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Evaluating Touch-Screen Vibration Modality for Blind Users to Access Simple Shapes and Graphics

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Abstract—Accessing visual information becomes a central need for all kinds of tasks and users (from accessing graphics and charts in news articles, to viewing images of items on sale on e-commerce sites), especially for blind users. In this context, digital tools of assistance, using adapted software (screen readers, talking browsers, etc.), hardware (force feedback mouse, piezo-electric pins, etc.), and more recently touch-screen technology (using smart phones or smart tablets) have been increasingly helping blind persons access and manipulate information. While effective with textual information, yet existing solutions remain limited when handling visual information. In this context, the goal of our study is to shed light on how the *vibration* modality can be perceived by blind users when accessing simple contour-based images and visual graphics on a touch-screen. In this paper, we target the vibration-only modality, compared with audio-kinesthetic or multimodal vibro-audio solutions. Our main motivation is that the potentials and limitations of touch-screen vibration-only feedback need to be fully studied and understood prior to integrating other modalities (such as sound, human speech, or other forms of haptic feedback). This could prove very useful in a range of applications: allowing blind people to access geographic maps, to navigate autonomously inside and outside buildings, as well as to access graphs and mathematical charts (for blind students). To achieve our goal, we develop a dedicated experimental protocol, titled EVIAC, testing a blind user's capacity in learning, distinguishing, identifying, and recognizing basic shapes and geometric objects presented on a vibrating touch-screen. Extensive tests were conducted on blindfolded and blind candidates, using a battery of evaluation metrics including: i) accuracy of shape recognition, ii) testers' average response time, iii) number and duration of finger strokes, iv) surface area covered by the testers' finger path trails, as well as iv) finger path correlation with the surface of the target shape. Results show that blind users are generally capable of accessing simple shapes and graphics presented on a vibrating touch-screen. However, results also underline various issues, ranging over: prolonged response time (e.g., blind users require 1 minute and 22 seconds on average to recognize a basic shape), reduced touch-screen surface coverage, and low correlation between the surface of the target shape and the tester's vibration trails. The latter issues need to be further investigated to produce optimal recipes for using touch-screen technology to support image accessibility for blind users.

Keywords—Blind users, data and image accessibility, tactile image, vibrating touch-screen, paper embossing, experimental evaluation protocol, empirical study.

1. Introduction

In the dawn of the 21th century, visual media tools and contents become ubiquitous, saturating our modern society (ranging over web pages, mobile applications, e-books, e-commerce, etc.). Accessing visual information becomes a central need for all kinds of tasks and users (e.g., from accessing data representative graphics and charts in news articles, to viewing images of items on sale on an e-commerce site), namely for blind users. According to its latest statistics produced in 2014, the World Health Organization (WHO) estimates at 285 million the number of people affected by visual impairments, among whom 39 million are totally blind; and these numbers are expected to double by 2020 (World Health Organization, 2014). In this context, and thanks to adapted tools of assistance (e.g., screen readers, digitalized Braille terminals, and screen magnifiers), computerized solutions are increasingly helping blind or visually impaired persons to access and manipulate information, and perform various kinds of activities previously deemed unfeasible for the visually impaired.

However, while effective with textual contents, (ANSI/NISO, 2005; Cooper M. *et al.*, 2008; Guillon B. *et al.*, 2004; Stephan F. and Miesenberger K., 2008), yet existing solutions remain limited when accessing visual contents and images. The most prominent studies in this context focus on low-vision users (i.e., users who are not totally blind) by providing visual aids and image enhancement techniques (Dolphin, 2016; Kennedy J.M., 1993; Lawton T.B., 1992; Peli E., 1994; Tang J. *et al.*, 2004; Zubair J., 2008), adapting image spatial frequency, or applying dedicated filters in order to adapt image quality to the user's visual impairment. Other approaches have exploited tactile imaging (Kennedy J.M., 1993; Shiose T. *et al.*, 2008) and 3D models (Oouchi S., 2004; Oouchi S. *et al.*, 2010) in order to reproduce graphics and images in an embossed representation, highlighting the senses of depth and distance in an image with superimposed layer structures. Some approaches have investigated haptic feedback: using a force feedback mouse (Yu W. and Brewster S. A., 2002), or piezo-electric pins (Pietrzak T. *et al.*, 2009), in order to access images (Abu Doush I. *et al.*, 2012) as well as mathematical charts and geographic maps (Kaklanis N. *et al.*, 2011). Yet, most of these techniques remain quite expensive, of limited use (single-purpose), and of limited portability (where bulky equipment are usually required and need to be configured for every user and device) (Maclean K.E., 2008).

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Several authors in (Buzzi M. *et al.*, 2015; Cohen R.F. *et al.*, 2005; Giudice N. A. *et al.*, 2012; Su J. *et al.*, 2010) have addressed accessibility of simple visual representations (basic shapes and charts) on vibrating touch-screens. They provide *vibro-audio* interfaces, combining touch-screen vibration and audio (sound and speech) feedback, allowing blind users to explore simple graphical information on a touch-screen, such as bar graphs, letter glyphs (Giudice N. A. *et al.*, 2012), and indoor navigation layouts (Su J. *et al.*, 2010). These solutions associate finger movements over the display with synchronized *audio* and *vibration* cues when the user touches visual elements on the touch-screen. In (Goncu C. and Marriot K., 2011), the authors suggest adding haptic feedback through external vibrators fixed to the user's fingers when manipulating the touch-screen. While they have been shown effective in improving accessibility by combining multiple modalities: vibration, audio, and/or haptic cues, yet, solutions in (Cohen R.F. *et al.*, 2005; Goncu C. and Marriot K., 2011; Su J. *et al.*, 2010) do not specifically focus on the perceptual aspects of the human user in employing each modality separately.

In this context, our study targets the *vibration* modality on a touch-screen, and aims to shed some light on how vibration can be perceived by blind testers when accessing simple visual graphics on the touch-screen. Our ultimate goal is to provide access to simple graphics and contour-based images (made of basic forms and geometric objects) for blind users, using i) an accessible and affordable (cost-efficient) solution (in contrast with existing expensive accessibility tools), ii) a solution based on off-the-shelf commercial hardware (in contrast with highly specialized equipment), and iii) a solution which is portable and can be deployed in different contexts and environments (in contrast with specialized and single-purpose solutions). In this context, vibrating touch-screens (embedded within smart-phones and computer tablets) fit the profile (i.e., they are readily available, cost effective, and portable) and seem to present promising opportunities. Hence, in this paper, we provide some insight on the vibration modality of the touch-screen technology, as a key step toward achieving our ultimate goal. Here, we target the vibration-only modality, compared with audio-kinesthetic or multimodal vibro-audio solutions. Our main motivation is that the potentials and limitations of touch-screen vibration-only feedback ought to be fully studied and understood prior to integrating other modalities (such as sound, human speech, or haptic feedback). To do so, we develop a dedicated experimental framework, titled *EVIAC* (EVALUATION of VIBRATION ACCESSIBILITY), in order to test a blind user's capacity in *mapping*, *distinguishing*, *identifying*, and *recognizing* basic geometric objects presented on a touch-screen. *Mapping* means allowing a blind person to match shapes presented on embossed paper with the same shapes presented on a vibrating touch-screen, in order to learn the correspondence between embossed paper and touch-screen representations. *Distinguishing* means being able to differentiate between pairs of shapes presented on the touch-screen. *Identifying* means being able to make out the shapes among a set of multiple choices, whereas *recognizing* is a stronger form of identification where a blind person is asked to make out the shapes without any additional indications (i.e., without multiple choices). A dedicated prototype system has been developed to implement the proposed experimental framework. Experiments on blindfolded and blind testers show promising results and pinpoint many interesting observations, highlighting not only the feasibility but also some major issues of using the touch-screen vibration modality to access simple shapes and graphics.

The overall design of *EVIAC* was introduced in (Awada A. *et al.*, 2012), and preliminary tests were discussed in (Awada A. *et al.*, 2013). This paper extends the experimental framework, adding a substantial experimental evaluation to study the finger path trails produced by testers and analyze their haptic exploration strategies as they attempt to recognize basic shapes and objects presented on a touch-screen. To do so, the paper introduces a battery of new tests to gauge and analyze different measures, including: i) *accuracy* of shape recognition (in percentage of correct answers), ii) testers' average *response time* in recognizing different shapes, iii) *number* and *duration of finger strokes* needed to perform different shape recognition tasks, iv) *surface area covered* (per experimental task, and per stroke) by the testers' finger path trails on the touch-screen, and v) *finger path trail correlation* with the surface of the target shape, while vi) comparing results with respect to blindfolded and blind testers.

The remainder of this paper is organized as follows. Section 2 briefly reviews the background on data accessibility for blind users. Section 3 presents our motivation and application scenario. Section 4 describes our *EVIAC* experimental framework, including the experimental prototype and protocol. Section 5 presents and evaluates our experimental results. Section 6 concludes the paper, and highlights ongoing challenges and future directions.

2. Background and Related Works

In this section, we provide an overview of computerized solutions allowing visual data accessibility for blind or visually impaired users. We categorize those solutions as: i) software-based, ii) hardware-based, and iii) touch-screen based.

2.1. Software-based Data Accessibility Solutions

Providing software-based data accessibility for blind people has been investigated since the early 1960s, mainly for text-based data (ANSI/NISO, 2005; Cooper M. *et al.*, 2008; Dolphin, 2016; Guillon B. *et al.*, 2004; Stephan F. and Miesenberger K., 2008). In most cases, given an input text-based document, the output is a document with a transcription of the structure, content, and illustrations from the original document, such that the transcription is accessible to the blind user via tactile (e.g., Braille print¹) or

¹The Braille system is a method based on tactile contact, widely used by visually impaired people in order to read and write text. A Braille character is made of six dot positions, arranged in a rectangle containing two columns of three dots each. A dot may be raised at any of the six positions to form sixty-four (2⁶) possible subsets (character encodings), including the arrangement in which no dots are raised.

acoustic (e.g., text-to-speech) means (ANSI/NISO, 2005). Illustrations (e.g., images, graphs, animations) in the original document are replaced by their textual metadata (e.g., image caption, graph label, or the text within the animation, if available) and integrated into the document's output transcription (DAISY, 2015; Guillon B. *et al.*, 2004). Other software-based solutions include *screen readers* (e.g., VoiceOver (macOS), YASR (Linux), Tiny Voice (Dos)) (Freedom Scientific Inc., 2016; HTCTU, 2016) and *Talking browsers* (Bryan H. and Anderson M., 2014; TextHelp, 2016) that attempt to identify and interpret what is being displayed on the screen of a computer (e.g., in a Web page): i) the text shown on screen is transformed into audio (speech) output, ii) images and other multimedia objects (such as animations and graphs) are first replaced by their alternative text descriptions (provided under their *alt* tags in HTML coding) which are then transformed into speech², and iii) some shortcuts are added to simplify user interaction (e.g., list of headings (insert+F6), list of links (insert+F7) (TextHelp, 2016)). Recent studies have focused on specific kinds of textual contents, such as chemical chains (Stephan F. and Miesenberger K., 2008) and mathematical formulas (Cooper M. *et al.*, 2008) mainly for educational purposes (accessibility for blind or visually impaired students (Costa L. *et al.*, 2015; Miesenberger K. and Ruemer R., 2006)). Other recent works in (Bou Issa Y. *et al.*, 2010; Bou Issa Y. *et al.*, 2009; Semaan B. *et al.*, 2013) have addressed Web page accessibility for blind Web surfers using semantic Web technologies (such as RDF-a³ (Sporny M., 2015)), focusing on the design and visual arrangement of text-based objects in a Web page in order to improve its presentation (using embossed paper printouts or talking browsers). Nonetheless, these works focus on Web graphics associated with text (e.g., labels, alternative texts⁴, surrounding paragraphs) and the visual arrangement/design of text-based objects in a Web page, and do not specifically target text-free graphics or images. (Wu S. *et al.*, 2017)

Discussion: One major advantage of software-based techniques is that they can be implemented on any basic computer system and do not require special hardware. Another advantage is that open source solutions (such as eSpeak and YASR screen readers (HTCTU, 2016)) are inherently cost effective. Yet, the main limitation of this family of solutions is that they are mostly designed to transform text-based data into Braille print or human speech output, and remain limited when processing visual contents or graphics which are only accessible through their textual metadata. In contrast, the goal of our study is to investigate whether users can access simple images and graphics “directly”, without an intermediary textual transcription, through vibrotactile feedback using touch-screen technology.

2.2. Hardware-based Data Accessibility Solutions

Traditional hardware-based techniques provide the user with hardware interfaces using the universal Braille language (used by 2 out of 10 blind people (Seymour-Ford J., 2002)). These are implemented through devices like the *Braille keyboard* (for data input) and the *Braille display* (for data output) (AFB, 2016; BliTab, 2016) (cf. Figure 1). While efficient with textual data, yet such solutions are not adapted to represent digital information made of visual graphics, such as images and graphical interfaces in computer-based systems and on the Web (Bou Issa Y. *et al.*, 2009).

