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How similar are braille letters? Towards the understanding of reading through the sense of touch.

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How similar are braille letters?

Towards the understanding of reading through the sense of touch.

A Master's Thesis

Presented to

The Department of Psychology

DePaul University

By

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November 27, 2018

Thesis Committee

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Biography

The author was born in Madrid, Spain, December 31st, 1991. She graduated in 2009 from La Dehesilla High School, in Cercedilla, Madrid, Spain. She received her Bachelor of Arts degree in Elementary and Physical Education from the Complutense University of Madrid in 2013. She received her Master of Arts degree in Cognitive Neuroscience and Specific Learning Needs from the University of Valencia in 2014.

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Abstract

Research on reading through the sense of touch is needed to understand the difficulties that surround the learning of braille and to improve our understanding of the brain mechanisms behind reading in general. The cognitive processes of braille reading have been little explored in comparison to visual reading mainly because the tools used in visual modality are not adapted to the tactile modality. A crucial aspect in the comprehension of reading processes is to determine how the elements of any written script are recognized for which it is needed to know what its salient characteristics are. The present MA Thesis aims to (1) describe the development of a passive haptic-reading instrument that allows researchers to have control over participants' exposure to the braille stimuli and record participants' responses ; and (2) to explore what the features of the braille writing system are by assessing the perceived similarity among the 26 alphabet letters. To this end, two groups of non-braille readers (i.e., Active and Passive) performed a same/different judgment task in which they had to classify a pair of braille letters as being the same two letters or two different letters. A 26×26 confusion matrix per group was generated in which each cell contained the proportion of correct responses for the row-column pair of letters. Similarity among letters was evaluated through hierarchical clustering and multidimensional scaling procedures, indicating that the number of dots and the way those dots are arranged across the cell's rows are salient features of braille characters. The differences in performance between active and passive groups were assessed through the visual comparison of the similarity results and the calculation of the Pearson's product moment correlation coefficient.

Results did not show differences in performance between active and passive conditions; a strong correlation is shown between the accuracy data of both groups which supports the use of passive haptic-reading instrument to investigate braille perception. The evidence shown here is important for understanding braille reading learning. Future research needs to examine what the salient features of braille letters are for expert readers to have more information about how knowledge influences the recognition process. This would be crucial to improve educational practices surrounding braille literacy.

How similar are braille letters? Towards the understanding of reading through the sense of touch.

Introduction

Tactile perception has interested neuroscience and psychology for as long as the fields have existed. The present document deals with a particular aspect of tactile perception: reading through the sense of touch via the braille writing system.

The braille Writing System

Braille is a system of raised dots that allows people to read through the sense of touch by moving their fingertips across those dots. It was developed by Louis Braille in 1824 to represent the French language, and nowadays braille systems are used in 133 languages worldwide (Perkins School for the Blind, International Council on English Braille & Library of Congress, 2013). Braille symbols are formed within units of space known as braille cells: 2×3 matrices of dots. The dots are identified by numbers from top to bottom: 1-3 in the left column and 4-6 in the right one. Different patterns of raised dots in one cell represent different letters. For example, the letter *a* is a braille cell where dot 1 is raised: ⠁. Sixty-four combinations can be configured in a braille cell, including the one in which none of the dots are raised (International Council on English braille, 2013).

Research on braille reading has practical and theory-development implications. Braille is the gateway to information, education, and to the labor market for millions of individuals with sight loss. Thus, on the applied end, investigating braille reading should help to improve blind people’s literacy rates and, consequently, their quality of life. Additionally, braille is a unique way of reading, since it is designed to be accessed through the sense of touch. Hence, on the theoretical end, research on braille reading could contribute to a more comprehensive account of reading in general.

Literacy Among Blind Population

Literacy is a dynamic concept. It is usually defined as the ability to read and write, but it has been expanded to include broader notions of education and knowledge. The United Nations Educational, Scientific and Cultural Organization –UNESCO– (2004) states it “is the ability to identify, understand, interpret, create, communicate and compute, using printed and written materials associated with varying contexts. Literacy involves a continuum of learning in enabling individuals to achieve their goals, to develop their knowledge and potential, and to participate fully in their community and wider society” (p.13). It is an essential ability in modern societies, as it impacts several aspects of an individual’s quality of life.

Despite its importance, literacy rates among the blind population are low: less than 10% of blind people can read braille. Moreover, those rates are correlated with educational level, the likelihood of employment, and income (National Federation of the Blind Jernigan Institute, 2009). Some factors that contribute to this issue are a lack of braille teachers, deficient teaching methodologies, misconceptions about the braille writing system that lead in negative societal attitudes towards it, and the greater reliance on technology that is being used as replacement instead of as supplement to braille (Ryles, 1996; National Federation of the Blind Jernigan Institute, 2009). Investigating the neurophysiological and cognitive skills that underlie braille reading is essential to improve the educational practices and to develop better teaching tools and techniques.

The Pursuit of a Universal Theory of Reading

The ability to read has been studied extensively over the years in pursuit of a universal reading theory. That is, a theory that explains the core mechanisms of reading. Generally, reading is done visually; therefore, research on reading has focused on this modality. To develop a theory of reading, researchers need to examine the cognitive mechanisms involved in this ability across different writing systems (Frost, 2012). The comparison between the sighted and non-sighted reading would allow us to uncover the differences and similarities among reading systems.

To investigate braille reading and to compare it to visual reading, researchers need (1) tools to control the timing of presentation of the tactile stimuli, record subject’s responses, and infer the timing of the mental processes; and (2) to understand what the salient features of braille are. The present MA Thesis deals with those needs by describing a way in which researchers could have said control (Section 1), and by validating such method in a study that aims to examine the features of the braille writing system (Section 2).

