



(c)



(d)



(e)

FIGURE 12. The index fingertip's coordinates distribution of each participant with the aid of heat map visualization together with marginal histogram on *x* and *y* axis on love (a), banana (b), apple (c), butterfly (d) and snake (c) diagram

EXPLORATORY PROCEDURES AND STRATEGIES

Next, participants' tactile graphic reading exploration styles are identified in the final segment. The data that were analysed pertained to the motions of participants' index fingertip. These movements were manually categorised based on the exploratory approaches given by Lederman and Klatzky (1987). There are two preliminary stages that must be elucidated before to embarking on the identification procedure. These stages encompass:

Distance measurement between the fingertip which is indicated by the attached color marker and the black raised line region (reading area). The measurement was conducted using the Euclidean distance formula, as represented by Equation 1 and the points taken are the centroid of the color marker and black line's pixel coordinates. This stage is explained in Figure 13. Distance measurements was done until the maximum number of frames is reached. All distance measurement data will be plotted as in Figure 14.

$$Euclidean\ distance, d\ (in\ pixel\ unit) = \sqrt{(x_2-x_1)^2 + (y_2-y_1)^2} \quad (1)$$

$P_1(x_1, y_1)$ – centroid's location of a colour marker

$P_2(x_2, y_2)$ – location of the black pixel of the tactile graphics

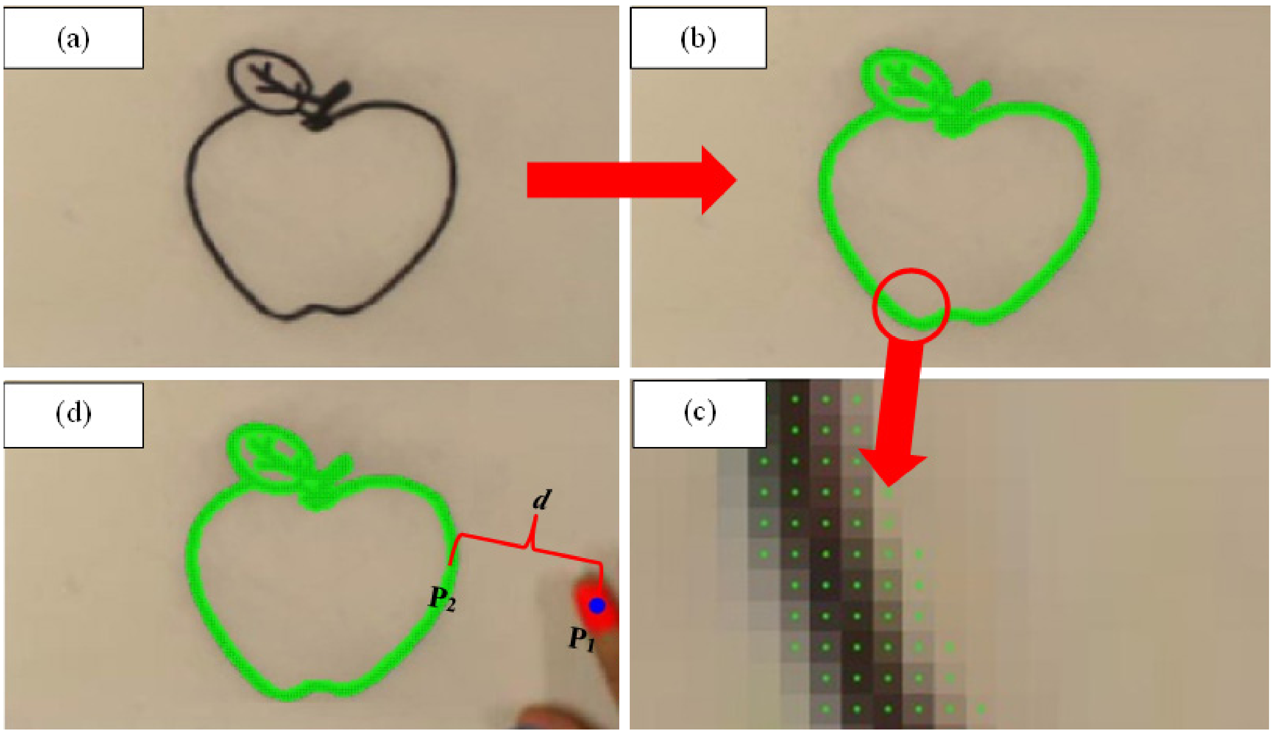


FIGURE 13. Firstly, the apple diagram in (a) has been processed to identify the black outline regions. The result is shown in (b) where the black outline is highlighted with green colour. From the closed-up view shown in (c), every identified black pixel has been marked its location. It is indicated by the green-coloured dots. Finally, in (d), the Euclidean distance, *d* is measured between the black pixel coordinate (P_2) from (c) and centroid of the colour marker (P_1) attached on the fingertip (indicated by a blue point).

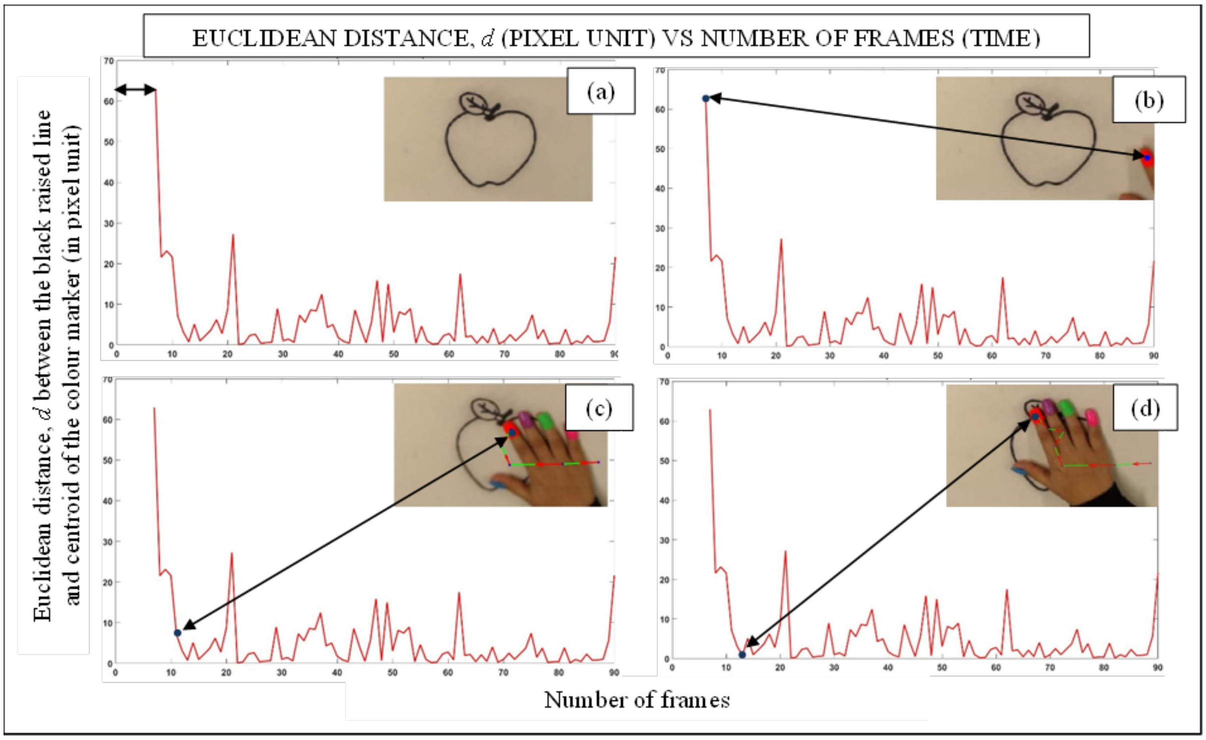


FIGURE 14. The graphs show the Euclidean distance, *d* against number of frames (time) at different situations. In (a), the hand of the participant was not inside the reading region, hence there was no value measured. In (b), the red colour marker appeared and the *d* value was at the peak. In (c), the red colour marker was approaching the black raised line and the *d* value was decreasing. Lastly in (d), the *d* value is at the lowest because the colour marker was very close to the black raised line.