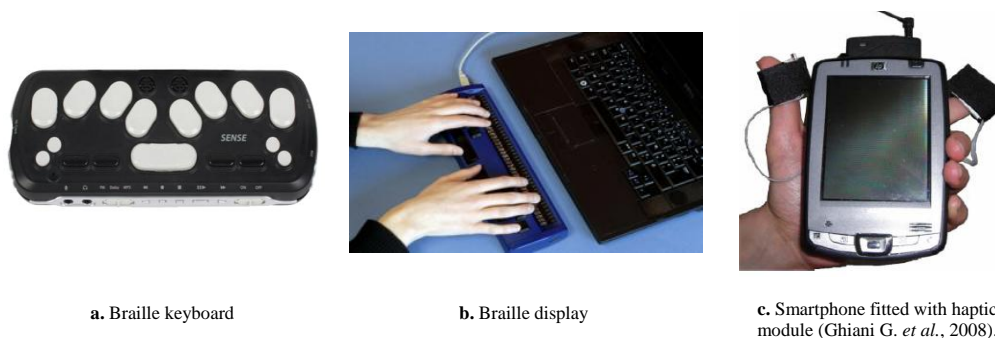


Figure 1. Some hardware-based accessibility techniques.

To allow more effective access to visual data and graphics, many studies have targeted low-vision users (i.e., users who are not totally blind (Kennedy J.M., 1993; Lawton T.B., 1992; Peli E., 1994; Tang J. *et al.*, 2004; Zubair J., 2008)), providing visual aids equipment (e.g., special lenses or monitors) coined with image enhancement techniques such as image contrast manipulation (Peli E. *et al.*, 1990), spatial filtering (Peli E., 1991), adaptive thresholding (Peli E. *et al.*, 1991), and compensation filters (Fine E. M. *et al.*, 1994), in order to adapt image quality to the user's visual impairment. Other approaches have exploited tactile imaging (Heller M.A. *et al.*, 2002; Kennedy J.M., 1993; Shiose T. *et al.*, 2008), where an image is printed by carbon-containing ink on a special paper coated with microcapsules which can be foamed thermally. Then, a stereo copying machine processes the paper such as the black portions of the image are raised so that the image becomes tactile. Several authors have explored 3D modeling

² In a recent study in (Wu S. *et al.*, 2017), the authors apply computer vision technology to identify faces, objects, and themes from social media photos to generate photo *alt*-text to be output using screen readers for blind users on Facebook.

³ RDF-a is a W3C recommendation allowing to integrate structured information such as relationships between places, people, and events, in an HTML Web page.

⁴ Test provided under the *alt* tag in HTML coding.

(Fujiyoshi M., 2010; Oouchi S., 2004; Oouchi S. *et al.*, 2010; Sanches E.C.P. *et al.*, 2017) in order to reproduce images in a layered representation. This technology allows representing shapes using a multilayered embossing: representing the senses of depth, distance, and the spatial composition of a picture with different layer structures (i.e., different levels of thickness). While 3D representations have been shown effective in allowing blind persons to appreciate drawings and art works (Oouchi S., 2004; Oouchi S. *et al.*, 2010), yet their production remains expensive, requiring: i) a 3D projection and sculpting solution to produce an adapted 3D representation for an (original) 2D image, ii) a 3D modeling software or a 3D scanner to digitalize the obtained 3D sculpture, and iii) a 3D molding machine (Oouchi S. *et al.*, 2010) or a Braille printer (Fujiyoshi M., 2010) in order to produce the output tactile image to be perceived by blind users.

Other solutions have focused on haptic feedback which can be produced in the form of a vibration feedback applied on the user's fingers, a force feedback applied on the hand or fingers, or a combination of both (Abu Doush I. *et al.*, 2012; Hribar V. E. and Pawluk D. T. V., 2011; Velázquez R., 2010; Yu W. and Brewster S. A., 2002). In (Ghiani G. *et al.*, 2008), the authors design and implement a guide system that uses two vibration motors which can be worn by the user on her/his index finger and the thumb of the hand holding the device (cf. Figure 1.c). The authors show that vibration feedback produced by their solution can be as effective as vocal feedback in helping the user navigate a certain geographic location following map coordinates being processed on the mobile device. A similar project in (Goncu C. and Marriot K., 2011) shows that graphs, shapes, and maps can be understood by blind users when learned from a touch-tablet with external vibrators fixed to the user's fingers. Some studies have also investigated haptic feedback using a force feedback mouse (Yu W. and Brewster S. A., 2002), or piezo-electric pins that dynamically move up and down (Pietrzak T. *et al.*, 2009), in order to access images (Abu Doush I. *et al.*, 2012), mathematical charts and geographic maps (Brock A. *et al.*, 2012; Kaklanis N. *et al.*, 2011). An integrated haptic display made of an adapted pin matrix coupled with a thermal display on which the warm-cold spectrum of colors is mapped is introduced in (Hribar V. E. and Pawluk D. T. V., 2011) to allow improved accessibility of paintings in a museum. Experiments in (Petit G. *et al.*, 2008) produce promising results when accessing tactile graphs and charts using a touch-screen coupled with multiple piezo-electric motors to stimulate the finger used for tactile sensation (i.e., perceiving vibration feedback with one single finger). Readers can also refer to (Velázquez R., 2010) for a survey of wearable assistive devices based on haptic feedback.

Discussion: Many hardware-based studies have targeted low-vision users by providing visual enhancements and aids (Kennedy J.M., 1993; Lawton T.B., 1992; Peli E., 1994; Tang J. *et al.*, 2004; Velázquez R., 2010; Zubair J., 2008). Solutions dedicated to blind users have been shown effective in accessing certain kinds of images and visual representations (like graphs and navigation maps (Ghiani G. *et al.*, 2008; Goncu C. and Marriot K., 2011; Petit G. *et al.*, 2008; Pietrzak T. *et al.*, 2009; Yu W. and Brewster S. A., 2002). Yet, prominent hardware-based techniques such as 3D modeling and haptic feedback devices (Fujiyoshi M., 2010; Oouchi S., 2004; Oouchi S. *et al.*, 2010) remain quite expensive (e.g., a typical tactile image printer costs around ten thousand US dollars), of limited use (designed for single-purpose applications, e.g., geo-navigation (Ghiani G. *et al.*, 2008; Goncu C. and Marriot K., 2011)), and of limited portability (they need to be mounted and/or configured manually on each computer system, e.g., PC, tablet, smart-phone, or PDA, to be utilized by the blind user) (Maclean K.E., 2008). Also, several interesting solutions using a touch-screen coupled with other media/sensors have been proposed. Nonetheless, one of the most ubiquitous haptic feedback devices remains the vibrating touch-screen, integrated with typical smart-phones and computer tablets. Due to its overwhelming usage and popularity compared with other haptic solutions, we view the vibrating touch-screen technology as a category on its own and discuss its accessibility solutions in more detail in Section 2.3.

2.3. Touch-Screen based Solutions

The unprecedented proliferation of vibrating touch-screen based devices (e.g., smart-phones and tablets) has opened the door to a new era of multimodal interfaces including combinations of auditory and vibro-tactile cues. With many of these devices, hand and finger movements over the display provide position and orientation indicators, through synchronized audio and vibration signals which are delivered when the user touches a visual element on the touch-screen. Here, one can distinguish between *audio-kinesthetic* interfaces, which couple text and sound cues with hand/finger movements on the screen; and *vibro-audio* interfaces, which add vibro-tactile feedback (Giudice N. A. *et al.*, 2012; Klatzky RL. *et al.*, 2014). On one hand, examples of audio-kinesthetic interfaces include *Timbremap*, which uses sonification for representing complex indoor layouts on a smart-phone's touch-screen (Su J. *et al.*, 2010), and the *PLUMB* project which uses sonification to describe auditory graphs presented on a touch tablet (Cohen R.F. *et al.*, 2005). Experiments with both solutions have shown their accurate perception of the experimental stimuli. Audio-kinesthetic interfaces have been successfully implemented in various commercial tools such as *iPhone VoiceOver* (Apple, 2016) supported by the iPhone operating system (iOS) which uses gestures for navigation, such that the text on the screen is spoken allowing the user to locate herself/himself on the screen while using the smart-phone (e.g., touch or drag a finger around the screen and VoiceOver tells what is happening; tap a button to hear a description; and double-tap to activate). Similar techniques have been developed for Android-based smart-phones such as *Slide Rule* (Shaun K. *et al.*, 2008) (cf. Figure 2.a).

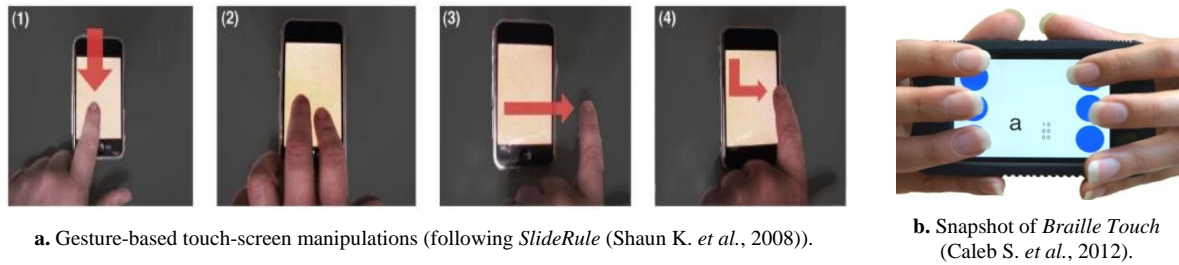


Figure 2. Sample touch-screen based solutions.

On the other hand, with vibro-audio solutions, the touch-screen vibration is generated by rotating electro-magneto vibration actuators which are fixed (built) internally in the device (Yairi I. *et al.*, 2009). An example of this approach is *TouchOver* map, which has shown that blindfolded participants can understand a road network through vibration coupled with auditory labels when feeling a smart-phone touch-screen, and can then reproduce the map (using vision) while simultaneously exploring the (later) hidden display (Poppinga B. *et al.*, 2011). A similar approach is developed in (Giudice N. A. *et al.*, 2012), enabling users to examine graphical information on the touch-screen of a speculative accessible tablet (in comparison with the smaller smart-phone touch-screen used in (Poppinga B. *et al.*, 2011)): by using synchronously combined triggering of vibration patterns and auditory information whenever an on-screen visual element is tapped. The authors also conduct experiments on purely vibro-tactile information to perform letter identification and shape recognition (similar to the stimuli used in our current study). Experiments realized in (Giudice N. A. *et al.*, 2012; Klatzky RL. *et al.*, 2014) have confirmed that the vibro-audio interface is a feasible multimodal solution for accessing dynamic visual information and supporting structural learning and the evolution of statements of graphical material. In a related work (Buzzi M. *et al.*, 2015), the authors describe an android-based application designed to allow blind children to make free hand drawings and play with simple geometric shapes on a vibrating tablet. Vibro-audio interfaces have also been successfully implemented in various tools such as *BrailleTouch* (Caleb S. *et al.*, 2012) (supported by iOS, cf. Figure 2.b) designed to facilitate input text entry by typing in Braille. It is based on six points located on both sides of the screen, representing the Braille matrix that can be used to type letters and numbers in Braille code. This application is practical for Braille writers since no additional hardware accessories are required to type in Braille on the touch-screen. It is only accessible for users who are familiar with Braille writing, and is restricted to text input (it does not provide an output medium). Other commercial solutions exist like *Perkinput* (Azenkot S. *et al.*, 2012) for Braille input (developed for android phones, android pads, and allowing to connect two android devices in order to benefit from their adjacent screens simultaneously), and *VBraille* (Jayant C. *et al.*, 2010) for Braille output which uses a 6 dots Braille matrix such that when the user touches a dot, the phone vibrates indicating that the dot exists in the character being read.

In a previous work (Awada A. *et al.*, 2012; Awada A. *et al.*, 2013), we focused on the vibration-only modality, aiming to provide an accessible and affordable solution for presenting simple pictures to totally blind users. We have introduced an experimental framework to evaluate the ability of a blind user in identifying, recognizing, and understanding simple contour-based images (made of basic forms and geometric objects such as lines and circles) presented on a vibrating touch-screen. Obtained preliminary results with blindfolded testers have shown that basic shapes such as horizontal and vertical lines, are easily accessible (recognizable), whereas more complicated shapes such as the zigzag line and the curved line, are more difficult to recognize. Our current study extends previous work (Awada A. *et al.*, 2012; Awada A. *et al.*, 2013) by further developing the experimental study to consider: i) more sophisticated geometric shapes (square, rectangle, triangle, and circle), ii) an extended battery of new evaluation parameters including *accuracy* of shape recognition, tester *response time*, tester *finger path trails* and their *correlation* with target shapes, *surface area covered*, and *stroke patterns*, as well as iii) a larger number of blindfolded and blind testers. Details are provided in the following sections.

Discussion: From a technical perspective, our current research falls in this category of methods (i.e., touch-screen based solutions). Yet, the first major difference between our approach and most existing works is that we target the *vibration-only* modality in our study, in comparison with *audio-kinesthetic* solutions (Cohen R.F. *et al.*, 2005; Su J. *et al.*, 2010), or multimodal *vibro-audio* solutions (Giudice N. A. *et al.*, 2012; Poppinga B. *et al.*, 2011), except for (Giudice N. A. *et al.*, 2012) where the authors also consider purely vibro-tactile information to perform letter identification and shape recognition. A second difference is that we only rely on the tablet's internal vibration motor with one point of contact (the dominant finger) on the touch-screen, in contrast with the usage of external vibration motors and multiple fingers during exploration (Ghiani G. *et al.*, 2008; Goncu C. and Marriot K., 2011). Third, the aim of our study is different from most existing contributions. Most existing studies provide technical solutions without performing empirical evaluations or utilizing formal experimental protocols to analyze their data: where designs are often driven by computational efficiency or intuitive assumptions of the designer without feedback regarding the functional utility of the technology or its ability to address the needs of users (except in (Giudice N. A. *et al.*, 2012) where the authors specifically focus on experimental evaluation). In contrast, our study aims to perform an experimental evaluation of vibration-only accessibility on a typical touch-screen, through a dedicated formal protocol and experimental prototype system.