Section 1: The tool

Researchers on texture perception have developed some tools that could be adapted to be used with braille stimuli (e.g., Ballesteros et al., 2009; Oddo et al., 2011; Moungou, Thonnard, & Mouraux, 2016); nevertheless, some limitations arise from them. For instance, the use of fixed stimuli, the use of expensive software, or the lack of portability. A possible solution that allows us to have control over the what and the when a participant perceives a tactile stimulus could be the use of passive touch. That is, instead of participants moving their finger against the stimulus, the stimulus is moved against the participant's finger.

Passive touch can refer to the perception mediated only by variations in cutaneous stimulation, also known as *tactile perception*. Additionally, it can also refer to the perception mediated by both variations in cutaneous stimulation and kinesthesis (i.e., movement) in which the perceiver does not have control over picking up stimulus information, also known as *passive haptic perception* (Loomis & Lederman, 1986). Studies that have compared active vs. passive haptic perception (see Loomis and Lederman, 1984 for a review) suggest that the latter could be a good substitute of the former. Therefore, we theorized that passive haptic reading could, in fact, be a solution to the lack of tools problem.

Passive haptic reading would allow researchers to control the timing of the presentation of the stimuli and would allow participants to stay still while perceiving braille, which will bring the possibility of using methods that record changes in neural activity (e.g., ERPs). Consequently, we developed a passive haptic reading tool by placing a refreshable braille display on a moving platform.

Hardware

The Moving Platform is a linear bearing constructed as follows: a stepper motor was assembled into a 136 mm × 44 mm × 6 mm plate, that is attached to a 4-wheel 160 mm × 90mm × 3.18 mm carriage plate (on which the refreshable braille display is placed). This platform is mounted to a 66mm × 50 mm × 25 mm rail. A toothed belt surrounding the rail is connected to the stepper motor, used to transfer the motion by it generated to the platform (Inventables, Inc., 2013). The stepper motor is connected to the Arduino Uno Board for power and control.

The Arduino Uno Board is an open-source ATmega328-based microcontroller board that has 14 digital input/output pins plus six analog inputs, a 16-MHz crystal oscillator, a USB connection, a power jack, an In-Circuit Serial Programming header, and a reset button (Arduino.cc., 2017). It can be powered either from a USB connection or power it with an AC-to-DC adapter or battery. The board can operate on an external supply of 6 to 20 volts. Each of the 14 digital pins that can be used as an input or output and they operate at 5 Volts (D’Ausilio, 2011). For this project, an Adafruit Motor Shield was attached to the board, to allow driving the stepper motor, controlling the speed and direction of movement.

Refreshable braille Displays are one of the most common ways to access braille written information, other than paper. They make the braille system very practical at present, allowing readers to interact with computers and smartphones, among other gadgets (Perkins School for the Blind, International Council on English Braille & Library of Congress, 2013). Braille displays use 8-dot braille cells, in which the last row is added to make computer interaction easier. For example, by showing the position of the cursor.

The moving platform is connected to the Arduino Uno board through the motor shield, to which the stepper motor is wired; the braille display is connected to a Mac OS computer through an USB cable. The Arduino Uno board is powered with an AC-to-DC adapter, and connected to the computer through an USB cable (see Figure 1).

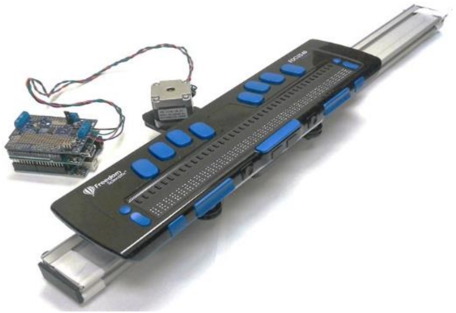

Figure 1. Passive braille reading tool.

Software

To control the platform movement, we used the Arduino Software (i.e., Arduino Integrated Development Environment: IDE), which compiles and uploads programs to the main Arduino board. The code, written using C or C++ language (for a language reference, see http://arduino.cc/en/Reference/HomePage), is stored in the board's memory, so it is triggered when the circuit is on.

To present stimuli on the braille display and trigger the Arduino board, we created a shell script using Bash syntax that enables the presentation of stimuli from a list, as well as the recording of responses. The Bash code can trigger the Arduino system, so the platform moves when the stimuli are on display and resets when a key is pressed (i.e., a response id made). We utilized the OS-X's VoiceOver accessibility feature to present the items on the screen on the braille display.

Section 2: braille letters' features

Reading is both a sensory and a linguistic ability; our senses have different advantages and limitations. Thus, the characteristics of writing systems must be different. The braille writing system's design reflects a compromise to use as much of the skin's acuity, while maximizing the amount of information per unit of surface. The standard distance from center to center of adjacent dots (horizontally or vertically, but not diagonally) in the same cell being 2.3 mm, and from center to center of corresponding dots in adjacent cells being 6.2 mm (The National Library Service for the Blind and Physically Handicapped (NLS), Library of Congress, 2008).

In order to understand how a stimulus is recognized, we need to know the salient properties of such stimulus. The study described below aims to explore what the features of braille letters are, as researchers on the visual reading field have done (e.g., Fiset et al., 2008; Gilmore, Hersh, Caramazza, & Griffin, 1979; Wiley, Wilson, & Rapp, 2016).