Segmentation of frames with Euclidean distance, d that are less than 11 pixels. This process is performed to identify the moments when the fingertip reached the black raised line of the diagram. It is assumed that when d value is below 11 pixels, the fingertip approached the black line. Figure 15 shows the graph of regions that need to be segmented indicated by range of frames. The results of the segmentation process from the full trajectory of movement (refer Figure 16) can be seen in Figure 16 which shows the results of selected segmented trajectories or movements of the fingertip at that were closed to the raised-raised line.

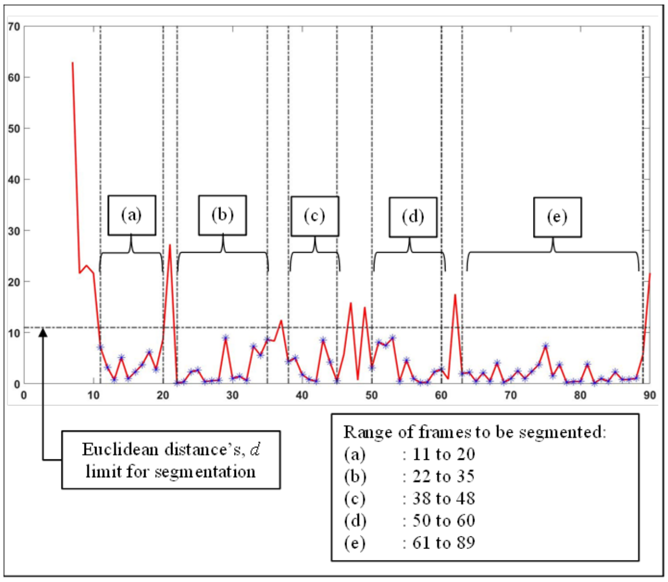


FIGURE 15. The graph shows the regions and the range of frames which has *d* values less than 11 pixels. There are five regions that will be segmented according to the given range of frames.