We view this as an essential step toward fully understanding the promises and limitations of the touch-screen vibration modality, and we put forth empirical findings and observations that need to be further investigated to help improve existing accessibility solutions or design new ones.

3. Motivation and Application Scenario

The main motivation of our ongoing research efforts is to develop an accessible and affordable (i.e., cost-effective) solution for presenting simple images for blind users. Our vision relies on efforts made in the fields of image processing and content-based image retrieval, and consists in providing a contour-based representation of a digital image, obtained using low-level feature extraction and filtering, which could be easily accessible to blind users using a fairly cheap and affordable technique: tactile perception on a vibrating touch-screen.

Accessing simple images and basic shapes on a vibrating touch-screen can serve many practical needs, namely: i) enhancing blind-computer interaction by adding the perception of simple 2D objects (such as icons) in the interaction process (Giudice N. A. *et al.*, 2012; TextHelp, 2016), ii) enhancing communication between blind and sighted users when trying to communicate a certain shape or geometric object to the blind (e.g., teacher trying to communicate the shape of a triangle, square, or chart to blind students (Costa L. *et al.*, 2015; Miesenberger K. and Ruemer R., 2006)), iii) enhancing geographic navigation in maps and perception of roads and points of interest (by perceiving and following simple vibration pointers on the touch-screen (Giudice N. A. *et al.*, 2012; Poppinga B. *et al.*, 2011)), and iv) enhancing navigation assistance in user interfaces (such as graphical software interfaces, Web pages, or adapted ATM⁵ machine interfaces (Bou Issa, 2010; Bou Issa Y. *et al.*, 2010)) by including adapted vibration indicators, and introducing new navigation models based on such indicators (compared to using embossed paper indicators (Bou Issa Y. *et al.*, 2009)).

The overall organization of our application scenario is depicted in Figure 3. It is divided into three main parts: i) image preparation, ii) image presentation, and iii) user feedback.

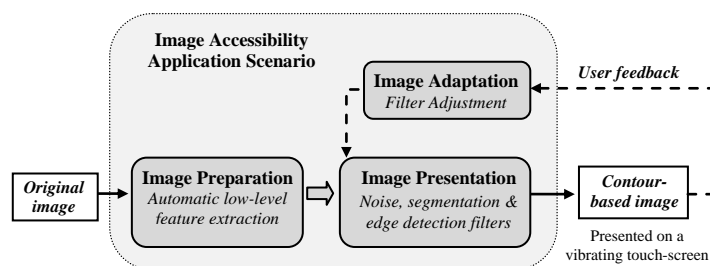


Figure 3. Overall organization of our application scenario.

Image preparation consists in extracting the visual features and semantic properties of images. Typical low-level (color, texture and shape) feature extraction and salient object identification techniques will be used in this phase (Liu Y.; Zhang D.; Lu G. and Ma W.-Y., 2006; Long F.; Zhang H.J. and Feng D.D., 2003). Automatic feature extraction can be augmented by manual/semi-automatic annotations, in order to better describe salient objects and semantic characteristics⁶. Image annotations can be provided to the user through text-to-speech synthesis, producing auditory output coupled with the vibration modality to further enhance accessibility for the blind (e.g., the user would be perceiving vibration feedback coupled with an auditory message describing the shape being perceived, its nature, its location on-screen, and its surrounding shapes). (Weinberger K.; Slaney M. and van Zwol R., 2008) (Liu Y.; Zhang D.; Lu G. and Ma W.-Y., 2006)

Image presentation consists in processing the prepared feature-based image via dedicated noise reduction, segmentation, and edge detection filters. Here, we can dynamically combine different techniques, namely linear (convolution) and non-linear (median and mean) local filters (Long F.; Zhang H.J. and Feng D.D., 2003), as well as Sobel, Roberts, Laplacian, and Canny edge detection filters (Philippe-Foliguet S., 2006; Sharifi M., 2002), in order to produce an adapted contour-based representation which can be effectively rendered and presented on a vibrating screen. Note that the resulting contour-based image presentation will not necessarily respect the standards and norms of tactile presentations (e.g., stipulating that a single contour line is at least 1 to 2

⁵ Automated Teller Machine

⁶ The automatic retrieval of information from pictures is usually based on extracting low-level information such as colors, shapes and textures, as well as more global objects (such as: face detection), and other object recognition processes. Yet, without the ability to automatically analyze low-level image contents, accessibility must only rely on textual metadata such as captions or keywords (Weinberger K. *et al.*, 1978). While keywords can be easily made accessible to the blind using text-to-speech synthesis, nonetheless, they are often ambiguous or expensive to produce (Weinberger K. *et al.*, 1978, Liu Y. *et al.*, 2006). In this context, we aim to improve the accessibility of image contents retrieved based on automatic analysis of low-level image features, in addition to extracting textual annotations when available.

millimeters thick, whereas the separation between two contour lines is at least 3 millimeters thick) (SOCRATE-COMENIUS, 2000), since the resulting image is to be presented on a vibrating touch-screen, and not on embossed paper. Hence, a dedicated experimental study is required to evaluate the difference between tactile perception (for a blind user) on embossed paper, on one hand, and perception on a vibrating touch-screen on the other hand.

Image adaptation via user feedback allows the user to interact with the system by providing information concerning images that are perceived correctly and those which are not perceived accurately. In fact, relevance feedback has been exploited with traditional image access and retrieval systems in order to improve image search results (Cox I. J. *et al.*, 2000; Xu X.S. and Huang T.S., 2003). Here, the question becomes whether or not the output presentation of the image is too complex to understand by touching a vibrating screen. Hence, user feedback will allow to simplify images to such a degree that blind users can understand them. Consider for instance a user trying to perceive a rectangle shaped icon presented on the touch-screen. If the user is unable to identify the icon, then the system will acquire the user’s answer (e.g., “unknown object”) using Braille or speech input as feedback, and attempt to adapt/re-order the filter functions to produce a new version of the contour-based representation of the icon. In doing so, the system attempts to increase the user’s chances of recognizing the icon correctly the next time it is perceived. A similar scenario can be used in navigating and understanding maps. For instance, when the user is undecided and does not know where to go since she/he is unable to correctly perceive a marked trail, the system can acquire the user’s indecision (e.g., long wait) as a feedback and adapt the filter functions to produce an updated/simplified visualization of the trail. Yet, another question here is: To what extent images should be simplified? In essence, this could depend on the haptic exploration strategies used by blind people (Shiose T., 2008 #736). Thus, experiments to examine hand movements of blind users while touching contour-based images presented on a vibrating touch-screen are required. Consequently, based on the users’ judgments in comparison with the actual contents of images, the system can dynamically update its filter configuration strategy and sorting functions (e.g., selecting certain filters, and re-ordering filters) to give a better contour-based presentation of the actual image. In other words, we aim to bring the user in the image processing loop to dynamically adapt the result.

In order to develop the application scenario briefly described above and achieve vibration (contour)-based image accessibility, we first identify the need to study the feasibility of adopting the vibrating touch-screen technology as a means for presenting contour-based images and simple graphics, which we investigate in this paper through a dedicated experimental framework.

4. Experimental Framework

The goal of our work is to better understand how the *vibration modality* can be perceived by blind users when accessing simple visual graphics on a touch-screen. This is an essential step for developing more sophisticated visual data accessibility and navigation techniques, namely our image accessibility scenario described in the previous section. To do so, we develop a dedicated experimental framework titled *EVIAC* (EValuation of Vibration Accessibility) in order to test a blind user’s capacity in *mapping, distinguishing, identifying, and recognizing* basic geometric objects presented on a touch-screen. *EVIAC* consists of: i) an experimental protocol describing the various steps to be followed by a test *coordinator* (e.g., a sighted person), in order to administer a set of experiments regarding image accessibility on a vibrating touch-screen to a *tester* (e.g., a blind or blindfolded person); and ii) an experimental prototype system, implementing *EVIAC*’s protocol on a (readily available, relatively inexpensive, and portable) computer tablet, allowing to easily run *EVIAC*’s tests and perform corresponding experimental measurements. Our experimental prototype and protocol are described in detail in Sections 4.1 and 4.2 respectively.

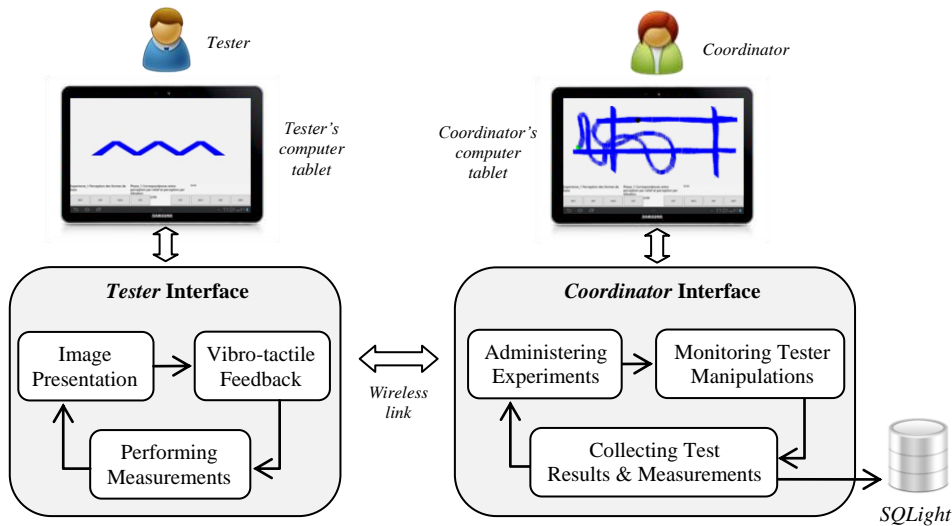


Figure 4. Overall prototype system architecture.

4.1. Prototype System Overview

Our prototype system was developed on a Samsung Galaxy Tab computer tablet with a 10.1 inch touch-screen, a 1280×800 screen resolution, running an Android operating system (version 3.2). The prototype consists of 2 main application modules: i) the user (*tester*) interface, and ii) the *coordinator* interface, each designed to run on a separate tablet, connected together via a synchronized wireless link (cf. prototype architecture in Figure 4). On one hand, the *tester* interface is manipulated by the test subject. It provides the *tester* with contour-based images (e.g., basic shapes and geometric objects) displayed on the tablet's vibrating touch-screen, and captures the finger movements of the *tester* while touching the images (among a battery of experimental measurements described in Section 5). On the other hand, the *coordinator's* interface allows administering the test: acquiring the *tester's* profile data in the beginning, and then allowing to go from one experimental test phase to another, while monitoring the manipulations and recording the answers of the *tester*, as well as the test phases' execution times. An SQLite database on the *coordinator's* tablet is utilized to store the experimental data (i.e., measurements collected from the *tester's* interface, and tester answers collected from the *coordinator's* interface), synchronized with a MySQL database for later processing on a personal computer.

Regarding the tester's interface, vibro-tactile stimuli are generated using the tablet's embedded electromagnetic actuator: an off-balance motor controlled by an embedded haptic player (developed by Immersion Corporation⁷). Vibro-tactile effects are configured and handled using the Universal Haptic Layer (UHL) package⁸, a JAR file containing classes and methods allowing the creation and manipulation of haptic effects on Android devices (we imported UHL as a plug-in to our JAVA Eclipse development platform to create the tester interface's experimental code). While many haptic stimuli can be manipulated and tested in this interface, yet in our current study, we use a pre-defined set of parameters established from earlier studies (Giudice N. A. *et al.*, 2012; Raja M. K., 2011): where the authors identified the vibro-tactile line width which is most conducive of line/contour tracing/following, and the vibration frequency which is best perceived by testers. Hence, based on the latter findings, we present our basic shapes/objects using 8.9 mm (0.35 inch) wide contours, which correspond to 56 pixels on the tablet's screen. This is also used as the minimum inter-line distance. The tester receives a constant vibration feedback of 250Hz (rendered using UHL's *Engine_100* effect), whenever and as long as her/his finger touches a shape/object on-screen. Vibration feedback stops when the tester's finger: i) touches outside of the shape/object's contour, or ii) releases the screen. Note that the vibration feedback involves the entire device (i.e., the whole device vibrates) and not the point of contact with the tester's fingertip. Hence, testers were instructed to use one finger only, namely the index finger, in perceiving and pointing to images on the tablet's screen (cf. Figure 5). This is based on observations in previous studies using touch-enabled devices (Goncu C. and Marriot K., 2011; Poppinga B. *et al.*, 2011) where experts found that the use of one finger was sufficient for vibro-tactile line tracing, and that little improvement (in exploration of haptic maps on a touch-screen) was shown when using multiple fingers simultaneously (Giudice N. A. *et al.*, 2002). Note that shapes and objects that we display on the tablet touch-screen are referenced to a fixed coordinate system, which allows making specific and detailed measurements (e.g., touch position coordinates and tester's finger path trails, cf. Section 5) whenever an on-screen visual element is touched. Auditory output, which is only used to help the tester navigate from one image/test to another (and not in perceiving or recognizing shapes/objects within *EVIAC's* experimental tests), is delivered from the device's onboard speakers.