To explore the braille features, we used a same-different judgment task in which two braille letters were presented simultaneously in a refreshable braille display; participants had to touch them with their Index finger in a serial manner from left to right. Then, they had to classify them, as fast and accurate as they can, as being *same* or *different* (e.g., “⠁ ⠁” : *same*; “⠁ ⠉” : *different*). The participants were non-braille readers to avoid prior experience and literacy as confounding variables. We assumed that pairs less accurately classified are indicative of shared salient features. Therefore, we assessed how similar braille letters are by generating confusability matrices to evaluate and infer the features of braille letters, as it has been done previously using different stimuli and modalities (e.g.,Gilmore, Hersh, Caramazza, & Griffin, 1979; Loomis, 1982; Townsend, 1971; Wiley, Wilson, & Rapp, 2016).

Method

A same-different judgment task was used to assess the features that underlie braille letter representations. In this task, participants used the index finger of their dominant hand to feel the braille letters, and the middle and index finger of their non-dominant hand to make the *same-different* responses using the M and N keys, respectively, on a keyboard. During the task, participants touched two braille letters presented simultaneously in a refreshable braille display with the index finger of their dominant hand in a serial manner (i.e., from left to right: Letter1 tauched before Letter 2). Then, classified them as fast and accurate as they can as being *same* or *different* (e.g., “⠁ ⠁” : *same*; “⠁ ⠉” : *different*). Two groups of participants performed this task. Group 1 did it actively, by moving their finger;

group 2 did it passively, by having the braille display slide underneath their finger. The setup and the stimuli lists were the same for both groups.

Apparatus

Two braille displays were used to present the braille letters (i.e., a Focus 40 blue, and a Smart Beetle). The braille display was placed in the pull-out keyboard tray of the desktop, to avoid participants seeing it, while the keyboard was placed on top of the desktop. Each braille display had 3D stickers separated 5 cm, indicating the area where the braille letters would appear. For the group performing the passive task only (i.e., Group 2), a display was placed on the moving platform described in the previous section.

Materials

Two braille letters per trial were presented in a refreshable braille display. The study used all possible 2-letter combinations: 676 pairs. Out of those pairs, 26 were the same two letters (i.e., “ ⠁ ⠁ ”), and 650 two different letters (i.e., “ ⠁ ⠃ ”). Thus, five different lists of pairs were created in which 130 were *same* pairs (i.e., formed by the same two letters), and 130 were *different* pairs (i.e., formed by two different letters). Each participant perceived 266 trials, where 6 were practice and 260 were target trials; all the target trials were presented in random order.

Group 1: Active haptic perception

Participants. Ninety undergraduate students at DePaul University who did not know how to read braille were recruited through the subject pool system

(SONA) participated in the study. They earned one course-credit for taking part in the study.

Procedure. The experiment took place either individually or in pairs, in a quiet room. Participants were instructed to use the index finger of their dominant hand, in a continuous left-to-right motion, to touch the braille letters presented in the display, and to use the middle and index fingers of the non-dominant hand to make responses by pressing the *same* and *different* keys – M and N, respectively – in the keyboard. Participants could only feel the pairs one time, after which they had to classify them as being *same* or *different*. Inter-trial-interval (ITI) was one second, time that participants had to use to reset the finger's position. Every time a new trial appeared in the display, the sound of the dots rising signaled participants to start the finger motion.

Group 2: Passive haptic perception

Participants. Eighty-seven undergraduate students at DePaul University who did not know how to read braille were recruited through the subject pool system (SONA) participated in the study. They earned one course-credit for taking part in the study.

Procedure. The procedure was very similar to the previous experiment, with the only exception that here participants did not move their fingers. They were instructed to rest their hand on a wrist holder, and to place their index fingertip on the start position to let the braille display slide against it. The braille display moved for 5 cm at 50 mm/s. This speed was chosen taking into account previous studies (see Legge, Madison, & Mansfield, 1999; Vega-Bermudez, Johnson, & Hsiao, 1991), and our own experience testing it. After moving said distance, it stopped until participants responded, and reset its position during the one-second ITI.

Analysis and Results

Participants who performed at chance level or below, and trials in which responses were either faster than 200 ms or slower than 15000 ms were excluded from the analysis. Table 1 shows the mean accuracy per group and condition.

Responses for each trial across participants were summarized as accuracy proportions in a confusion matrix, where each cell contains the percentage of trials on which the row stimulus and the column stimulus yielded a correct response. In Experiment 1, 22241 data points were analyzed (#trials [23050] – low accuracy – timeouts). From those data points, 11208 were pairs formed by two different letters. Table 2 shows the resulting confusion matrix. In Experiment 2, 21045 data points were analyzed (#trials [22470] – low accuracy – timeouts). From those data points, 10518 were pairs formed by two different letters. Table 3 shows the resulting confusion matrix. Those matrices represent the overall similarity among braille letters perceived by naïve readers. Hierarchical clustering and multidimensional scaling techniques were then used to evaluate the underlying features of those letters

Table 1.

Mean classification accuracy per group and condition

	Accuracy	CI
Active group		
Same	0.776	[0.768-0.784]
Different	0.688	[0.680-0.697]
Passive group		
Same	0.794	[0.786-0.802]
Different	0.651	[0.642-0.660]

Table 2.

