Exploring tactile identification accuracy through advanced braille embossers: the dynamic combination of dot density and dot elevation

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Abstract

The scope of this paper is to examine the potential capabilities of embossed printers under the lens of Information Technology (IT). One of the main principles of IT is to manage and deliver information into accessible formats to all users with and without disabilities. The present study investigates the discriminability of lines and squares by participants who had severe visual impairment. These lines and squares, produced by braille embossers, represented shapes, figures, and diagrams from a variety of textbooks. Hence, it was expected that the more discriminable these tactile formats are by touch, the more accessible and understandable will be by people who are blind, enhancing the level of collaborative learning and performance. Thirty-four volunteers participated in experiments, and they were invited to conduct matching activities through touch. The researchers, during the experimental phase, recorded a. all participants' matching stimuli responses and b. the time taken for each identification during the matching activities. The tactile stimulus material - tactile lines and square areas - was produced by an advanced braille embosser. Four levels of dot heights (0.030, 0.079, 0.227, and 0.468 mm, respectively) were combined with two versions of densities (10 and 20 dpi, respectively) to create embossed dotted lines and square areas. The results indicated that lines had roughly the same success proportion at the two resolutions (10dpi vs 20dpi). However, squares had a significantly greater success proportion at 10dpi than at 20dpi. In fact, squares were better than lines at 10 dpi but worse than lines at 20 dpi. Finally, the present study highlights the need to examine further the discriminability among the combinations of embossed lines and areas in order to have a clear-cut "picture" of what is really perceived by participants who are blind and then attempt to develop and propose a standardized protocol to incorporate it in the assistive technology market and in the educational reality as well. Many researchers hold the view that apart from the increased accessibility of students who have visual impairments in the content of their classes, communication and discussions will also be enhanced because of the increased interaction and collaboration among students. According to the researchers, this outcome may enhance the dynamics of an inclusive setup, ensuring a potential well-balanced social integration. Finally, it is argued that the production of outstanding and fine tactile graphs will enable students with vision disability to have access to relevant educational content (such as in science and mathematics), ensuring equity and effective inclusion.

Keywords. Vision disability, embossed printers, dot density, dot elevation, Assistive Technology, IT

1. Introduction

Information Technology (IT) constitutes a broad domain that incorporates a great variety of hardware, software, and services in order to convert, store, process, and transmit information. A plethora of technological advances, in the context of assistive technology, have been designed and applied in the field of communication, labor market, and education in order to enhance integration and social inclusion (Rehan Youssef & Morsy, 2023). As a result, IT is in line with issues of

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integration, inclusion, and equity, and for this, it has extended its market by adopting the principles of universal design for learning (UDL) coupled with aspects of access by providing all learners equal opportunities to learn (Meyer et al., 2014).

More specifically, Information technology has greatly enriched and facilitated the process of delivering accessible information to people who have vision disability (i. e., people who are totally blind or have light perception) or to people who have low vision. Nowadays, there is a vast range of specialized strands which can be captured under the umbrella of technology, such as assistive, augmentative, communicative or/and alternative technologies, which have positive impact on the quality of life of people with vision disability. This positive influence can be noticed in everyday life, such as in transport, in health sectors, and of course in education (i. e. differentiated material, differentiated instruction, differentiated assessments, instructional practices and curricula, for example see Argyropoulos & Gentle, 2019).

In fact, technology and assistive devices increased the degree of accessibility of people with disabilities through a range of medium (i.e. from electronic to printed material). In the case of people with vision disability, it appears that this kind of conversion from one medium to another constitutes an unlimited capability to access any type of information, offering many educational and vocational opportunities (Cooper & Nichols, 2007; Kerscher, 2001). For example, transcription into braille constitutes a big issue in the education of students with vision disability because it involves many learning subjects that deal with graphs, images, and figures (e.g., mathematics, physics, science, etc.), and all this material has to be transcribed accurately into braille (Nkiko et al., 2018). One example of "technological evolution" which seems that can meet the above challenges combined with IT dynamic capabilities, is the case of braille embossers. Embossed graphics produced by braille embossers occupy a lot of characteristics that enable users who are blind to recognize them and grasp an understanding exploring them by touch. ViewPlus Tiger® embossers, for example, can produce a range of eight different dot heights in combination with a variety of dot densities (Gardner, 2005; Gardner et al., 2009). In addition, embossed graphics can be produced very quickly and in many combinations such as on the same hard copy sheet which has braille on it and can be produced by the same device as well as on a regular braille document. It is worth mentioning here that braille embossers can produce high-quality tactile graphics at a much lower cost compared to other common techniques, such as the stereo-copying technique (i.e., technique that uses swell or pop-up paper) or the thermoforming technique (i. e., technique that uses plastic sheets) (Prescher et al., 2014).,