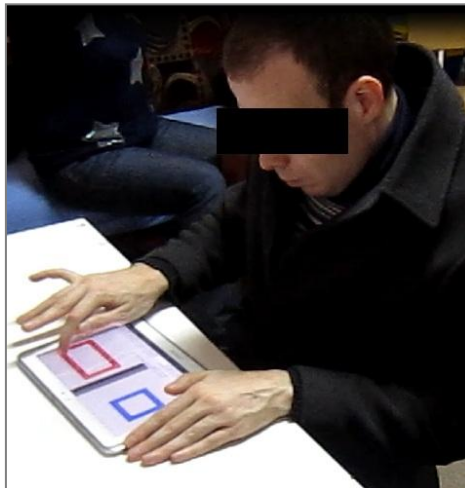


Figure 5. Snapshot of tester using the prototype system during experimental evaluation.

⁷ A developer and licenser of touch feedback (haptic) technology, <https://www.immersion.com/>

⁸ Developed by Immersion Corporation, <https://www2.immersion.com/developers/phocadownload/>

Our current prototype system implements the *EVIAC* experimental protocol, including all experiments, phases, and steps, described in Section 4.2. Yet, note that it can be easily extended to allow additional functionality⁹, and can be integrated and used with any off-the-shelf (Android) touch-screen device with an embedded vibration motor. (El Lahib M. *et al.*, 2017)

4.2. Experimental Protocol

As for *EVIAC*'s experimental protocol, it consists of two main experiments: i) Recognizing basic shapes, and ii) Recognizing simple geometric objects. All experiments are detailed in the following sub-sections.

Note that prior to executing the experiments, an *environment familiarization and discovery* step is required, to explain for each test candidate: the experiments to be conducted, the nature of each experiment, the tasks to be completed, and how to handle the touch-screen (prototypical) environment (e.g., how shapes and objects are presented on the vibrating screen, and control buttons). In addition, the test subject's profile data (e.g., name, age, gender, type of blindness: since birth or after birth) are recorded at this stage. Also, after completing the experiments, a short discussion is conducted with every tester, organized as an open interview where any feedback can be provided by the participant. The test coordinator leads the way with two or three questions to jumpstart the discussion, namely: i) "Can you describe how you perceived shapes and objects on-screen?", ii) "Did you enjoy the experiments?", and iii) "Do you have any further comments?". Feedback from these short discussions is highlighted in the remainder of the paper along with experimental results.

4.2.1. Experiment 1: Recognising Basic Shapes

The goal of this experiment is to verify the following hypothesis: *Blind users are capable of mapping, distinguishing, identifying, and recognizing basic line shapes presented on a vibrating touch-screen.* To do so, we utilize the 6 basic line shapes presented in Figure 6, including: horizontal like, vertical line, 45° sloped line (slash), -45° sloped line (backslash), zigzag line, and curved line. These generally constitute the simplest shapes which compose basic geometric objects (such as squares, triangles, etc.).

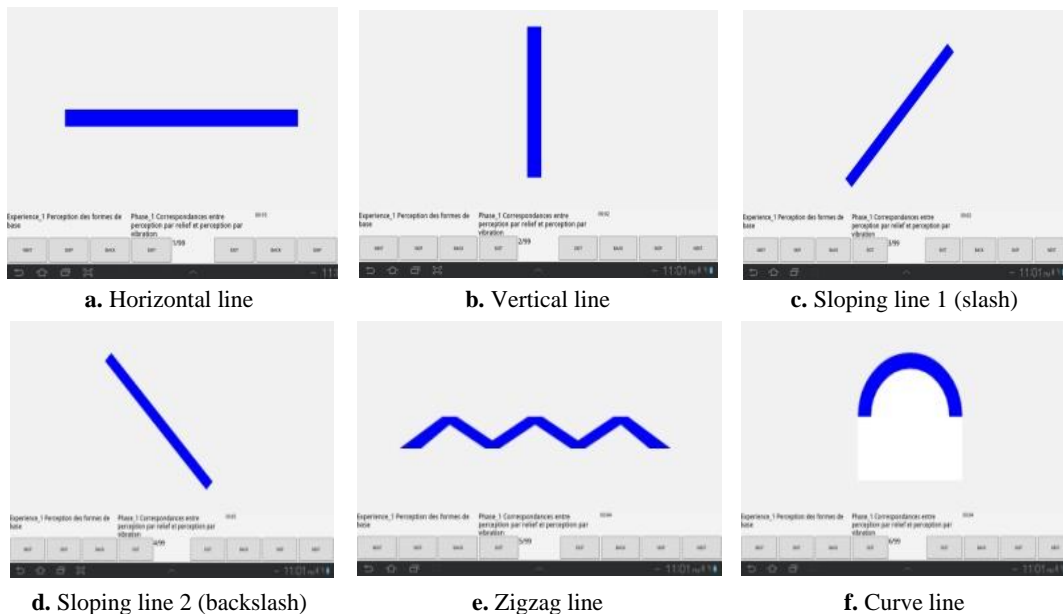


Figure 6. Prototype snapshots of the basic shapes used in Experiment 1.

The experiment is divided in 4 main phases, designed to confirm (or reject) the experiment's main hypothesis (stated above).

- **Phase 1:** Mapping (correspondence) between embossed paper and vibrating screen tactile perceptions.

The objective of this phase is to test if a blind person is capable of identifying the correspondences between shapes presented on an embossed paper, and their counterparts presented on a vibrating touch-screen. It is also considered as a learning phase, providing the *tester* with the correct answers in order to allow the blind person to learn the right correspondences. The experiment is conducted as follows:

- Presenting to the *tester* each of the 6 basic shapes (cf. Figure 6), on an embossed paper¹⁰, in-order, while vocally naming each shape,

⁹ We have extended our experimental prototype to conduct new experiments: evaluating Fitts' Law and the pointing task (El Lahib M. *et al.*, 2017).

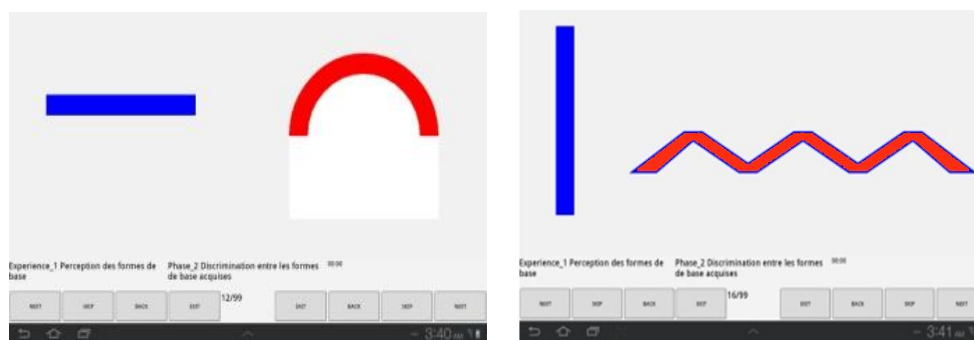
- ii. Presenting to the *tester* each of the 6 shapes on a vibrating touch-screen, in-order, while asking if the *tester* is able to recognize each shape,
- iii. Following each response, the *coordinator* informs the *tester* if the answer is correct or not, and (in case of a false answer) provides the *tester* with the correct response,
- iv. The procedure is repeated three times, allowing the *tester* to spot and learn the correspondences between embossed paper and vibrating screen presentations of the basic line shapes. The results of the tester's last trial are retained for empirical analysis.

Various parameters such as the number of correct answers, tester finger trails on the touch-screen, stroke properties (length, duration, and frequency) as well as tester response time (among others, cf. Section 5) are stored and analyzed later (to study and compare the difficulty levels and training times required by different test candidates). This is repeated for each experimental phase in *EVIAC*.

- Phase 2: Distinguishing between basic shapes

The objective of this phase is to test if a blind person is capable of distinguishing between the basic shapes acquired in the previous phase, presented as doublets on a vibrating touch-screen. The experimental procedure here is conducted as follows:

- i. Presenting on the vibrating touch-screen a number of doublets of basic shapes among those in Figure 6 (for instance, a doublet can be formed of a horizontal line and a sloping line, cf. Figure 7), without any additional indications. Objects in a doublet are distinguished using two dedicated auditory signals (i.e., one of two audio signals saying: “*Object 1*” or “*Object 2*”, is activated when touching each object). Doublets are presented in random order. In order for candidates to complete the tests in a timely manner, only 7 selected doublets were used: horizontal/vertical, horizontal/slash, horizontal/curve, vertical/zigzag, vertical/vertical, backlash/backslash, and curve/curve. These include: i) doublets consisting of different shapes, and ii) doublets made of identical shapes, in order to test whether candidates can tell the difference between different shapes, and whether they can also pinpoint identical ones.
- ii. Asking if the *tester* is able to identify whether the two shapes presented in each of the doublets are identical or not (by answering: “*true*” for identical or “*false*” otherwise).



a. Doublet consisting of a horizontal line and a curved line.

b. Doublet consisting of a vertical line and a zigzag line.

Figure 7. Prototype snapshots of doublets of basic shapes used in Experiment 1.

Note that the tester's answer is acquired by the coordinator without providing the tester with any feedback (i.e., without telling her/him whether the answer is correct or not), which is also the case for the remaining phases (2, 3, 4) of the experiment. This is different from phase 1 (where feedback is provided to the tester) designed as a learning phase.

- Phase 3: Identifying basic shapes (with multiple choices)

The objective of this phase is to test if a blind person is capable of identifying, via multiple choice interrogations, the basic shapes already acquired in the previous phase, presented on a vibrating touch-screen. The experimental procedure is conducted as follows:

¹⁰ Shapes on embossed paper were constructed using balsa sticks, following the standard norms of tactile presentations (SOCRATE-COMENIUS, 2000), where contours are 0.5 mm thick and 2 mm wide.

- i. Presenting to the *tester* a number of basic shapes (among those in Figure 6) on the vibrating touch-screen. Shapes are presented in random order,
- ii. Providing (vocally or on embossed paper) for each of the presented shapes, multiple choices (i.e., 3 possible answers), concerning the name of the shape,
- iii. Asking the *tester* to identify the basic shape presented on the vibrating touch-screen, by choosing one answer from the multiple choices.

- **Phase 4:** Recognizing basic shapes (without multiple choices)

The objective of this phase is to test if a blind person is capable of recognizing, without any additional indications (i.e., without multiple choices), the basic shapes already acquired in the previous phases, presented on a vibrating touch-screen. The corresponding experimental procedure is conducted as follows:

- i. Presenting to the *tester* a number of basic shapes (among those in Figure 6) on the vibrating screen. Shapes are presented in random order,
- ii. Asking the *tester* to identify the basic shape presented on the vibrating touch-screen, without assistance or further indications (e.g., without multiple choices).

4.2.2. Experiment 2: Recognizing Simple Geometric Objects

The second experiment in our protocol aims to verify the following hypothesis: *Blind users are capable of mapping, distinguishing, identifying, and recognizing simple geometric objects presented on a vibrating touch-screen.* To prove this hypothesis, we utilize the 4 simple geometric objects presented in Figure 8, including: square, rectangle, triangle, and circle. These generally constitute the simplest objects used in drawing contour or vector-based images.

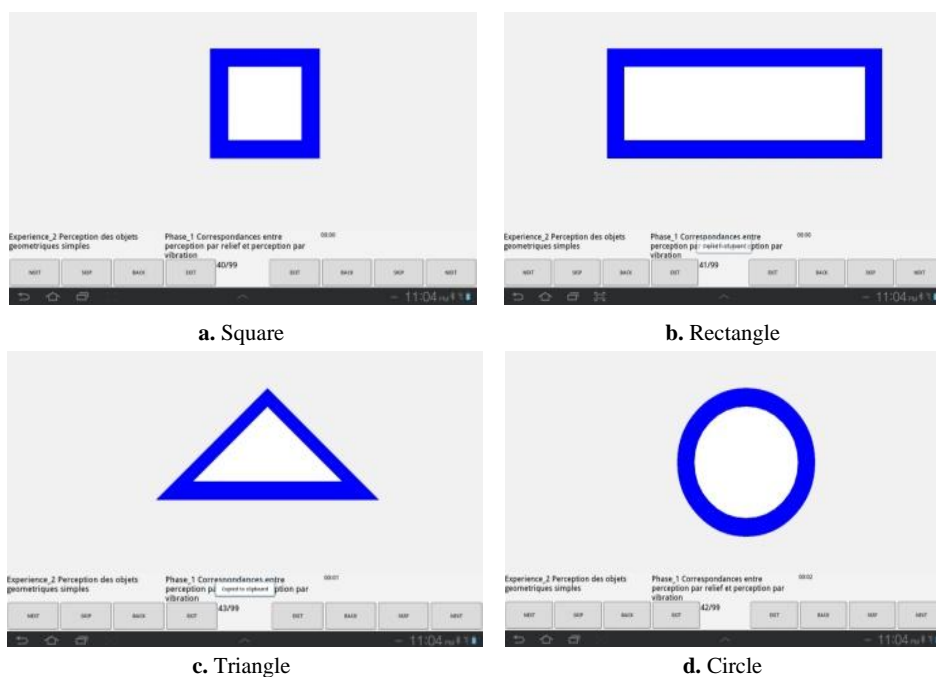


Figure 8. Prototype snapshots of the simple geometric objects used in Experiment 2.

Similarly to its predecessor, this experiment is divided into 4 main phases, allowing to confirm (or reject) the experiment’s main hypothesis (stated above):

- **Phase 1:** Mapping (correspondence) between embossed paper and vibrating screen tactile perceptions,
- **Phase 2:** Distinguishing between simple geometric objects¹¹,
- **Phase 3:** Identifying simple geometric objects (with multiple choices),
- **Phase 4:** Recognizing simple geometric objects (without multiple choices).