Active group confusion matrix

	⠁	⠃	⠉	⠙	⠑	⠋	⠛	⠓	⠊	⠚	⠅	⠇	⠍	⠝	⠕	⠏	⠟	⠗	⠎	⠞	⠥	⠧	⠺	⠭	⠽	⠵
⠁	0.898	0.688	0.661	0.76	1	0.922	1	0.974	0.917	0.947	0.972	1	0.967	0.974	0.939	1	0.972	1	0.913	0.971	0.918	0.937	0.974	0.974	0.946	1
⠃	0.688	0.84	0.638	0.55	0.677	0.745	0.607	0.712	0.706	0.707	0.749	0.688	0.944	0.972	0.872	0.833	0.912	0.853	0.889	0.859	0.818	0.846	0.802	0.912	0.912	0.944
⠉	0.661	0.638	0.844	0.753	0.485	0.621	0.817	0.611	0.605	0.716	0.969	0.884	0.828	0.906	0.95	0.882	0.946	0.947	0.859	0.908	0.787	0.882	0.861	0.862	0.906	0.875
⠙	0.76	0.55	0.753	0.715	0.498	0.489	0.41	0.314	0.767	0.454	0.788	0.618	0.662	0.777	0.844	0.712	0.799	0.686	0.697	0.753	0.733	0.939	0.716	0.849	0.847	0.849
⠑	1	0.677	0.485	0.498	0.766	0.667	0.875	0.611	0.556	0.743	0.691	0.749	0.727	0.849	0.818	0.875	0.971	0.969	0.759	0.844	0.812	0.885	0.875	0.919	0.929	0.912
⠋	0.922	0.745	0.621	0.489	0.667	0.773	0.274	0.402	0.674	0.397	0.862	0.824	0.767	0.866	0.787	0.513	0.722	0.456	0.57	0.516	0.887	0.765	0.513	0.889	0.938	0.756
⠛	1	0.607	0.817	0.41	0.875	0.274	0.832	0.48	0.875	0.459	0.894	0.727	0.789	0.675	0.748	0.492	0.282	0.512	0.816	0.451	0.912	0.748	0.337	0.818	0.686	0.686
⠓	0.974	0.712	0.611	0.314	0.611	0.402	0.48	0.78	0.601	0.4	0.781	0.647	0.83	0.811	0.73	0.712	0.615	0.665	0.749	0.702	0.742	0.66	0.503	0.789	0.832	0.572
⠊	0.917	0.706	0.605	0.767	0.556	0.674	0.875	0.601	0.741	0.423	0.799	0.792	0.859	0.838	0.806	0.811	0.827	0.855	0.644	0.838	0.853	0.922	0.913	0.84	0.913	0.895
⠚	0.947	0.707	0.716	0.454	0.743	0.397	0.459	0.4	0.423	0.703	0.747	0.627	0.826	0.743	0.52	0.733	0.728	0.56	0.689	0.508	0.818	0.812	0.701	0.785	0.841	0.85
⠅	0.972	0.749	0.969	0.788	0.691	0.862	0.894	0.781	0.799	0.747	0.832	0.66	0.337	0.658	0.515	0.822	0.83	0.757	0.542	0.794	0.362	0.628	0.822	0.697	0.882	0.882
⠇	1	0.688	0.884	0.618	0.749	0.824	0.727	0.647	0.792	0.627	0.66	0.862	0.742	0.799	0.759	0.612	0.88	0.608	0.627	0.631	0.676	0.642	0.734	0.656	0.85	0.858
⠍	0.967	0.944	0.828	0.662	0.727	0.767	0.789	0.83	0.859	0.826	0.337	0.742	0.723	0.58	0.33	0.529	0.676	0.772	0.544	0.6	0.382	0.542	0.572	0.43	0.794	0.462
⠝	0.974	0.972	0.906	0.777	0.849	0.866	0.675	0.811	0.838	0.743	0.658	0.799	0.58	0.736	0.267	0.59	0.544	0.45	0.624	0.383	0.581	0.608	0.417	0.374	0.358	0.232
⠕	0.939	0.872	0.95	0.844	0.818	0.787	0.748	0.73	0.806	0.52	0.515	0.759	0.33	0.267	0.741	0.536	0.743	0.557	0.548	0.577	0.299	0.399	0.556	0.344	0.603	0.172
⠏	1	0.833	0.882	0.712	0.875	0.513	0.492	0.712	0.811	0.733	0.822	0.612	0.529	0.59	0.536	0.767	0.312	0.344	0.402	0.539	0.647	0.518	0.288	0.553	0.417	0.428
⠟	0.972	0.912	0.946	0.799	0.971	0.722	0.282	0.615	0.827	0.728	0.83	0.88	0.676	0.544	0.743	0.312	0.808	0.284	0.851	0.456	0.882	0.516	0.353	0.653	0.467	0.384
⠗	1	0.853	0.947	0.686	0.969	0.456	0.512	0.665	0.855	0.56	0.757	0.608	0.772	0.45	0.557	0.344	0.284	0.737	0.749	0.446	0.664	0.45	0.354	0.549	0.413	0.278
⠎	0.913	0.889	0.859	0.697	0.759	0.57	0.816	0.749	0.644	0.689	0.542	0.627	0.544	0.624	0.548	0.402	0.851	0.749	0.695	0.294	0.625	0.599	0.598	0.617	0.856	0.676
⠞	0.971	0.859	0.908	0.753	0.844	0.516	0.451	0.702	0.838	0.508	0.794	0.631	0.6	0.383	0.577	0.539	0.456	0.446	0.294	0.75	0.75	0.513	0.479	0.549	0.588	0.382
⠥	0.918	0.818	0.787	0.733	0.812	0.887	0.912	0.742	0.853	0.818	0.362	0.676	0.382	0.581	0.299	0.647	0.882	0.664	0.625	0.75	0.787	0.454	0.781	0.412	0.692	0.5
⠧	0.937	0.846	0.882	0.939	0.885	0.765	0.748	0.66	0.922	0.812	0.628	0.642	0.542	0.608	0.399	0.518	0.516	0.45	0.599	0.513	0.454	0.765	0.617	0.508	0.404	0.548
⠺	0.974	0.802	0.861	0.716	0.875	0.513	0.337	0.503	0.913	0.701	0.822	0.734	0.572	0.417	0.556	0.288	0.353	0.354	0.598	0.479	0.781	0.617	0.73	0.515	0.5	0.479
⠭	0.974	0.912	0.862	0.849	0.919	0.889	0.818	0.789	0.84	0.785	0.697	0.656	0.43	0.374	0.344	0.553	0.653	0.549	0.617	0.549	0.412	0.508	0.515	0.783	0.344	0.301
⠽	0.946	0.912	0.906	0.847	0.929	0.938	0.686	0.832	0.913	0.841	0.882	0.85	0.794	0.358	0.603	0.417	0.467	0.413	0.856	0.588	0.692	0.404	0.5	0.344	0.819	0.382
⠵	1	0.944	0.875	0.849	0.912	0.756	0.686	0.572	0.895	0.85	0.882	0.858	0.462	0.232	0.172	0.428	0.384	0.278	0.676	0.382	0.5	0.548	0.479	0.301	0.382	0.75