Despite the richness of embossed graphics in characteristics and conveyed information, many users who are blind have stated several issues that need to be taken into consideration by educators and researchers as well. These issues may be grouped as following: a. issues of readability by touch; sometimes readability by touch is hard process because a subset of the characteristics of the embossed graphic is not discriminable, b. issues of dot elevation; the range of dot elevation is poor and may not facilitate the blind user to clarify different qualities within an embossed graphic (i.e., little variation), c. issues of point symbols; if there any point symbols, then these symbols are usually difficult to discern, and d. issues of textures; the range of the number of textures which is available by the embossers to use is quite restricted. Touch discriminability and its comparisons to sight discriminability h been an enticing subject for many researchers and for many years. For example, Heller (1989) conducted a comparative study with participants with and without vision disability. In specific, one group consisted of congenitally blind individuals, the second group consisted of late blind individuals (i.e., this meant that the specific participants had visual memories), and the third group consisted of sighted individuals. The participants were invited to conduct matching activities by touch using embossed shapes. Heller found that the sense of touch seemed inferior compared to vision when participants tried to perceive by touch two-dimensional patterns and pictures; on the other hand, he also found that touch was superior compared to vision (i.e.. higher accuracy) when participants were invited to identify and match tactile surfaces in finer texture identification. Furthermore, Johansson and

LaMotte (1983) investigated detection thresholds in terms of dot elevation, and they found that all types of single edges could be detected at an elevation of 0.85 μm compared to flat backgrounds. In addition, physiological studies can have a great input in the embossing process because new features may be revealed of haptic sensitivity and comprehension when studying the sensitivity of the fingertip (Jehoel, 2009). For example, LaMotte and Srinivasan (1987), found that sharp or pointed edges trigger more intense neural reactions in the fingertip receptors compared to gradually sloping or curved edges. It seems evident that different textures may result in different haptic stimuli and as a result may lead in different levels of understanding or conceptualization (Panotopoulou et al., 2020).

From the above, it may be argued that the combined case "richness of embossed graphics" and "tactile sensitivity" is an open field of research. A small number of studies have investigated levels of tactile sensitivity in conjunction with different levels of dot elevation of tactile graphics, even though it is documented that the variable "elevation" constitutes a crucial parameter regarding recognition by touch. Frascara et al. (1993), arrived at the conclusion that: a. the elevation of tactile area symbols should be higher than 0.5 mm, b. the elevation of line tactile symbols should start from 1.0 mm, and c. the elevation of tactile points should be higher from 1.5 mm. Jehoel et al. (2009) investigated aspects of tactile perception in individuals with and without vision disability, during performances in recognizing differences regarding dot elevation of tactile shapes. In specific, the researchers used inkjet technology and the TIMP printer (McCallum & Ungar, 2003a; 2003b) with symbols - circles, squares, and triangles- printed on matt PVC at a variety of six elevations (7, 14, 22, 30, 38 and 47 μm) and five sizes. Contrary to what was suggested by Frascara et al. (1993), Jehoel et al. (2009) found that symbols with rough features are preferred by blind and sighted participants in their experiments and that the symbol elevations necessary for identification are about 0.040 to 0.080 mm. Also, Jehol et al. (2009) suggested that "symbols height with good legibility is considerably lower than would be expected based on existing tactile maps (generally 0.5 mm or higher) and design guidelines (0.4 mm)" (p. 219). In line with the previous study, Shiah et al. (2011) found that the level of touch recognition is decreasing nonlinearly as the degree of dot elevation is increasing.