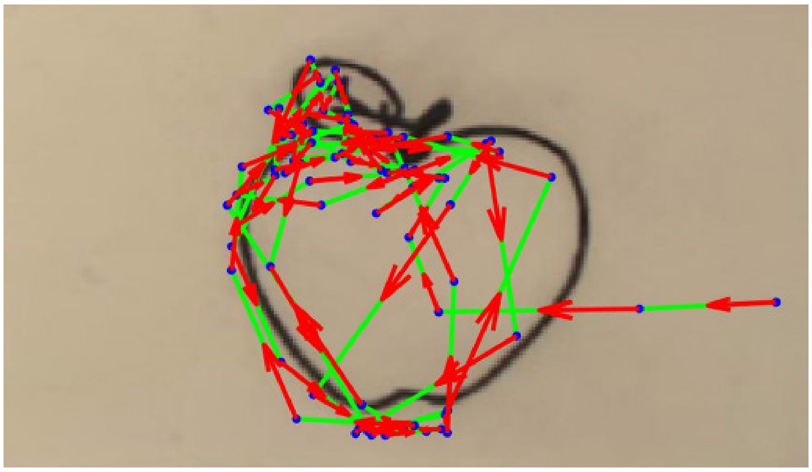


FIGURE 16. Full trajectory of movement on apple diagram

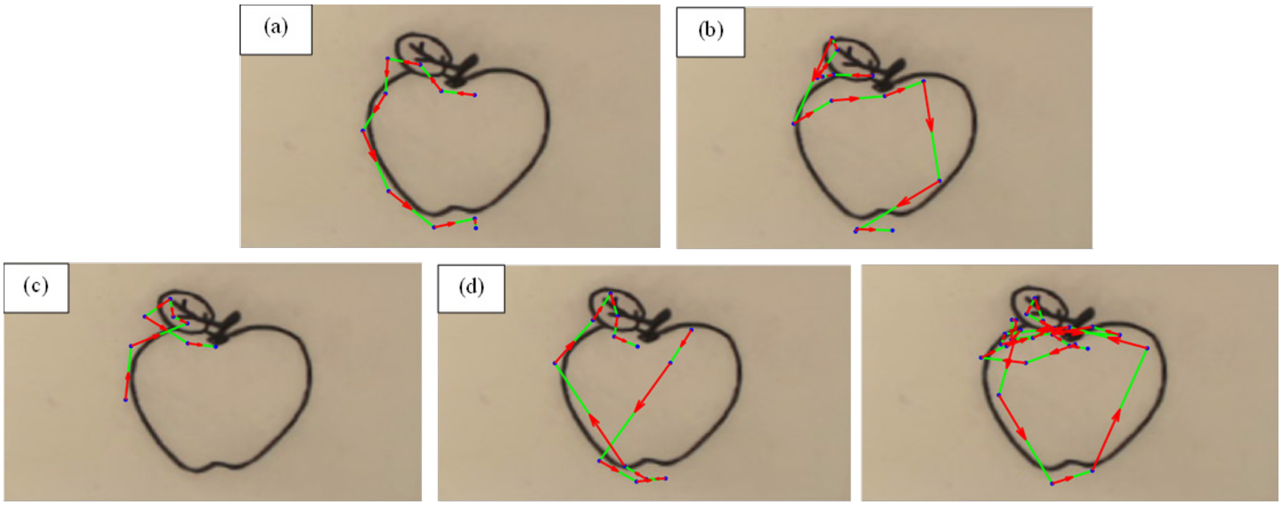


FIGURE 17. Results of the segmented trajectory that were closed to the raised-line

The results shown in Figure 18 to Figure 22 are the best segmented visualizations of fingertip movements from every participant. Then, the chosen results have been determined and characterized into two categories of exploratory procedures stated by Lederman and Klatzky (1987) which are contour following and lateral motion. Here, those two exploratory procedures were being highlighted due to the fact they are the most usual behaviours to be employed when reading the two-dimensional raised line drawings.

Note that the presented trajectories of movement are based on the index finger only for every participant. From Figure 18, P1 and P2 were identified to perform complete contour following movement along the love diagram. But, no contour following visualisations were found for P3 and P4. Even with their full trajectory of the finger movements P3 and P4 movement were too erratic and didn't focus on the love form. Figure 19 indicates all participants completed contour following on the banana diagram. Based on the trajectory plotted, P1, P2, and P4 have displayed a tidy contour following movement along the banana's outlines, except for P3, which may have done many lateral motions.

Figure 20 showed that all participants concentrated on the apple diagram leaf. Due to trying to recognise the leaf component of the diagram, all participants made many lateral motions. Although all participants executed contour following movement, it was incomplete and did not span the entire apple diagram.

Figure 21 illustrates P1 and P2's imperfect contour-following movement along the butterfly's body. P2 also demonstrated lateral motion on butterfly's antenna. After trajectory segmentation, P4's sole noteworthy showed the lateral movement at the butterfly's antenna. For P3, the reading was too random and didn't focus on any butterfly portion, therefore no significant movement can be identified. Finally, in Figure 22, all participants followed the snake's swirl pattern using segmented motions. No participant showed a complete and decent contour following snake movement. They appeared to move randomly without focusing on the snake diagram.

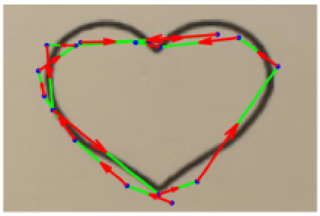
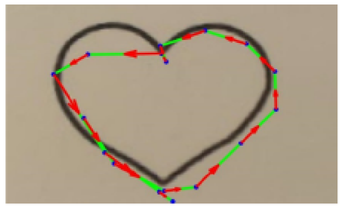
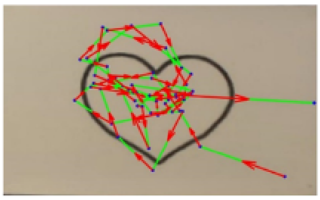
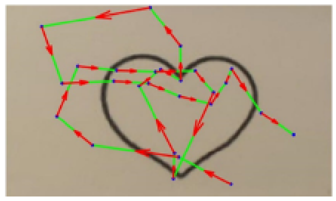
P1	P2
	
Description: P1 showed a complete contour following movement along the love diagram with similar pattern as P2.	**Description:** P2 also showed a complete contour following movement along the love diagram with similar pattern as P1
P3	**P4**
	
Description: Since there was no visualization showing good contour following movement and lateral motion, a full trajectory visualization was presented. P3 showed a very random and unfocused movement. It was intrepreted that P3 movements appeared to be unpredictable, and without any discernable pattern.	**Description:** Since there was no visualization showing good contour following movement and lateral motion, a full trajectory visualization was presented. P4 also showed a very random and unfocused movement. It was intrepreted that P4 movements appeared to be unpredictable, and without any discernable pattern.