¹¹ In order for candidates to complete the tests in a timely manner, only 7 doublets were used: square/rectangle, square/triangle, square/circle, rectangle/triangle, rectangle/rectangle, triangle/triangle, and circle/circle.

5. Experimental Evaluation

This section describes our experimental evaluation study. We first introduce our evaluation metrics and experimental context in Sections 5.1 and 5.2. Then Section 5.3 describes, discusses, and analyzes our experimental results. The reader can refer to Section 5.4 for a recap and summarized description of the experimental results and observations.

5.1. Experimental Metrics (TEKLI J. ET AL., 2015; TEKLI J. ET AL., 2012)

We have recorded various experimental evaluation metrics¹² in order to analyze and evaluate the results obtained with each of our experimental trials. These include: i) the *percentage of correct answers* provided by the tester, ii) the tester's *response time* in providing an answer to the trial at hand, iii) the *number and duration of strokes* used by a tester to perceive a shape/object, iv) the *touch-screen surface covered* by the tester's finger when the latter is exploring the screen and trying to touch the shape/object, and v) the tester's *finger path correlation* with the shape/object being perceived.

To conduct the above measurements, our prototype system stores the tester's finger coordinates when touching the tablet's screen in order to trace all finger-screen contact points and produce a full representation of the tester's finger path. Yet, given that the tablet only allows capturing one contact point per finger touch (i.e., identifying the so-called contact pixels), the produced finger paths would consist of thin (one pixel thick) lines (cf. Figure 9.a) which would not be very useful in performing our measurements. To solve this issue, we post-processed the generated finger paths to include a certain width: consisting of 8.9 mm (i.e., 0.35 inches, established in earlier studies (Giudice N. A. *et al.*, 2012; Raja M. K., 2011) as the most conductive width for vibration patterns), which corresponds to 56 pixels on our tablet's screen (with a 149 pixels-per-inch resolution, cf. Figure 9.b).

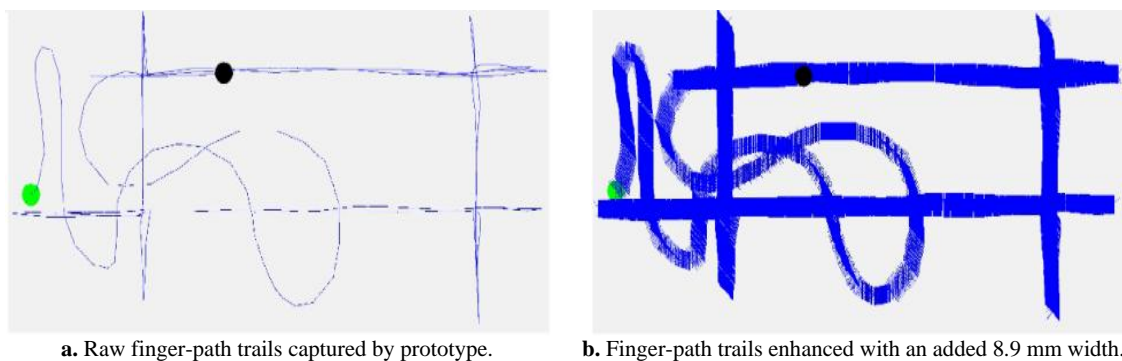


Figure 9. Prototype snapshots of raw (a) and enhanced (b) finger-path trails¹³.

5.2. Experimental Context

Experiments were conducted with twenty-nine testers, consisting of sighted (blindfolded) and blind candidates aged between 21 and 30 years old, all of whom are familiar with personal computers and tablets: i) six Blind Since Birth (i.e., BSB) testers (1 female and 5 males), ii) seven Blind After Birth (i.e., BAB) testers (5 females and 2 males) who have been totally blind since childhood¹⁴, and iii) sixteen Blindfolded (i.e., BF) testers (8 females and 8 males). BSB and BAB testers were student volunteers from the Lebanese School for the Blind and Deaf¹⁵, while BF testers were undergraduate and graduate students as well as faculty who volunteered from the authors' educational institutions. All testers volunteered to participate in the experiments and did not receive any remuneration. Blind testers were specifically motivated by the nature of the work, since most of them were young university students who were already familiar with and using smart-phones and touch-screen technology for more than 3 years (at least). Most blind participants explicitly expressed their interest in our work and their hunger for more tools and technological breakthroughs that could help them access information easier. During the initial screening of potential testers, we required that all participants have clean health records and do not experience any physical or mental impairment that could impede their performance in the experiments. The tests were coordinated by the authors and their research assistants.

5.3. Experimental Results

Following Experiment 1 (*recognizing basic shapes*), each tester completed the 4 experimental phases (mapping/learning, distinguishing, identifying, and recognizing shapes) for each of the 6 basic shapes considered (horizontal, vertical, sloping, zigzag, and curved lines). The same process was undertaken with Experiment 2 (*recognizing basic geometric objects*, applied on the square, rectangle, triangle, and circle objects). Each experimental trial in both experiments lasted around 84 and 105 seconds

¹² The term *metric* here designates an *experimental evaluation measure*, and not a *metric function* in a metric space (Tekli *et al.*, 2012, Tekli *et al.* 2015).

¹³ The green and black dots are the finger-path trajectory starting point and the ending point respectively.

¹⁴ Most BAB testers were born with visual impairments, and became totally blind between the ages of 3 and 6 years.

¹⁵ <http://www.lsbdbaabda.com/about.php>

(on average), each experimental phase lasted almost 9-11 minutes, and each experiment lasted almost 36-44 minutes. Participants could take breaks between trials/phases whenever they needed. All in all, each tester performed: 4 (phases of Experiment 1) × 6 (basic shapes) + 4 (phases of Experiment 2) × 4 (basic geometric objects) = 50 experiment trials.

The following subsections present and discuss the results obtained with each evaluation metric, including: i) percentage of correct answers (Section 5.3.1), ii) response time (Section 5.3.2), iii) number and duration of finger strokes (Section 5.3.3), iv) surface area covered by the testers' finger path trails (Section 5.3.4), and v) finger path correlation with the surface of the target shape (Section 5.3.5). For every metric, we present the *average* (arithmetic mean) and the *standard deviation* of the results obtained with every group of testers in each experimental phase. We use averages as representatives of their datasets, and utilize them to compare and contrast experimental results. We also provide standard deviation levels to highlight the quality of the corresponding averages: as good or bad representatives of their datasets¹⁶. In addition, we make use of two-sample t-tests¹⁷ to verify that the averages of two sample groups being compared are statistically different from each other, which is usually true when the groups' standard deviations are low¹⁸ (Rice J.A., 2006). Note that the limited size of our participant samples¹⁹ does not allow us to conduct a more detailed statistical analysis of the different groups of testers. Yet we believe that the results obtained in this work provide valuable insight and highlight interesting observations that need to be later statistically generalized using a larger number of participants.

5.3.1. Evaluation Metric 1: Percentage of Correct Answers

Figure 10 and Figure 11 present the percentage of correct answers obtained when performing phases 1 to 4 of Experiments 1 and 2. They show the percentage of testers who provided correct answers, where each tester provided one answer per trial for each experimental phase.

Regarding **phase 1 of Experiment 1** (learning basic shapes, cf. Figure 10.a and Figure 12.a), one can realize that most BSB testers are able to effectively establish the correct correspondences/mappings between basic shapes presented on the vibrating touch-screen and those on embossed paper, with an overall average of 94.45% correct answers. Only 1 out of the 6 BSB testers fails to identify the zigzag and curved line shapes. Results of BF testers are very close to (and statistically non-distinguishable from) those of BSB testers, with an average of 91.67% correct answers, where 4 of the 16 testers fail to identify the backlash, zigzag, and curved line shapes. Yet with BAB testers, the average percentage of correct answers drops significantly to 66.5%, where 3 of the 7 testers fail to identify zigzag and curved lines.

Results of **phases 2, 3 and 4 of Experiment 1** (cf. Figures 10, 11, and 14) reflect similar observations to those in phase 1, where BSB and BF testers produce higher percentages of correct answers, compared with those obtained with BAB testers. More particularly:

- In phase 2 (distinguishing between basic shapes with multiple choices): BSB testers achieve an overall average of 83.34% correct answers, where 2 of the 6 testers fail to match the horizontal and curved lines. BF testers achieve an overall average of 80.36% correct answers, where 8 of the 16 testers fail to distinguish the horizontal and curved lines. Yet with BAB testers, the average percentage of correct answers drops to 59.18%, where 4 out of the 7 testers fail to distinguish the backlash and curved lines.
- In phase 3 (identifying basic shapes with multiple choices): BSB testers achieve an overall average of 88.89% correct answers, where 2 of the 6 testers fail to identify the curved line. BF testers achieve an average of 89.58% correct answers, where 4 out of the 16 testers fail to identify the backlash and curved lines. Yet with BAB testers, the average percentage of correct answers drops to 69.05%, where 3 out of the 7 testers fail to correctly identify the curved line.
- In phase 4 (recognizing basic shapes without multiple choices): similar results are obtained where BSB and BF testers achieve very close averages of 80.56% and 81.25% correct answers respectively, followed by BAB testers where the average significantly drops to 64.29%. Similarly to the previous phases, the backlash and curved lines seem to be the most difficult to recognize (e.g., 2 of the 6 BSB testers, 4 of the 16 BF testers, and 3 of the 7 BAB testers, fail to identify the curved line).

¹⁶ A low standard deviation indicates that the data points tend to be close to the average point of the dataset, and thus the latter can be considered as a good representative of the dataset. A high standard deviation indicates that the data points are spread out over a wider range of values farther away from the average, such that the latter might not be a good representative of the dataset.

¹⁷ We utilize *two-sample t-tests assuming unequal variances*, since our samples come from different groups of testers (BSB, BAB, and BF).

¹⁸ The *t-test* evaluates whether the arithmetic means of two groups of data points are *statistically* different from each other. Two groups seem to be different or distinct from each other when their means are different and their standard deviations are low (i.e., low variability), meaning the groups share little (if any) overlap among their data curves. In contrast, the same difference between group averages becomes less sticking when comparing groups having high standard deviations (i.e., high variability), meaning the groups' data curves might heavily overlap (Rice J.A., 2006)

¹⁹ This is the case of many studies involving blind participants, where a reduced sample size of blind or blindfolded candidates is usually used (Bou Issa Y. *et al.*, 2010, Guidice N. *et al.*, 2012).

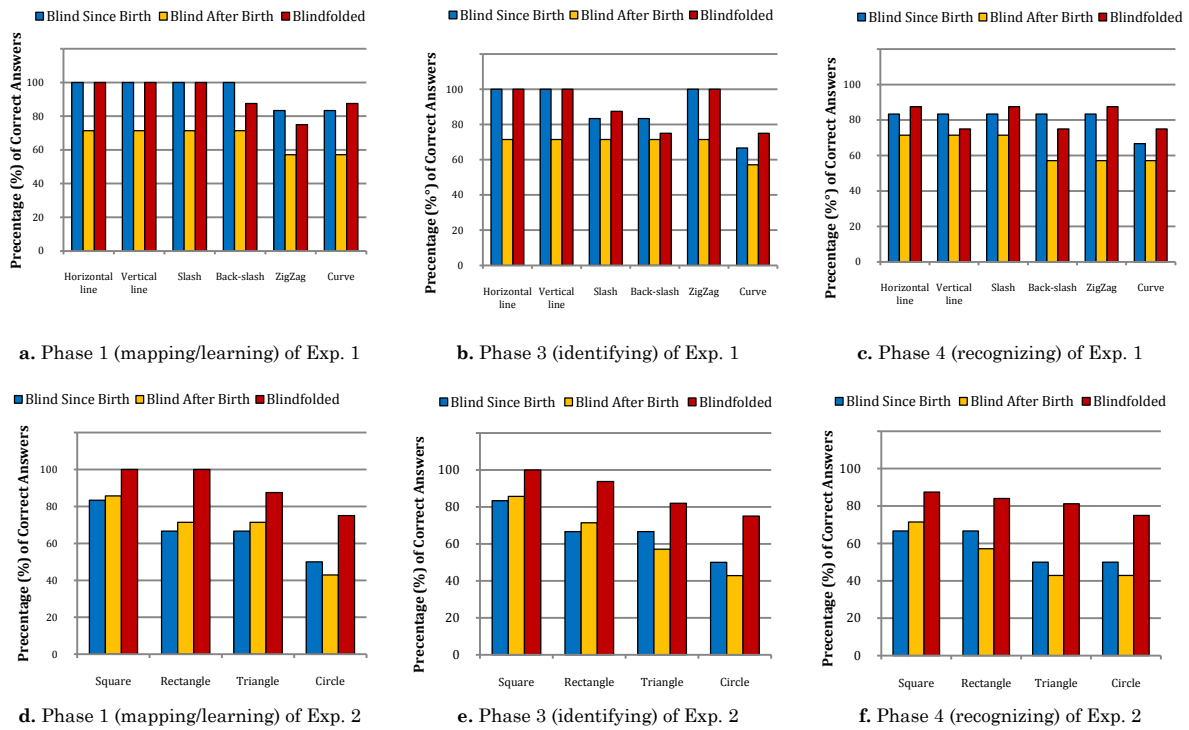


Figure 10. Percentage of correct answers for phases 1, 3, and 4 of Experiments 1 and 2.

In short, considering the results of all 4 phases of Experiments 1, one can realize that most testers are able to effectively perceive basic shapes presented on the vibrating touch-screen. Also, one can realize that the sloping, zigzag and curved lines seem to be more difficult to perceive (by at least 50% of the testers) than horizontal and vertical lines (which are correctly identified by more than 75% of the testers). A third interesting observation is that BSB and BF testers generally perform better than BAB testers, considering all phases of Experiment 1 (as well as those of Experiment 2, which we further discuss hereunder).