It seems that the role of the third dimension (i.e., height) of tactile stimuli's little is known and much more investigation is needed. Dot height coupled with dot density constitute the two significant parameters that dominate the recognition and conceptualization of tactile embossed graphics by individuals with vision disability (Krufka & Barner, 2006). This was also confirmed, especially for embossed graphics produced by Braille embossers (BEG) like Tiger Pro Embosser, where these parameters are precisely controlled by specialized software (i. e., Tiger Software Suite) (Gardner 2005; Gardner et al., 2009). Even though research has shown that a. the parameter "dot elevation thresholds" plays a pivotal role in processes of tactile detection and discrimination, and b. the response of fingertip receptors, from a physiological point of view, varies with texture, little is known about the impact of these parameters on the identification of embossed stimuli especially when stimulus is context free (Martos et al., 2021).

When it comes to educational terms and educational settings, access to diagrams is a big issue for students with vision disability. Especially in subjects such as mathematics and science, where the majority of concepts are usually conveyed by diagrams, students with blindness may feel very frustrated because of their limited or fragmented access to these diagrams. This situation constitutes serious obstacles to their understanding, and as a result, many students with vision disability prefer to drop science and mathematics subjects in higher classes (Rule et al., 2011). In the same line, Doore et al. (2023) underlined that despite the fact that graphic representations are ubiquitous in the learning of STEM (science, technology, engineering, and mathematics), they are not always accessible to students who are blind; this situation, according to Doore et al. (2023), has a negative impact on blind students' development because it creates barriers to pursuing STEM educational and career pathways. The above research team worked out many methods of design and evaluation of

universally accessible systems for communicating graphical representations in STEM classes (students with and without visual impairments). Their findings suggest that access to information through tactile representation not only enhances students' (sighted and non-sighted) understanding and conceptualization but also enhances communication and discussion amongst students who have different visual abilities in a classroom.

All of the above constitute significant factors in promoting successful inclusive setups at schooling. An inclusive set up incorporates all appropriate accommodations in order to facilitate the active participation of students with vision disability in their classes. Tactile graphs and fine diagrams seem to added value to students' understanding. For example, Teke and Sozbilir (2019) used two-dimensional embossed representations of molecular structures supported with braille and sighted typesetting in order to make them accessible for both sighted and non-sighted students. They argued that this method gave the opportunity to all students with and without visual impairments to get a better understanding of the molecular structure of compounds, improving inclusion and active participation in the class workflow. In addition, De Greef et al. (2021) discuss a lot about the practicalities that embossed tactile graphics offered in their work, such as rich representations of numeric tables or embossed variants of multi-series scatterplots. The same research team noticed that apart from the increased accessibility of the students who had visual impairments in the content of their classes, the element of communication was very vivid and intensive because the interactions during classes were also increased. This outcome, according to the researchers, enhanced the dynamics of an inclusive setup.

Hence, apart from issues of accessibility and communication, which are extremely important in terms of equity and inclusion, the production of outstanding and fine tactile graphs helps students with vision disability to develop and consolidate fine tactile skills. According to many researchers, it seems that individuals develop their tactile skills throughout life, beginning very early (Bradley-Johnson et al., 2004; Mukhiddinov & Kim, 2021; Steri, 2003). Tactile graphics can be used for diverse objectives in education, entertainment, and navigation. The vast peculiarity of tactile graphics, such as tactile line styles, tactile areas, and filling patterns (i.e., different textures and different formats), require from students with a vision disability to develop proficient tactile skills as well as tactile strategies. Hence, it may be argued that the good quality and accuracy of tactile graphics have a great impact on the development of hand and finger dexterity, in other words, in the development of fine tactile skills, which lead to robust haptic apprehension (Argyropoulos & Papazafiri, 2017; McLinden, 2004, 2012).

From the above, it may be argued that fundamental elements of an inclusive setup are ensured by detailed research on embossed tactile patterns, shapes, and figures since a. content access is maximized, b. communications and discussions amongst students with and without visual impairments are enhanced, and c. blind students develop effective fine motor skills improving their haptic apprehension and understanding. Based on the above considerations, Martos et al. (2021) attempted to explore thoroughly a variety of thresholds regarding the identification of embossed tactile lines and embossed squares at various dot elevations by blind users. More specifically, the researchers used a ViewPlus Tiger® embosser to produce eight different dot heights in a variety of dot densities. In turn, they administered embossed graphics, which included lines and squares to 30 congenitally blind individuals. For the eight dot elevations, from 0.030 mm to 0.468 mm that the ViewPlus Tiger® embosser was capable to produce, [each height was numbered from 1 to 8 (H1 to H8), starting from the lower elevation], the researchers found out that amongst the eight dot heights, the better-perceived textures from the lowest to the highest were four in total (H1, H2, H4, and H8). These four dot heights were described by Martos et al. (2021) as follows:

a) The number 1 height (H1) was the lowest elevation, approximately 0.030 mm, and caused little confusion compared with the numbers 2 and 3 heights (H2 & H3).