Table 3.

Passive group confusion matrix

	⠁	⠃	⠉	⠙	⠑	⠋	⠛	⠓	⠊	⠚	⠅	⠇	⠍	⠝	⠕	⠏	⠟	⠗	⠎	⠞	⠥	⠧	⠺	⠭	⠽	⠵
⠁	0.909	0.603	0.542	0.908	0.971	0.938	0.969	0.938	0.812	0.91	0.939	0.971	0.941	0.969	1	0.941	1	0.971	0.938	1	0.971	0.933	0.906	0.938	1	0.933
⠃	0.603	0.835	0.542	0.728	0.531	0.531	0.908	0.706	0.648	0.575	0.75	0.667	0.871	1	0.969	0.844	0.875	0.882	0.75	0.871	0.873	0.969	0.812	0.938	0.971	0.969
⠉	0.542	0.542	0.89	0.688	0.487	0.469	0.849	0.625	0.656	0.757	0.882	0.875	0.938	0.844	0.967	0.969	0.938	0.938	0.767	0.938	0.939	0.971	0.969	0.881	0.939	0.941
⠙	0.908	0.728	0.688	0.751	0.393	0.343	0.333	0.393	0.759	0.548	0.808	0.656	0.625	0.818	0.695	0.625	0.844	0.533	0.719	0.783	0.794	0.781	0.667	0.881	0.881	0.693
⠑	0.971	0.531	0.487	0.393	0.802	0.625	0.808	0.627	0.657	0.695	0.72	0.71	0.781	0.938	0.844	0.908	0.906	0.969	0.812	0.881	0.808	0.744	0.844	0.841	0.904	0.937
⠋	0.938	0.531	0.469	0.343	0.625	0.773	0.213	0.267	0.677	0.219	0.875	0.82	0.794	0.792	0.699	0.515	0.624	0.691	0.562	0.5	0.869	0.789	0.406	0.908	0.656	0.844
⠛	0.969	0.908	0.849	0.333	0.808	0.213	0.838	0.515	0.971	0.567	0.882	0.756	0.688	0.667	0.735	0.406	0.441	0.438	0.625	0.646	0.849	0.577	0.562	0.562	0.638	0.483
⠓	0.938	0.706	0.625	0.393	0.627	0.267	0.515	0.744	0.5	0.469	0.688	0.588	0.638	0.728	0.667	0.629	0.777	0.542	0.765	0.656	0.688	0.483	0.417	0.794	0.647	0.719
⠊	0.812	0.648	0.656	0.759	0.657	0.677	0.971	0.5	0.721	0.438	0.515	0.688	0.906	0.871	0.816	0.849	0.869	0.82	0.742	0.699	0.719	0.904	0.875	0.75	0.908	0.838
⠚	0.91	0.575	0.757	0.548	0.695	0.219	0.567	0.469	0.438	0.764	0.719	0.656	0.722	0.688	0.574	0.636	0.849	0.844	0.421	0.676	0.853	0.667	0.607	0.908	0.781	0.824
⠅	0.939	0.75	0.882	0.808	0.72	0.875	0.882	0.688	0.515	0.719	0.833	0.5	0.483	0.933	0.671	0.735	0.82	0.75	0.559	0.601	0.431	0.706	0.781	0.688	0.908	0.812
⠇	0.971	0.667	0.875	0.656	0.71	0.82	0.756	0.588	0.688	0.656	0.5	0.868	0.671	0.647	0.875	0.648	0.75	0.625	0.419	0.562	0.607	0.517	0.789	0.742	0.732	0.688
⠍	0.941	0.871	0.938	0.625	0.781	0.794	0.688	0.638	0.906	0.722	0.483	0.671	0.776	0.375	0.406	0.5	0.625	0.502	0.358	0.603	0.565	0.531	0.511	0.395	0.469	0.412
⠝	0.969	1	0.844	0.818	0.938	0.792	0.667	0.728	0.871	0.688	0.933	0.647	0.375	0.794	0.344	0.406	0.243	0.469	0.625	0.344	0.562	0.517	0.419	0.443	0.182	0.362
⠕	1	0.969	0.967	0.695	0.844	0.699	0.735	0.667	0.816	0.574	0.671	0.875	0.406	0.344	0.791	0.426	0.417	0.265	0.5	0.469	0.375	0.382	0.421	0.469	0.278	0.312
⠏	0.941	0.844	0.969	0.625	0.908	0.515	0.406	0.629	0.849	0.636	0.735	0.648	0.5	0.406	0.426	0.793	0.344	0.284	0.265	0.184	0.487	0.421	0.519	0.344	0.406	0.329
⠟	1	0.875	0.938	0.844	0.906	0.624	0.441	0.777	0.869	0.849	0.82	0.75	0.625	0.243	0.417	0.344	0.841	0.243	0.824	0.312	0.688	0.367	0.352	0.36	0.241	0.312
⠗	0.971	0.882	0.938	0.533	0.969	0.691	0.438	0.542	0.82	0.844	0.75	0.625	0.502	0.469	0.265	0.284	0.243	0.801	0.667	0.26	0.625	0.281	0.312	0.364	0.31	0.366
⠎	0.938	0.75	0.767	0.719	0.812	0.562	0.625	0.765	0.742	0.421	0.559	0.419	0.358	0.625	0.5	0.265	0.824	0.667	0.715	0.292	0.515	0.594	0.382	0.562	0.6	0.719
⠞	1	0.871	0.938	0.783	0.881	0.5	0.646	0.656	0.699	0.676	0.601	0.562	0.603	0.344	0.469	0.184	0.312	0.26	0.292	0.777	0.406	0.312	0.412	0.579	0.492	0.438
⠥	0.971	0.873	0.939	0.794	0.808	0.869	0.849	0.688	0.719	0.853	0.431	0.607	0.565	0.562	0.375	0.487	0.688	0.625	0.515	0.406	0.759	0.395	0.562	0.301	0.594	0.632
⠧	0.933	0.969	0.971	0.781	0.744	0.789	0.577	0.483	0.904	0.667	0.706	0.517	0.531	0.517	0.382	0.421	0.367	0.281	0.594	0.312	0.395	0.813	0.353	0.353	0.417	0.388
⠺	0.906	0.812	0.969	0.667	0.844	0.406	0.562	0.417	0.875	0.607	0.781	0.789	0.511	0.419	0.421	0.519	0.352	0.312	0.382	0.412	0.562	0.353	0.777	0.385	0.406	0.438
⠭	0.938	0.938	0.881	0.881	0.841	0.908	0.562	0.794	0.75	0.908	0.688	0.742	0.395	0.443	0.469	0.344	0.36	0.364	0.562	0.579	0.301	0.353	0.385	0.781	0.25	0.281
⠽	1	0.971	0.939	0.881	0.904	0.656	0.638	0.647	0.908	0.781	0.908	0.732	0.469	0.182	0.278	0.406	0.241	0.31	0.6	0.492	0.594	0.417	0.406	0.25	0.752	0.276
⠵	0.933	0.969	0.941	0.693	0.937	0.844	0.483	0.719	0.838	0.824	0.812	0.688	0.412	0.362	0.312	0.329	0.312	0.366	0.719	0.438	0.632	0.388	0.438	0.281	0.276	0.745