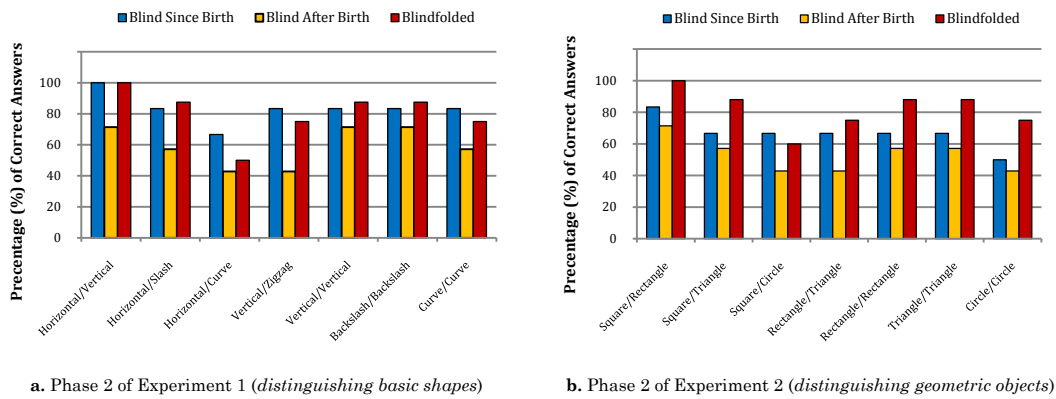


Figure 11. Percentage of correct answers for phase 2 (distinguishing shapes/objects) of Experiments 1 and 2.

Considering the results of **Experiment 2**, we can make three additional observations. First, one can realize that geometric shapes are generally more difficult to map/learn (phase 1), distinguish (phase 2), identify (phase 3), and recognize (phase 4) than the basic shapes utilized in Experiment 1. BSB testers achieve average 58.34%-to-66.67% correct answers in all phases of Experiment 2 (compared with 80.56%-to-94.45% in Experiment 1); and BAB testers achieve average 53.06%-to-67.86% correct answers in Experiment 2 (compared with 59.18%-to-69.05% in Experiment 1, even though the difference is not statistically meaningful compared with BSB testers, cf. t-test indicators in Figure 12.b). Nonetheless, a second interesting observation can be made regarding BF testers, who achieve average percentages in Experiment 2 (81.94%-to-90.63%) which are very close to those produced in Experiment 1 (80.36%-to-91.67%, cf. Figure 12.a). In other words, while BSB and BAB testers generally find geometric objects to be more difficult to perceive than basic shapes, yet BF testers seem to perceive both of them with similar ease/difficulty levels. Based on discussions with testers conducted after completing the experiments, we can identify one possible

reason for the above results. BF testers are used to perceiving basic shapes and geometric objects visually, and thus have (throughout the years) constructed clear mental representations of them in their visual memories, which apparently helps them imagine what the shapes/objects would look like when presented on the vibrating touch-screen. This is quite different from the way BSB testers perceive shapes/objects, where the testers almost solely rely on their tactile sensation: comparing what they felt/learned on embossed paper with what they perceived on the vibrating screen.

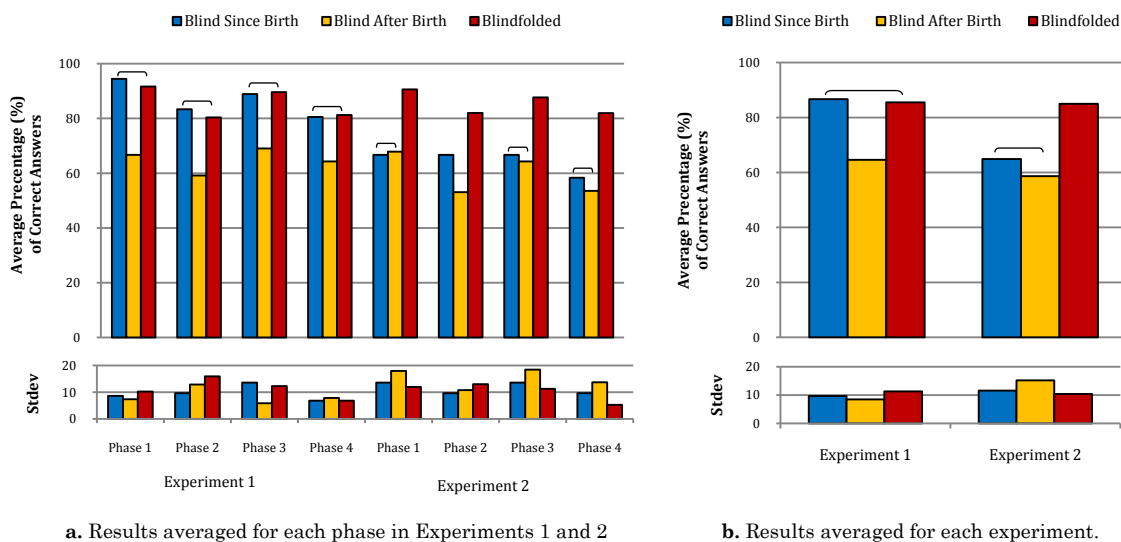


Figure 12. Percentages (%) of correct answers averaged overall all four phases of Experiments 1 and 2, including corresponding standard deviation levels and t-test indicators²⁰.

A third observation can also be made regarding the nature of the geometric objects used in Experiment 2. Results with all testers clearly show that the square object is easier to perceive (having a higher percentage of correct answers) than the rectangle, followed by the triangle, and then the circle. This somewhat concurs with the results in Experiment 1 where horizontal and vertical lines (i.e., the basic constructs of a square and/or rectangle) were generally easier to perceive than sloped lines (basic constructs of the triangle), followed by the curved line (basic construct of a circle) which was the most difficult to perceive.

To sum up, Figure 12 compiles the percentages of correct answers for each experiment. Results show a 75.79% average percentage of correct answers for BSB testers, 61.61% for BAB testers, and 85.25% for BF testers (over both Experiments 1 and 2). Thus, results show that our accessibility method based on the vibrating modality seems feasible for perceiving simple contour-based images presented on a touch-screen. Additional metrics (such as finger path trails, haptic exploration strategies, and trail correlations with shapes) might help provide more insight on the above results, and could help explain the differences between different groups of testers.

5.3.2. Evaluation Metric 2: Response Time

We also captured the average time required by testers to provide an answer in each phase of Experiments 1 and 2. Results are presented in Figure 13 and Figure 14, and compiled in Figure 15. They highlight various interesting observations. First, one can realize that testers generally take more time in perceiving more “elaborate” shapes (such as zigzag and curved lines with Experiment 1, and triangle and circle objects in Experiment 2) compared with “simpler” ones (such as horizontal and vertical lines in Experiment 1, and square and rectangle objects in Experiment 2). Second, one can realize that phase 2 (in both Experiments 1 and 2) is generally more time consuming than phases 1, 3 and 4 for most testers. This is because phase 2 requires twice as much effort as the others, i.e., identifying 2 shapes (in a doublet) instead of 1, in order to establish (or not) the correspondence (or discriminate) between shapes. Third, results seem to indicate that BSB and BF testers are generally faster in providing answers than BAB testers. In particular, BSB and BF testers achieve 65.5 seconds and 67.5 seconds average response times respectively, followed by BAB testers requiring on average 96.5 seconds per trial. Yet, we note that these differences are not statistically significant due to high group standard deviation levels, as underlined by the t-test indicators in Figure 15.

²⁰ Horizontal arc shaped indicators are added to the graphs to highlight the results of t-tests conducted on every pair of sample groups: they identify group averages (means) which are not statistically different from each other (i.e., where the difference between means is compensated by high standard deviations). Detailed t-test results can be found in (Tekli J. *et al.*, 2017).

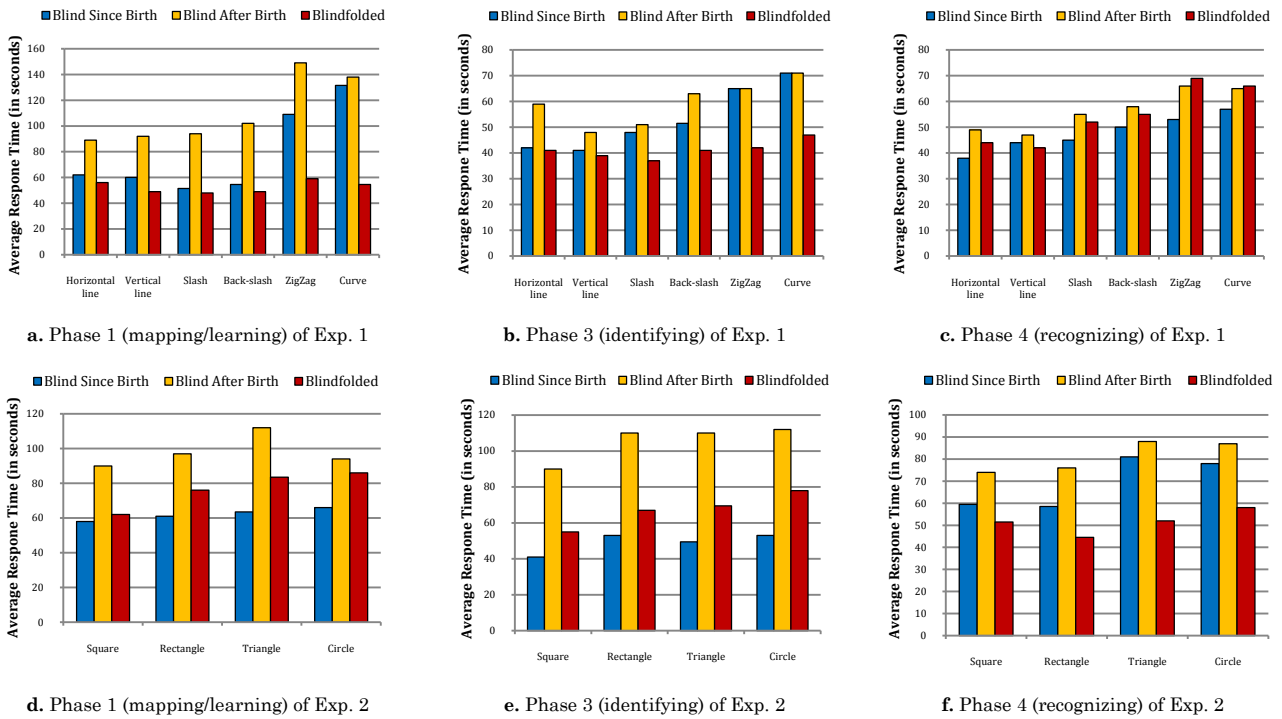


Figure 13. Average response time for phases 1, 3, and 4 of Experiments 1 and 2.

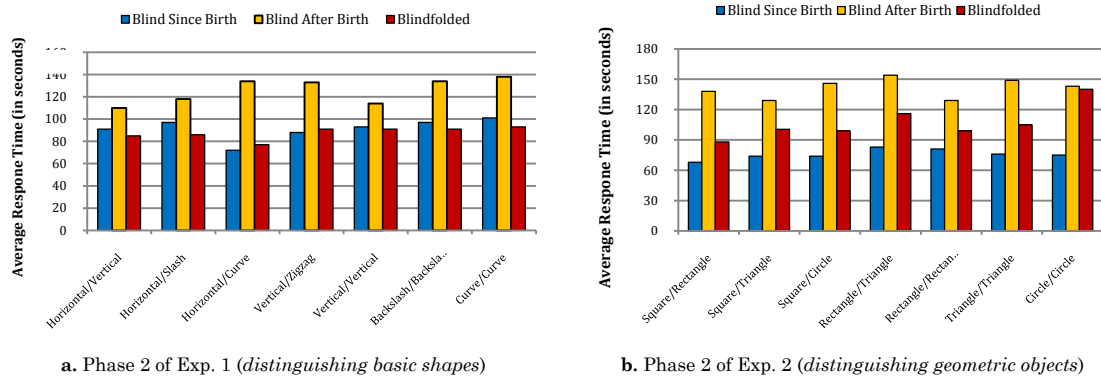
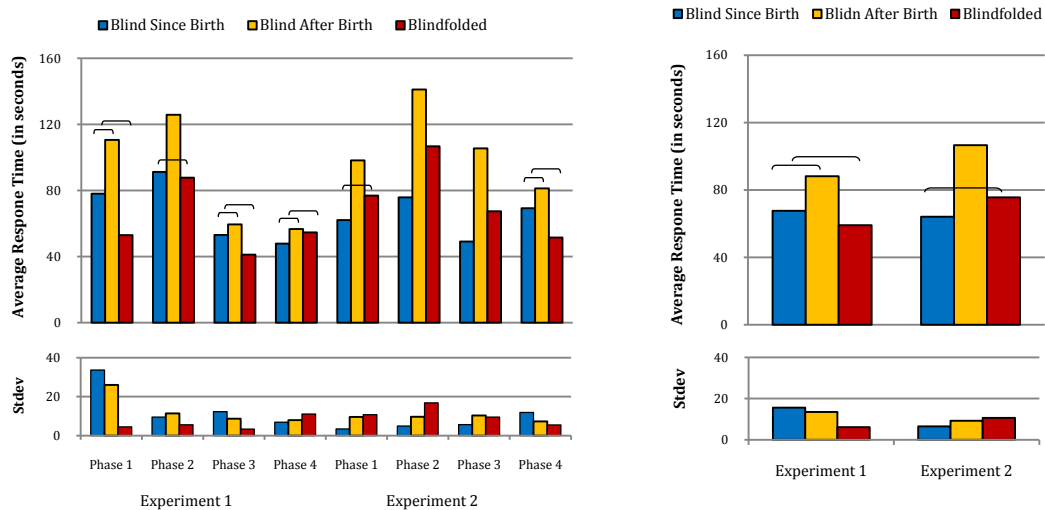


Figure 14. Average response time for phase 2 (distinguishing shapes/objects) of Experiments 1 and 2.