b) The number 2 height (H2), approximately 0.079mm, seemed that caused a slightly greater confusion in recognition compared to numbers of height 1, 3, and 4 respectively (H1, H3, and H4).

c) The number 4 height (H4) - approximately 0.227mm – as well as the number 8 height - approximately 0.468mm – seemed to create less confusion in recognition, whereas the greatest confusion was observed in the heights 5, 6, and 7 respectively (H5, H6, and H7) (Kouroupetroglou et al., 2016; Martos et al., 2021).

Some of the results of Martos' et al. research are in line with previous research carried out by Jansson and Juhasz (2007), who used embossed graphics produced by a Tiger Embosser and suggested that three dot heights are better perceived starting with the lower dot heights, but they did not mention the actual dot height. Another similar study was conducted by Bath and Davis (1984), where dot height perception was studied although paper embossing was produced by another technique called "Plate Embossing Apparatus for Raised Lines" (PEARL). According το Bath and Davis (1984), the appropriate embossing height was: 0.025 inch for any given point symbol and approximately 0.020 inch for any given linear symbol. They also found that for areal symbol elevation for paper the height should be approximately 0.010 inch up to 0.015 inch for any given areal pattern including background grids composed of either solid or dotted lines (Bath & Davis, 1984).

As mentioned above, few studies focused on tactile sensitivity to elevation (third dimension), and even fewer studies used embossed samples produced by braille embossers such as ViewPlus Tigers. Nowadays, more and more, researchers are paying more attention to the role of height of tactile stimuli to increase readability of tactile graphics (Douglas et al., 2008; Gupta et al., 2017, 2022; Reichinger et al., 2011, 2012, 2016).

In line with the above, the authors of this paper decided to carry out a study, which constituted a follow-up of the research conducted by Martos et al. (2021). More specifically, the present research aimed to investigate furthermore issues of discriminability and detectability amongst the prevailed four dot heights which were traced in Martos et al. (2021), following a similar reasoning to that of Newton–Raphson method, which is a root-finding algorithm following successively better approximations to the roots of a "real situation/function".

Hence, the research questions of the present study were framed by the following:

1. Are the four dot elevations, which have been traced in the research of Martos et al. (2021), equally discriminable and detectable towards scoring and time taken when blind individuals explore tactile lines and surfaces by touch?
2. Was the overall accuracy of Research Question 1, evenly distributed amongst the four dot elevations? Did any modification take place regarding the classification model of stimuli clusters on dot elevation based on blind participants' high accuracy?

2. Method

The present study focuses on experiments that deal with tactile identification processes. It attempts to explore the identification accuracy of textures that combine two variables; that is, dot heights and dot densities. The experiments were conducted by participants with severe visual impairments.

2.1 Participants

Thirty-four volunteers who were blind (age: 32.8 ± 10.7 years, 13 males and 21 females) participated in this study. The participants' level of education ranged from Secondary Education, (n = 10) to Higher Education (n = 24) and all of them

had a good grasp of the braille code (i.e., all participants were reading and writing braille for more than nine years). All participants were informed about the aim and the procedure of the experiments, and in turn they gave their consent to the whole process. Finally, the present research was approved by the Ethics Committee of the National and Kapodistrian University of Athens.

2.2 Materials

Two types of stimuli were used in the experiment: raised dot lines (7 cm length, one-dimensional pattern) and raised dot squares (2 X 2 cm, two-dimensional pattern). All haptic materials (tactile lines and square areas) were produced by a Tiger Braille Embosser (VP200) on free dust paper of 160 g/m^2, in two dot densities (10 dpi and 20 dpi). Similar materials were used in the Martos' et al. (2021) research, and the present study focused on a subset of this material, namely combinations of four dot heights: H1, H2, H4, and H8 (see introduction).