FIGURE 18. Selected segmented trajectory of movement when reading love diagram

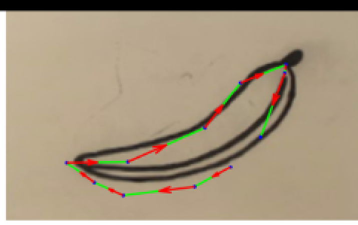
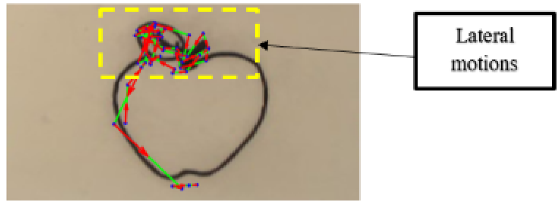
P1	P2
	
Description: P1 showed a nearly complete contour following movement along the outline of banana diagram. It can be seen that P1 was tracing the shape of the diagram with similar pattern as P2 and P3.	**Description:** P2 showed a complete contour following movement along the outline of banana diagram. It can be seen that P2 was tracing the shape of the diagram with similar pattern as P1 and P4.
P3	**P4**
	
Description: It was interpreted that P3 was performing contour following movement and also lateral motion along the outline of banana diagram. Plus, the movements appeared to be unpredictable, and without any discernable pattern.	**Description:** P4 showed a nearly complete contour following movement along the outline of banana diagram. It can be seen that P4 was also tracing the shape of the diagram with similar pattern as P1 and P2.

FIGURE 19. Selected segmented trajectory of movement when reading banana diagram

P1

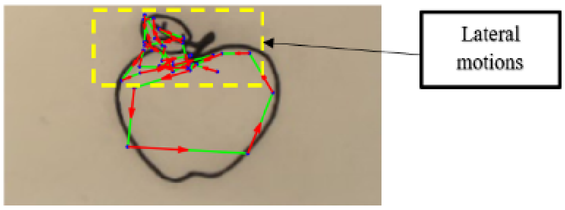
Description: It was interpreted that P1 was performing more lateral motions on the leaf part of the apple diagram compared to contour following movement around the apple's body.

P2



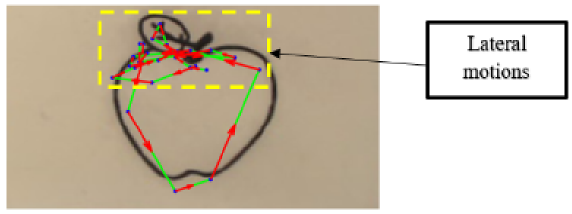
Description: It was interpreted that P2 was performing more lateral motions on the leaf part of the apple diagram compared to contour following movement around the apple's body.

P3



Description: It was interpreted that P3 was performing more lateral motions on the leaf part of the apple diagram compared to contour following movement around the apple's body.

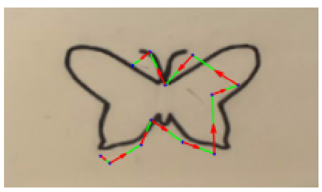
P4



Description: It was interpreted that P4 was performing more lateral motions on the leaf part of the apple diagram compared to contour following movement around the apple's body.

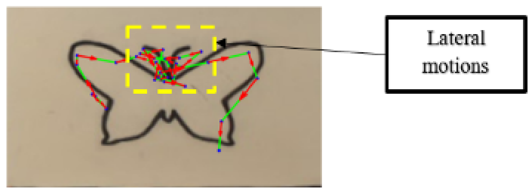
FIGURE 20. Selected segmented trajectory of movement when reading apple diagram

P1



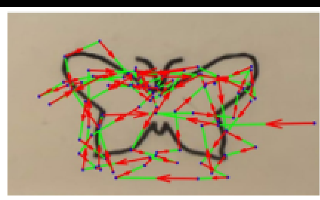
Description: It was interpreted that P1 was performing contour following movement along the outline of butterfly diagram. However, it was incomplete.