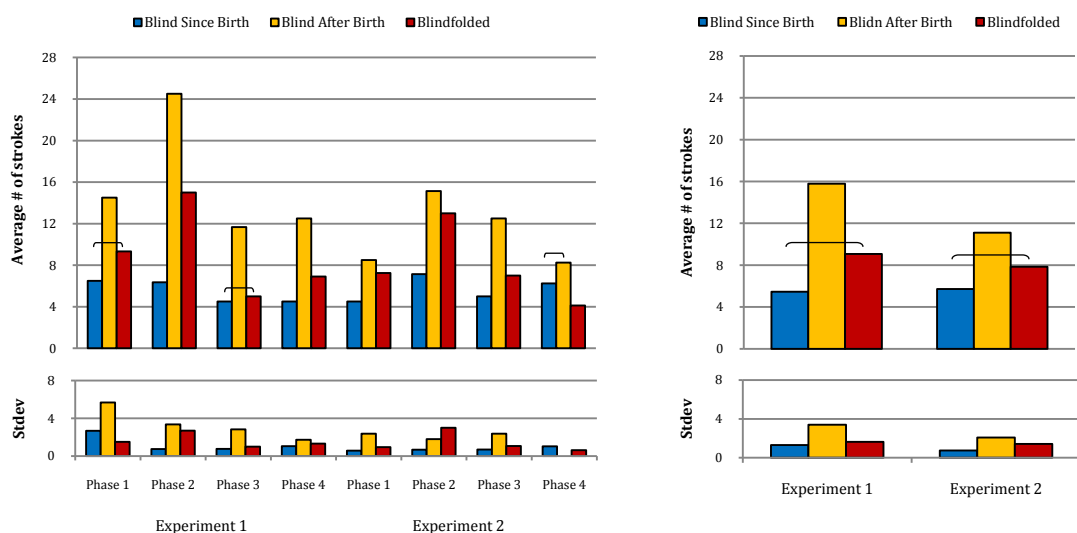
By comparing the average *percentage of correct results* versus the average *response time* of testers, one can realize that BSB and BF participants are generally faster and more accurate in providing answers than BAB candidates, who lost vision later on in their lives; more in particular, BSB testers are on average 31.53 seconds faster and 18.7% more accurate than BAB candidates, as can be noticed in Figure 15 and Figure 12 respectively. BF testers are on average 10% more accurate but take around 1.55 seconds more time (such that the difference is not statistically significant) compared with BSB participants. Yet, BAB testers produce the least accurate perceptions and seem to require the most amount of time to provide answers. Based on discussions with testers conducted after completing the tests, we realize this could be due to the fact that BSB testers heavily rely on their cutaneous sense in perceiving shapes on the touch-screen, compared with BAB testers who rely less on tactile sensation and more on their mental representations of the shapes/objects (as they remember them). While visual memory serves BF testers well (as discussed with *evaluation metric 1*), yet, visual memory coupled with tactile sensation seems to be a source of distraction for BAB testers. This could be due to the fact that BF testers have clearer mental representations of shapes and objects, since they are used to seeing them more regularly in their daily lives, whereas BAB testers are relying on fuzzier mental representations which they had acquired before losing sight.



a. Results averaged for each phase in Experiments 1 and 2 b. Results averaged for each experiment
Figure 15. Response time averaged for all four phases of Experiments 1 and 2.

5.3.3. Evaluation Metric 3: Number and Duration of Strokes

In addition to evaluating the percentage of correct results and average response time, we also captured the number and duration of strokes made by each tester in perceiving each basic shape/object in Experiments 1 and 2. Studying the properties of tester strokes provides an indication of the haptic exploration strategies used by the different groups of testers when using the vibrating touch-screen.



a. Results averaged for each phase in Experiments 1 and 2 b. Results averaged for each experiment
Figure 16. Average number of strokes for all four phases of Experiments 1 and 2.

Figure 16 shows the average number of strokes used to perceive an image in each phase of each experiment. On average, BSB testers use 5 strokes per image, followed by BF testers with 8 strokes per image, and then BAB with 13 strokes per image. This shows that BSB testers follow more accurately the vibration produced by shapes presented on the touch-screen, compared with BF and BAB testers who have a higher tendency to lose track of the vibration and thus try to re-place their fingers again on some new starting point (starting with a new stroke) to regain/relocate the vibration path. While the difference in average percentages of number of strokes between BSB and BF is statistically significant (BF testers produce on average 60% more strokes than BSB testers), however, the striking difference appears with BAB testers (who produce on average 160% more strokes than BSB testers, and 62.5% more strokes than BF testers). This concurs with the observations and discussions conducted with

testers when evaluating the first two experimental metrics: BAB testers tend to rely on their mental visualization of the shapes rather than fully focusing on their tactile perception, which apparently distracts them from correctly following the vibration paths of the shapes/objects and requires them to relocate their fingers on the screen: producing new strokes to re-capture vibration paths.

Note that detailed per shape/object results (omitted here for clarity of presentation, and provided in (Tekli J. *et al.*, 2017)) show that testers usually tend to use more strokes in perceiving more “elaborate” shapes (namely zigzag and curved lines with Experiment 1, and triangle and circle objects in Experiment 2) compared with “simpler” ones (such as horizontal and vertical lines in Experiment 1, and square and rectangle objects in Experiment 2).

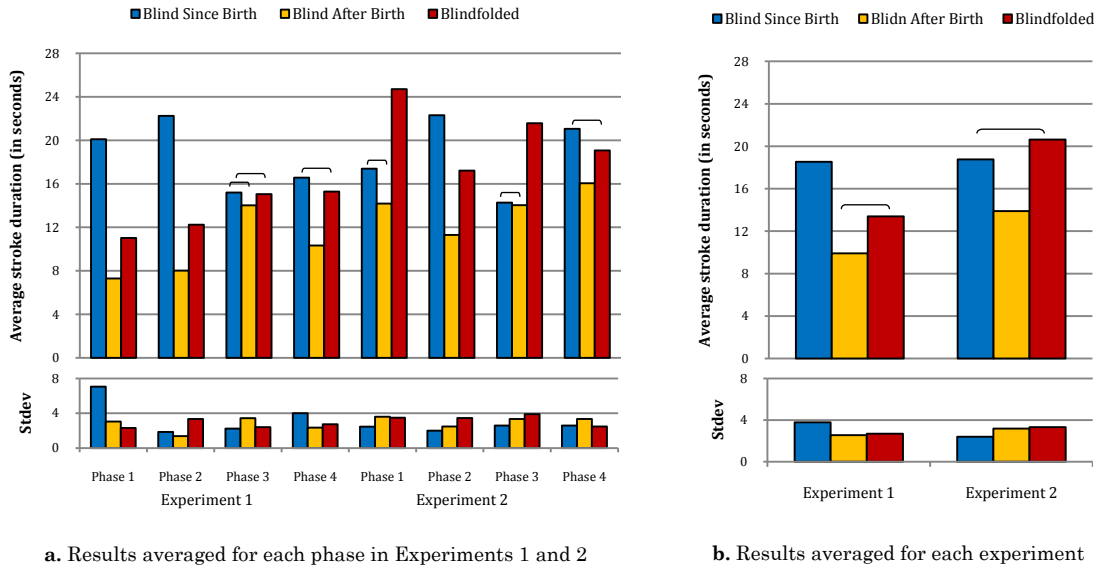


Figure 17. Average stroke duration with all four phases of Experiments 1 and 2.

In addition to the number of strokes, Figure 17 provides the average duration per stroke. Results here show that BSB and BF testers usually take more time per stroke, followed by BAB testers who generally utilize strokes of shorter durations. In particular, BSB and BF testers take on average 18.5 seconds and 17.5 seconds per stroke respectively, followed by BAB testers with an average 12.5 seconds (which is a statistically significant difference, given the low group standard deviation levels and the corresponding t-test indicators in Figure 17). This means that BAB testers tend to lose the vibration path quicker than BSB and BF testers, resulting in short duration strokes. This also re-affirms that BAB testers, who lost vision later on in their lives, seem to be generally less effective than their counterparts in using their tactile sensation.

Per shape/object stroke duration results (omitted here, and provided in (Tekli J. *et al.*, 2017)) show that testers tend to use strokes of shorter durations in perceiving more “elaborate” shapes (namely zigzag and curved lines with Experiment 1, and triangle and circle objects in Experiment 2) compared with “simpler” ones (such as horizontal and vertical lines in Experiment 1, and square and rectangle objects in Experiment 2) where testers tend to use longer duration strokes. This means that testers tend to lose the vibration path quicker when processing more elaborate shapes, which is expected: based on the increased number of strokes required to perceive the latter, compared with simpler shapes.

5.3.4. Evaluation Metric 4: Touch-screen Surface Covered

Another evaluation metric utilized to better understand the testers’ haptic exploration strategies is the *touch-screen surface covered* by the tester’s finger when the latter is exploring the screen and trying to perceive the target shape/object. Here, we capture the screen surface covered: i) *with repetition*, i.e., when the user passes her/his finger more than once on a single point (square pixel) on screen, and ii) *without repetition*, i.e., considering each on-screen contact point only once and disregarding points covered more than once by the tester’s finger. The former reflects the tester’s “absolute” screen surface coverage including passage through the same area more than once, whereas the latter only highlights the “actual” screen surface covered. Figure 18 shows the average screen surface covered per experimental trial (a and b) and per stroke (c and d). For clarity of presentation, we only show the compiled results of all experimental phases combined, and omit the detailed results obtained per experimental phase (which can be found also in (Tekli J. *et al.*, 2017)).

Results in Figure 18 highlight various interesting observations. First, one can realize that the *actual* (without repetition) surface covered (Figure 18.b and d) is almost half of the *absolute* (with repetition) surface covered (Figure 18.a and c). This shows that most testers, after detecting the vibrating paths, tend to pass over parts of the vibration paths more than once, in order to regain a lost location or to better recognize/verify the detected shape/object. Second, results show that the three groups of

testers produce average surface coverages which are almost (statistically) identical; more in particular following Figure 18.a, BSB testers produce an *absolute* surface coverage per trial of around 333,137 square pixels on average, closely followed by BAB testers covering on average 327,375 square pixels, and then BF testers covering on average 322,163 square pixels. Results in the remaining graphs follow a similar tendency. An interesting observation here is that the absolute and actual surfaces covered by BF testers are very close and sometimes even less than those produced by BAB testers. At first glance, this might seem to contradict with the results of previous evaluation metrics: we were expecting BF testers to be better in covering the touch-screen surface when perceiving vibration feedback, compared with BAB testers who produced the lowest *percentage of correct answers* and highest average *response time*. The reason BF testers produce lower surface coverages is their haptic exploration strategies. By watching BF testers work, we could see that most of them were trying to guess the shapes/objects presented on-screen by using non-traditional haptic exploration strategies (such as navigating the screen horizontally from left to right, and then vertically from top to bottom without however following the vibration paths). They were trying to identify patterns in the vibrations (e.g., a square would vibrate twice horizontally and twice vertically, with the same time difference between vibrations) which proved useful in effectively recognizing certain shapes/objects, thus reflecting their high *percentage of correct results* and low *response times*, versus their low *on-screen surface coverage*, compared with blind testers.

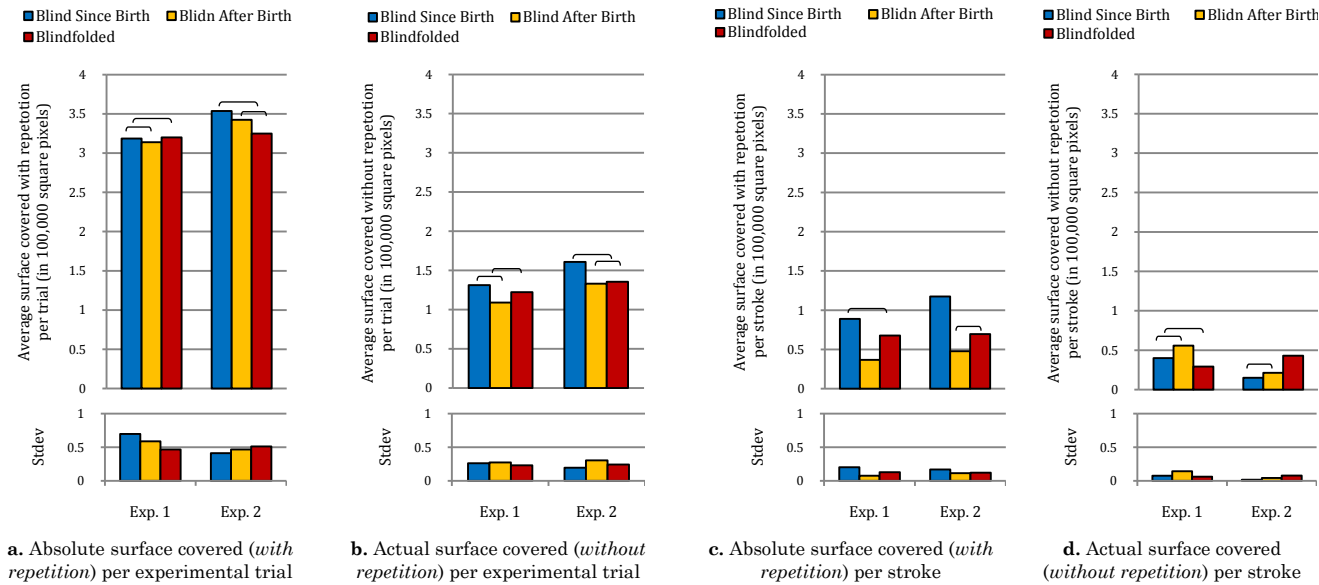


Figure 18. Surface covered with and without repetition, averaged per experimental trial (a, b) and per stroke (c, d).