A test stimulus was created consisting of an embossed dotted line and an embossed dotted square area in each one of the four dot elevations. As mentioned above, these heights constituted a subset of the material that was used in Martos' et al. (2021) research. The table below describes the new coding which was adopted in the present research:

Table 1. New Dot coding and corresponding heights to Martos' et al. study (2021)

Dot Height (according to Martos et al., 2021)	Dot Height (new corresponding coding)	Height (mm)
H1	DH1	0.030
H2	DH2	0.079
H4	DH3	0.227
H8	DH4	0.468

Each embossed test stimulus was created in the center of an A4-size sheet of paper in portrait orientation in two versions of densities (of 10 dpi and 20 dpi), respectively. Thus, in total, there were 16 independent test stimuli.

Likewise test stimulus, a target set was created including the same type of stimuli, namely embossed dotted lines, and square areas with 10 and 20 dpi density, respectively. Figure 1 shows an example of a target set configuration for the case of square areas. Hence, the total number of stimuli regarding embossed square areas was also 16. Each target set consisted of an arrangement of computer-generated random-order embossed stimuli in four A4-size sheets of paper that were fixed on an A3-size hardboard.

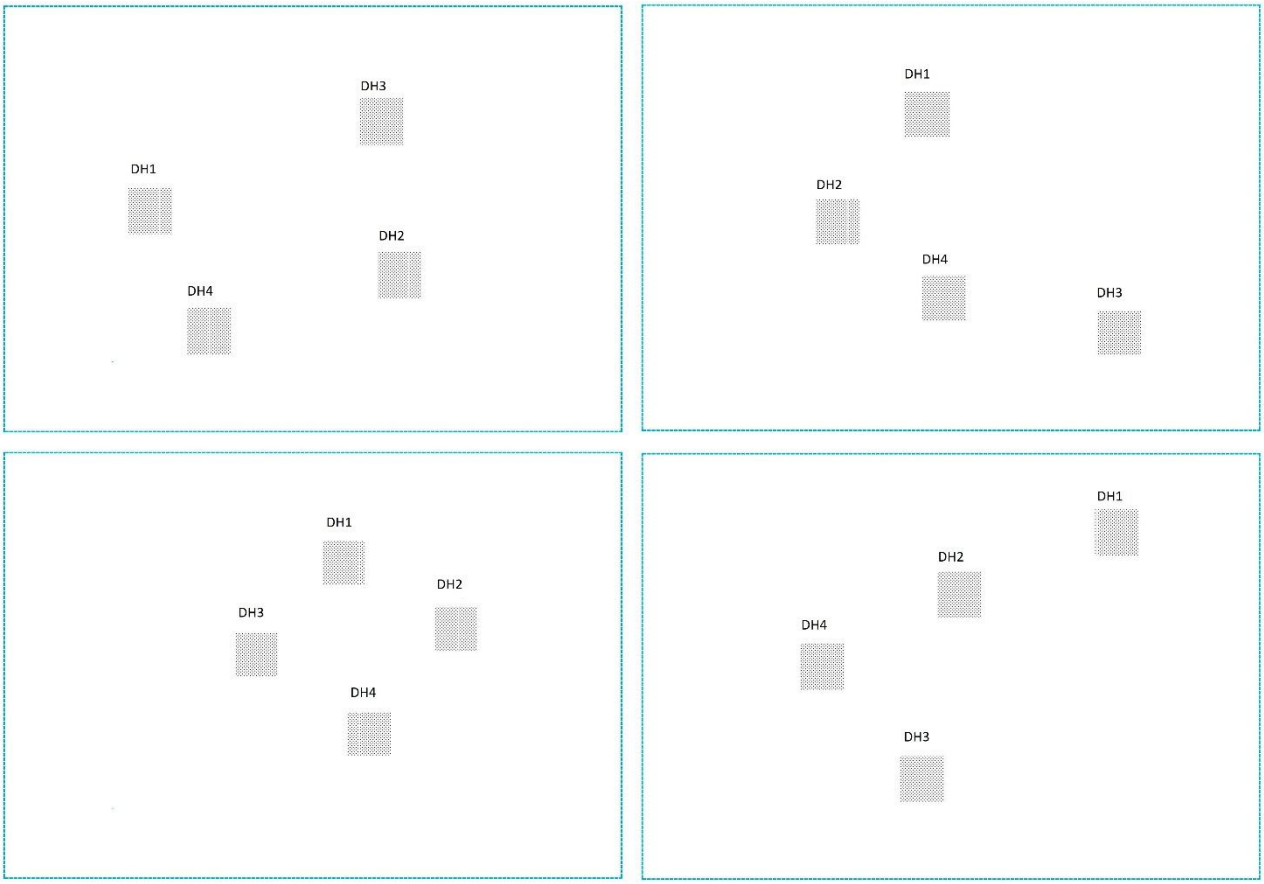

Figure 1. An example of a target set configuration of square areas

2.3 Research Design - Procedures

The research design consisted of two phases: the preliminary and the experimental phase, respectively. During the preliminary phase, all participants, individually, were informed about the aim and the objectives of the study, and in turn, they had the chance to get familiarized with sample identification tests with different dot heights of all classes (i. e., DH1, DH2, DH3, and DH4, see Table 1) coupled with different dot densities (10 dpi or 20 dpi). The researchers answered all participants' queries during the preliminary phase and put great emphasis on the outcomes of the experiments. The experimental phase commenced after the participant felt comfortable enough to start. An adjustable height desk was used, and the researchers placed on it the stimulus test (dotted lines and embossed square areas in two density versions of 10dpi and 20dpi respectively) as well as the corresponding target set with the same type of stimuli. All stimuli were randomly selected among the four elevation levels (see Table 1). In turn, the researchers asked the participant to actively explore by touch all shapes in the test stimulus and then identify again by touch the corresponding shape in the target set by matching them as fast and accurately as possible. All participants were allowed to use any haptic technique regarding their haptic exploration (i. e. one hand, both hands, all fingers with or without using their palms, etc.). Finally, both the preliminary phase and the experiments took place in the university's lab.