Hierarchical clustering

This technique is useful to visualize groupings based on structural similarity. The algorithm treats each object as a separate cluster, then identifies the two clusters that are closest together and merges them into a single cluster, repeating it until all the clusters are merged. To perform this analysis, we transformed each confusion matrix into a symmetrical matrix by taking the mean value of the two possible presentation orders for each pair. Then, those symmetrical matrices were transformed into distance matrices using a Euclidian method, and a dendrogram per distance matrix was generated using a complete linkage method (*stats* package in R). Figure 2 shows the resulting dendrograms. For comparison purposes, cluster colors are held constant between the two dendrograms. Four main clusters are evident: (1) letters with one or two dots risen in the upper two rows; (2) letters with three or four dots risen in the upper rows; (3) letters with two or three dots risen in either first and third row or in all three rows; and (4) more than three dots risen in either first and third row or in all three rows. These results are non-dimensional. Thus, to further explore the characteristics that underlie braille-letter similarity, the distance matrices were decomposed into a dimensional representation through the Multidimensional Scaling procedure.

Multidimensional Scaling

This technique is useful to uncover the spatial representation underlying perceptions. The algorithm places each object in a space with a specific number of dimensions while preserving, as well as possible, the distances between the objects. Hence, each object is assigned coordinates in each one of the dimensions. Using an ordinal scaling, and a random method of choosing starting points, two dimensions were found to be an acceptable fit (stress = 0.143). Table 4 shows the coordinates given to each letter on those dimensions per group, and Figure 3 shows the visual representation of the results. Dimension 1 has objects such as ⠁ , ⠑ , or ⠅ in one end and, objects such as ⠵ , ⠽ , or ⠗ in the other, possibly indicating the number of dots risen. Dimension 2 has objects such as ⠃ , ⠙ , or ⠋ in one end, and objects such as ⠝ , ⠥ , or ⠭ in the other, potentially representing the position of the risen dots among the braille cell's rows.

Correlation between groups

The Pearson's product moment correlation coefficient was calculated for the symmetrical matrices of both groups to compare the results of the active and passive groups using statistics in addition to the previous visual comparison. Results show strong linear association between the two data sets, r = 0.858. The scatterplot in Figure 4 summarizes the results. Each data point in the scatterplot is a pair of braille letters. The x-axis shows the distribution of mean accuracy in the active condition, in red. The y-axis shows the distribution of mean accuracy in the passive condition, in purple.