5.3.5. Evaluation Metric 5: Finger-Path Correlation with Image

In addition to evaluating the touch-screen surface covered by the testers' fingers when attempting to perceive a shape/object presented on-screen, we also measured the testers' finger-path correlation with the surface covered by the target shape/object being perceived. Given A the surface covered by the tester's finger-path trail and B the surface covered by the target shape/object on screen, where $|A|$ and $|B|$ designate the number of square pixels in A and B respectively, we measure correlation as: $|A \cap B| / |A| \in [0, 1]$, where maximum (=1) correlation designates that the tester's finger-path trail has actually covered all the surface of the target shape/object, whereas correlation decreases (toward 0) as the finger-path trail deviates from the surface of the target shape/object being perceived. Figure 19 shows the correlation scores considering both absolute (with repetition) and actual (without repetition) screen surface coverages, averaged per experimental trial (a and b) and per stroke (c and d).

First, one can realize that the *actual* (without repetition) average finger-path correlation levels (Figure 19.b and d) are almost half of the *absolute* (with repetition) average correlation levels (Figure 19.a and c). This concurs with the surface coverage results obtained with the previous metric where most testers tend to pass over parts of the vibration paths more than once to regain a lost location or to better follow or verify the detected shape/object. Second, considering per trial results (in Figure 19.a and b), one can realize that the three groups of testers produce close finger-path correlation scores; more in particular, BF candidates produce an actual (without repetition) correlation score of around 0.6096 (averaged over both Experiments 1 and 2), closely followed by BSB testers with 0.5765, and then by BAB testers with 0.5567. In other words, all testers seem to be almost equally good in detecting and tracking the vibrations produced by shapes/objects presented on the touch-screen (without being able to always correctly and/or quickly identify/recognize the shapes/objects, as discussed in the results of previous experimental metrics). Nonetheless, per stroke correlation results (in Figure 19.c and d) show a slightly different observation: where BSB and BF testers produce

almost identical average correlation scores such that the latter are significantly higher than those produced by BAB testers. More in particular, BSB and BF testers produce average 0.2183 and 0.1912 actual per stroke correlation scores (over all phases of Experiments 1 and 2) followed by BAB with a significantly lesser 0.0928 average correlation score (i.e., 57.49% and 51.54% less than those of BSB and BF testers respectively). This observation can be best explained by looking back at the results of *experimental metric 3* (evaluating the *number and duration of strokes*) where BAB testers produced significantly higher numbers of strokes per experimental trial, with significantly lower stroke durations. In other words, it seems that BAB testers tend to lose track of the vibration path relatively faster than BSB and BF testers, and tend to use a larger number of short duration and not so accurate strokes to re-capture the target shape/object's vibration path.

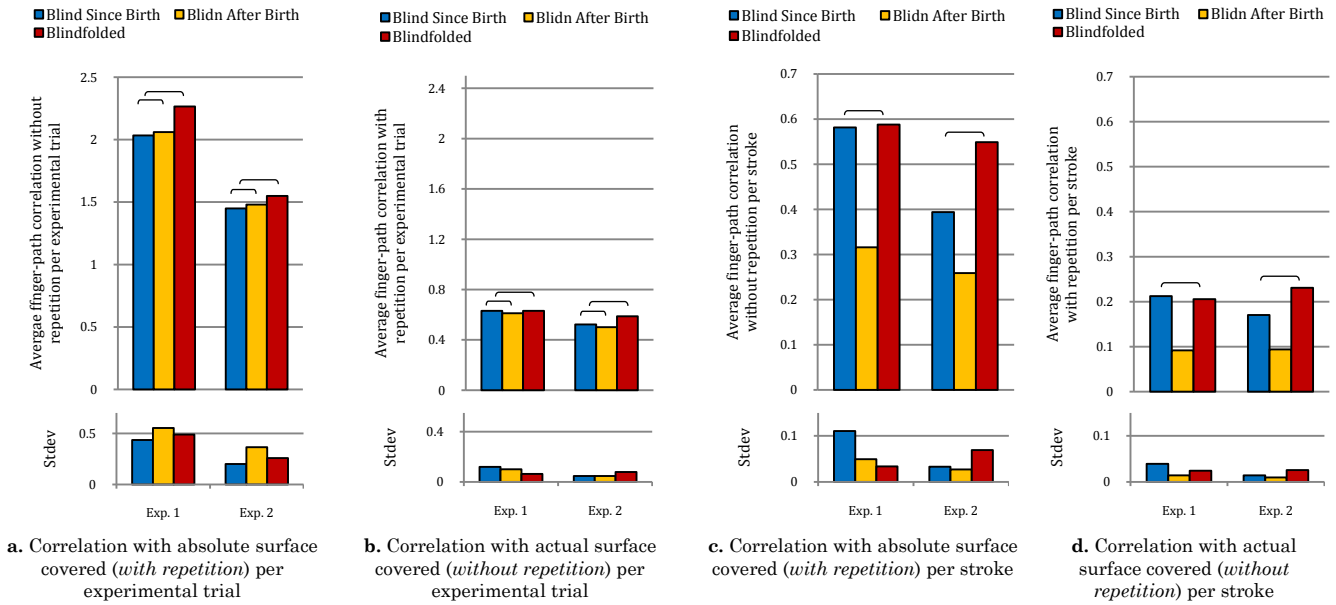


Figure 19. Correlation of the testers' finger-paths with shapes/objects presented on-screen, averaged per experimental trial.

5.4. Recap of Experimental Results

To sum up, we short-list our observations in Experiments 1 and 2 as follows:

- Results of *evaluation metrics 1* (percentage of correct answers) and *2* (response time) show that accessibility based on the vibrating modality seems feasible for perceiving simple contour-based images presented on a touch-screen, achieving an overall 74.22% percentage of correct answers in an average of 1 minute and 22 seconds time for all testers.
- By comparing results of *evaluation metrics 1* and *2* (i.e., response time), we realize that BSB and BF testers are generally (almost 18%) more accurate and (around 31 seconds) faster in their perceptions than BAB testers who lost their vision later on in their lives.
- Results of *evaluation metrics 3* (i.e., number and duration of strokes) show that BAB testers tend to use more strokes of shorter durations compared with their BSB and BF counterparts. Based on discussions with BAB testers, we assume that they tend to rely (to a certain extent) on their mental visualization of the shapes rather than fully focusing on their tactile perception, which might distract them from correctly following the vibration paths of the shapes/objects and requires them to relocate their fingers on the screen and start with new strokes to re-capture the shapes/objects' vibration paths.
- Results of *evaluation metrics 4* and *5* (i.e., finger-path correlation), show that most testers, after detecting the vibrating paths, tend to pass over parts of the vibration paths more than once, in order to regain a lost location or to better recognize/verify the detected shape/object.
- Also, results of *evaluation metrics 4* and *5* show that BSB and BF testers tend to cover more (absolute and actual) on-screen surface than BAB candidates, which means that they are able to better track and follow vibration paths than their BAB counterparts.
- BF testers tend to use non-traditional haptic exploration strategies, such as navigating the screen horizontally from left to right, and then vertically from top to bottom without however following the vibration paths.
- Following *evaluation metrics 3* and *5*, BAB testers tend to lose track of the vibration paths faster than BSB and BF testers, and tend to use a larger number of short and not so accurate strokes to re-capture the target shape/object's vibration path.

- Also, results of all evaluation metrics show that testers were generally less effective (producing fewer correct answers, requiring more response time, and using more strokes of shorter durations and lower finger-path correlation) in perceiving more “elaborate” shapes (namely zigzag and curved lines with Experiment 1, and triangle and circle objects in Experiment 2) compared with “simpler” shapes (such as horizontal/vertical lines in Experiment 1, and square and rectangle objects in Experiment 2).

All in all, results tend to support Experiment 1 and 2’s hypotheses: *blind users seem to be capable of mapping, distinguishing, identifying, and recognizing basic line shapes (1) and simple geometric objects (2) presented on a vibrating touch-screen*. Results also highlight various issues mentioned above, and need to be further investigated and generalized with larger candidate samples.

6. Conclusion

In this paper, we provide some insight on how the *vibration* modality is perceived by blind users to access simple shapes and visual graphics presented on a touch-screen. To do so, we first reviewed and discussed a wide variety of approaches allowing visual data accessibility for blind or visually impaired users. We then introduced a dedicated experimental framework, titled *EVIAC* (EValuation of Vibration ACcessibility), in order to test a blind person’s capacity in perceiving basic shapes and graphics presented on a touch-screen. Experiments on blindfolded and blind testers produced encouraging results. On one hand, results tend to support our experimental hypotheses, and show that *blind users are generally capable of mapping, distinguishing, identifying, and recognizing basic line shapes* (Experiments 1) and *simple geometric objects* (Experiment 2) presented on a vibrating touch-screen, achieving an overall 74.22% percentage of correct answers for all tests. On the other hand, results underline various issues, ranging over: *prolonged response time* (e.g., blind users require 1 minute and 22 seconds on average to recognize a basic shape), different groups of users (i.e., blindfolded, blind since birth, and blind after birth) tend to use *different haptic exploration strategies* when perceiving shapes and objects on the touch-screen, resulting in *reduced touch-screen surface coverage*, and *mild finger-path correlation* with vibration trails. Given the limited size of our blind participant samples (which remains a major challenge in many studies involving blind candidates since they are hard to come by), it would be prudent not to generalize all of the latter observations to the blind community. We believe that observations made in this study need to be further investigated and validated using large scale statistical studies that separately target different groups of users and different metrics. In other words, we view our current study as a stepping stone toward more complete and generalizable evaluations, which are required in order to produce optimal recipes for using the touch-screen technology to support contour-based image accessibility for blind users.

We are currently extending our experimental study to evaluate a blind user’s capability of distinguishing and recognizing spatial relations between simple geometric objects presented on a vibrating touch-screen, namely directional (e.g., *top-of*, *left-of*, etc.), metric (e.g., *far*, *near*, etc.), as well as topological relations (e.g., *disjoint*, *adjacent-to*, etc.). We are also undertaking experiments to evaluate Fitts’ Law and the pointing task when using a vibrating touch-screen (El Lahib M. *et al.*, 2017; Sasangohar F. *et al.*, 2009), studying blind users’ perception (estimation) of target size and distance, as in how far apart two shapes of different sizes are presented on the touch-screen, and how easy/difficult it seems for the tester to point from one shape to another. Another interesting direction is to investigate hand/finger movements (e.g., longitudinal motion, lateral motion, circular motion, tapping), and whether different classes of such movements can be identified and correlated with different dimensions of desired knowledge about graphics (e.g., recognizing, pointing to, or following objects) presented on a vibrating touch-screen. While hand/finger movement classes (e.g., squeezing, holding, rubbing, and contour following) have been identified and thoroughly studied with traditional tactile exploration of 2D and 3D objects (Lederman S.J. and Klatzky R.L., 1987), yet very little has been done on capturing finger traces and movement behaviors on touch-screens. The basic haptic exploration tasks realized in this study (e.g., navigating the screen from left to right or from top to bottom), could provide initial hints toward (possibly) establishing such classes. In the near future, we plan to evaluate a blind user’s ability to track trajectories presented as a discrete set of points or as a continuous line on-screen, which is central in various applications ranging over navigating 2D indoor layouts (Su J. *et al.*, 2010) as well as accessing software and Web-based graphical user interfaces (i.e., GUIs) (Bou Issa Y. *et al.*, 2010; Bou Issa Y. *et al.*, 2009). A major concern in this context is the limited touch-screen real estate which hinders access to large-scale graphics and trajectories, especially when navigating maps. In this context, several authors in (Palani H. and Giudice N.A., 2017; Palani H. *et al.*, 2016) have recently investigated non-visual panning and zooming methods using single finger and two-finger drag techniques, and have shown that their solutions clearly improve accessibility of graphical information for blind users. Hence, building on the latter findings to develop adapted and dynamic large-scale trajectory tracking solutions seems very promising. Here, we remind that a major problem with vibrating touch-screen technology is that the vibration feedback involves the entire device (i.e., the whole device vibrates, not the point of contact with the tester’s fingertip), which naturally impedes the whole accessibility process, including shape/object recognition and trajectory tracking. Yet, a new technology that could overcome this limitation is offered by Tesla Touch (Bau O. *et al.*, 2010), using the principle of electro-vibration that produces a dynamic friction between the fingertip and the screen’s surface resulting in a localized haptic feedback. Thus, investigating next generation touch-screen prototypes based on localized electro-vibration technology, and integrating different modalities (such as

sound, human speech, and thermal display (Hribar V. E. and Pawluk D. T. V., 2011)) to provide a full-fledged image accessibility solution for blind users (following our application scenario) remains our strategic goal.

We hope that the unified presentation of visual data accessibility on a vibrating touch-screen, and the empirical results and analysis in this paper will contribute to strengthen and motivate further research on the subject.

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