P2



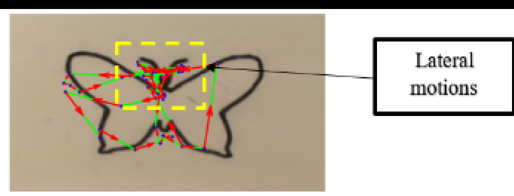
Description: It was interpreted that P2 was performing contour following movement along the outline of butterfly diagram. However, it was incomplete. Then, more lateral motions occurred on the antenna part of the butterfly

P3



Description: Since there was no segmented visualization showing good contour following movement and lateral motion, a full trajectory visualization was presented. P3 showed a very random and unfocused movement. It appeared to be unpredictable, and without any discernable pattern.

P4



Description: It was interpreted that P4 was performing more lateral motions on the antenna part of the butterfly diagram compared to contour following movement around the butterfly's body. However, it appeared to be unpredictable, and without any discernable pattern.

FIGURE 21. Selected segmented trajectory of movement when reading butterfly diagram

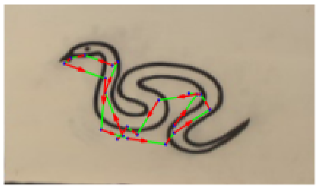
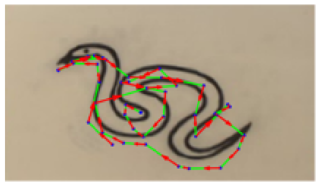
P1	P2
	
Description: It was interpreted that P1 was performing contour following movement along the outline of snake diagram. The movement showed that P1 was following the swirl pattern on the snake' body. However, it appeared to be unpredictable, and without any discernable pattern.	**Description:** It was interpreted that P2 was performing contour following movement along the outline of snake diagram. The movement showed that P2 was following the swirl pattern on the snake' body. However, it appeared to be unpredictable, and without any discernable pattern.
P3	**P4**
	
Description: It was interpreted that P3 was performing contour following movement along the outline of snake diagram. The movement showed that P3 was following the swirl pattern on the snake' body. However, it appeared to be unpredictable, and without any discernable pattern.	**Description:** It was interpreted that P4 was performing contour following movement along the outline of snake diagram. The movement showed that P4 was following the swirl pattern on the snake' body. However, it appeared to be unpredictable, and without any discernable pattern.

FIGURE 22. Selected segmented trajectory of movement when reading snake diagram

CONCLUSION

To investigate how BVI people read and explore the raised-line tactile graphics, a computer vision system has been used. The approach used was using the colour markers detection technique to track, record and visualize the fingertips movement on the tactile graphics. However, the system can only be used to detect five fingertips of a single hand. Although all five fingertips were being tracked, we only focused on analyzing the index fingertip's data because all participants responded that it is their most sensitive fingertip to read braille or tactile graphics materials.

The findings presented in this study offer a significant contribution to understanding BVI individuals interact with raised-line tactile graphics which can be categorized as follows:

1. Identification of salient regions

Our data revealed that every diagram has salient regions that have been touched by every participant for recognition and interpretation of the tactile graphic. Through heat map visualization and coordinate distribution analysis of the index fingertip's movements, the study highlights specific areas crucial for interpretation across all diagrams. It shows that BVI people will look for important attributes of the diagram to be able to understand the tactile graphics presented. This insight is important for designing tactile graphics that emphasize these essential attributes for better comprehension.

2. Exploratory procedures

In addition, our data also revealed the exploratory procedures and strategies performed by BVI people when reading tactile graphics. It was identified that the way of reading by every participant was unsystematic and too random. Nevertheless, most of them performed two types of exploratory procedure which are contour following movement and lateral motions. These two strategies hold significant implications for the development of assistive devices for tactile graphics reading. For instance, a feedback mechanism can be incorporated into the assistive device to mimic or guide contour following movements and lateral exploration. This could probably enhance the user experience and improve the efficiency of tactile graphic interpretation.

In conclusion, the methods and results that have been presented in this paper can be a reference to understand how the BVI people read and explore tactile graphics materials. It is a fact that to read tactile material using touch perception is a cognitive overload task. The implications through this research could extend to educational practices, design considerations of tactile graphics materials and even to the development of assistive devices for reading tactile graphics.

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DECLARATION OF COMPETING INTEREST

None

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