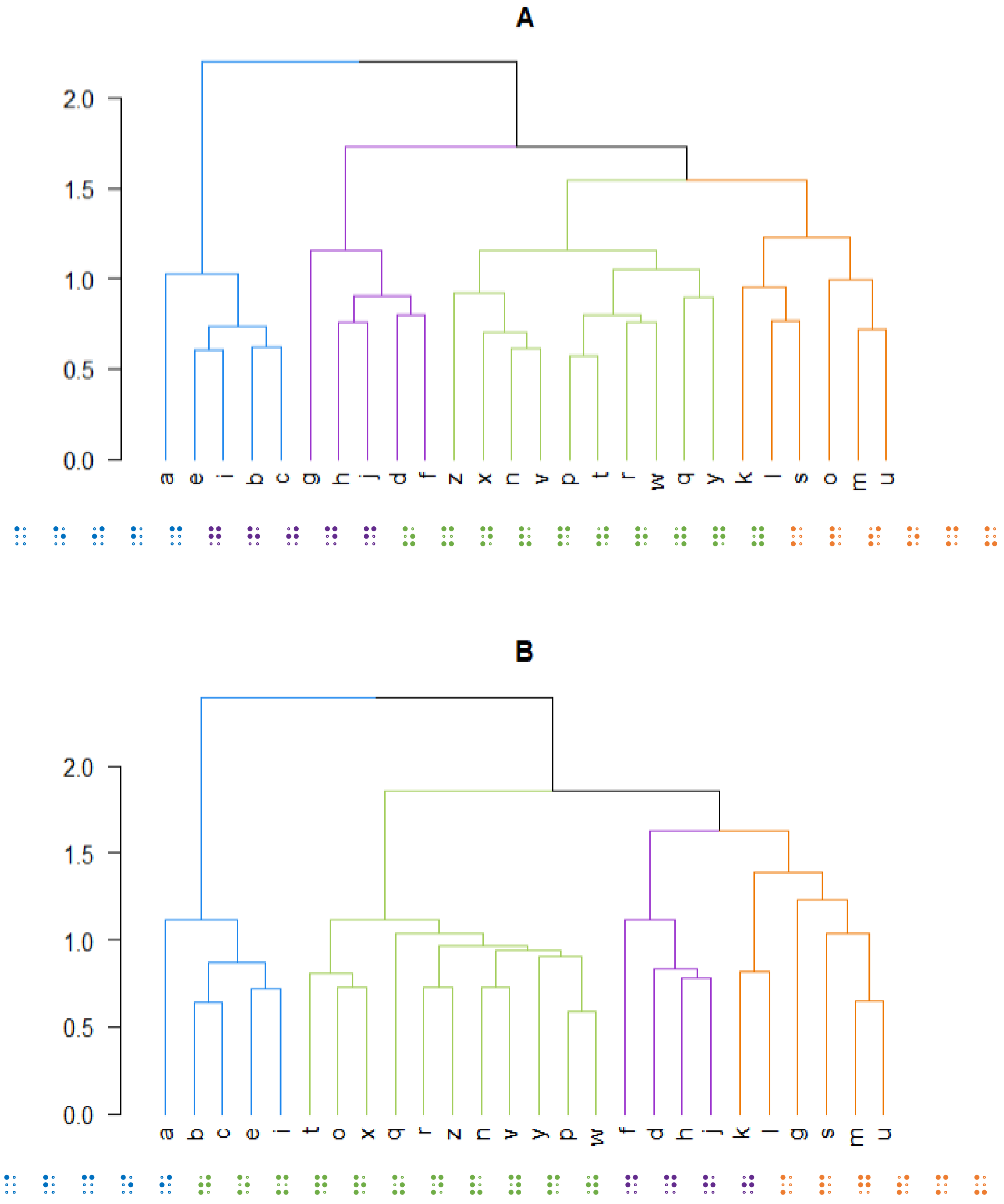

Figure 2. Hierarchical clustering solution. **A**) Dendrogram resulting from the Active group data. **B**) Dendrogram resulting from the Passive group data.

Table 4.

Coordinates assigned to each object in the two-dimension multidimensional scaling solutions

	Active Group		Passive Group	
	D1	D2	D1	D2
⠁	-1.18	-0.675	0.907	0.997
⠃	-0.551	-0.617	0.523	0.883
⠉	-0.712	-0.647	0.563	1.015
⠙	-0.182	-0.627	-0.018	0.594
⠑	-0.668	-0.536	0.454	0.748
⠋	0.13	-0.629	-0.403	0.708
⠛	0.521	-0.478	-0.34	0.11
⠓	0.076	-0.486	-0.104	0.367
⠊	-0.515	-0.519	0.45	0.62
⠚	-0.027	-0.487	0.083	0.536
⠅	-0.531	0.19	0.462	0.246
⠇	-0.257	-0.14	0.179	0.189
⠍	-0.157	0.466	-0.133	-0.312
⠝	0.298	0.59	-0.136	-0.62
⠕	0.045	0.781	-0.365	-0.458
⠏	0.516	0.291	-0.027	-0.621
⠟	0.685	0.029	-0.478	-0.604
⠗	0.653	0.252	-0.121	-0.734
⠎	-0.126	0.131	0.154	-0.151
⠞	0.41	0.195	-0.43	-0.386
⠥	-0.313	0.503	0.086	-0.315
⠧	0.159	0.427	-0.131	-0.524
⠺	0.562	0.138	-0.288	-0.355
⠭	0.155	0.616	-0.385	-0.588
⠽	0.408	0.492	-0.299	-0.704
⠵	0.601	0.738	-0.206	-0.641

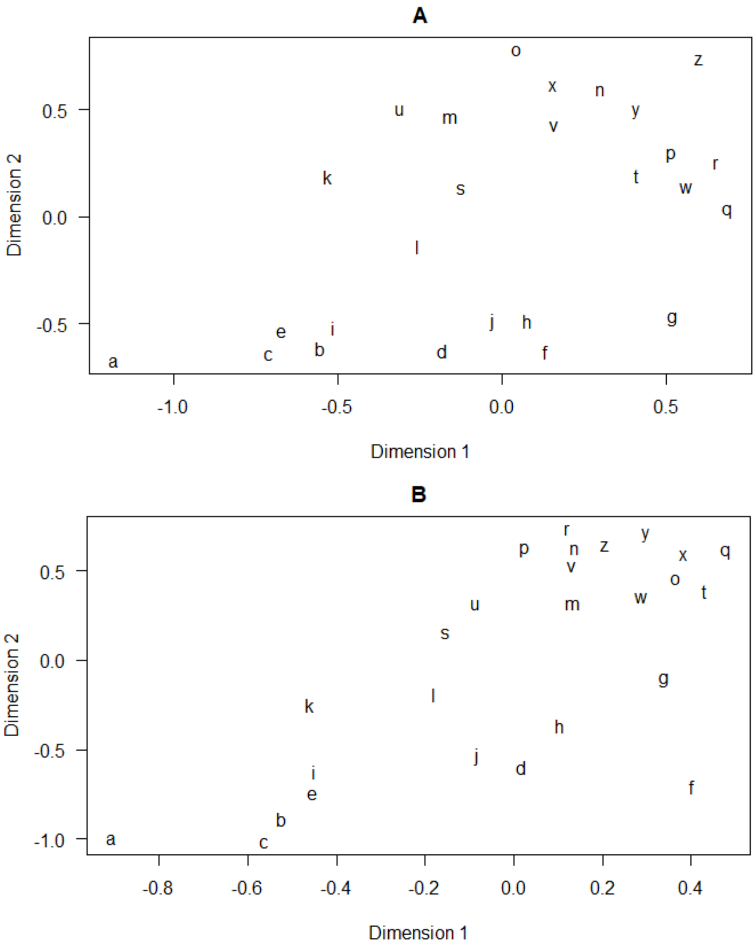

Figure 3. Multidimensional scaling solutions. **A**) Configuration plot resulting from the Active group data. **B**) Configuration plot resulting from the Passive group data.

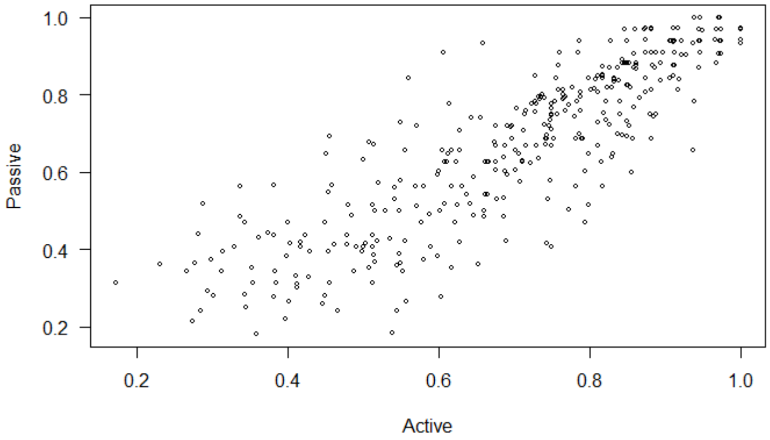

Figure 4. Correlation between confusion matrices obtained from the active and passive groups' data.

Discussion

We developed a tool to control the timing of the presentation of braille stimuli using passive touch and validated it in a study that examined the salient features of braille for non-braille readers. The tool is a moving platform operated by an Arduino Uno board that carries a refreshable braille display; it allows passive haptic perception, that is the perception of braille stimuli moving across the fingertip while staying still. To validate it, we designed a same/different judgement task in which participants touched a pair of braille letters in a continuous and serial manner and then classified them as being *same* or *different*. 90 participants (i.e., Active group) performed the task in an active manner, by moving their index finger across the braille display, and 87 participants (i.e., Passive group) performed the task in a passive manner, by letting the braille display slide against their index finger, for which we used the previously described tool.

We generated a confusion matrix per group summarizing the percentage of correct responses for each pair of letters (i.e., row-column) and analyzed it to assess the letter similarity through hierarchical clustering and multidimensional scaling procedures. Results of both techniques showed that, for non-braille readers, braille letters' similarity is based on the number of risen dots and the arrangement of those dots across the cell, those features being the foundation of the four clusters found through the former procedure, as well as of the two dimensions found through the latter procedure. There were no differences between the active and passive groups. The outcomes of the two analysis techniques were very similar; the correlation test revealed a strong relationship between the two confusion matrices, $r=0.858$.

This study produced two main outcomes: (1) we show that the passive haptic-reading tool can be used to investigate braille perception and reading, and (2) we identified specific similarities in the tactile feature perception of braille letters by non-braille readers. Knowing what the salient features of braille are is essential to understand the information processing operations that underlie braille letter perception; such processing informs about the way in which people become proficient in braille reading. Thus, it is helpful to develop techniques and methodologies to improve the teaching of braille.

It is important to note that although we did not find significant differences between active and passive haptic braille perception, perhaps the method used to access braille input influences performance on other tasks, such as sentence comprehension. Further research needs to clarify the extent of the correspondence between the two methods. Additionally, the study does not address what letter features those who know how to read braille attend to. A comparison between naïve and expert braille readers is required to identify the effects of knowledge on the processing of this writing script, as well as to improve the educational practices that surround braille learning.

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