During the experimental phase, the researchers recorded a. all participants' matching stimuli responses (MSR) and b. the time taken for each identification. Four was the maximum number of responses and each matching – otherwise identification – was terminated when the participant stated that she/he had identified the four target stimuli (no matter if the matching was correct or incorrect) or after a 1-min time-out. The same pattern was followed with all four stimuli (see

Table 1). The hypothesis of random selections of the stimuli was ensured through a computer software. The above procedure was repeated for each dot density (10 dpi and 20 dpi, respectively); hence, the maximum number of trials was 32 during the experimental phase.

2.4 Data Selection and Analysis

All participants' responses were recorded through a software application which incorporated a timer and a database where the data were stored. In specific, MS-Access 2010 and Visual Basic were used to develop the application and to analyze each participant's response, a separate window was used with a graphical user interface to store responses and the time taken for each response. The timer stopped automatically immediately after the response was recorded or after a 1-min-time-out (i. e., no response after the limit of 1 min for each trial). A total of 1,088 trials were performed and recorded (=34 participants X 32 trials), and the scores fluctuated from 0 to 4 correct answers for each trial. The identification accuracy and response time of the matching task were examined for each type of test stimuli.

Two parts composed the process of the data analysis. The first one referred to the identification accuracy and response time of the matching task, and the second one referred to confusion matrices providing conclusions about: a. lines, b. surfaces, and c. overviews.

3. Results

The results are organized and presented in accordance with the research questions. The first question deals with issues of equal or equivalent levels of discriminability and detectability when blind participants explored through touch embossed lines and surfaces in different densities. Two variables were measured in order to meet this research question; that is, a. scores and b. time taken to complete all trials.

3.1 Regarding Research Question 1

As mentioned above, 34 participants performed 1,088 trials (quartets), so that in each trial the score could vary between 0 and 4 successes. The results of this score and its percentage form are described in Table 2, whereas the distribution of the successes throughout the four elevation of dot heights (i.e., DH1, DH2, DH3, & DH4, see Table 1) is presented analytically in Table 3 and graphically in Figure 2:

Table 2. Percentage form of the scores through all trials

		Total	Percent
N	Valid	1088	1088
	Missing	0	0
Mean		3.25	81.27
Std. Deviation		1.294	32.353

Table 3. Frequency of the successes during haptic exploration

	Frequency	Percent (%)

Valid	0	91	8.4
	1	66	6.1
	2	64	5.9
	3	125	11.5
	4	742	68.2
	Total	1088	100.0

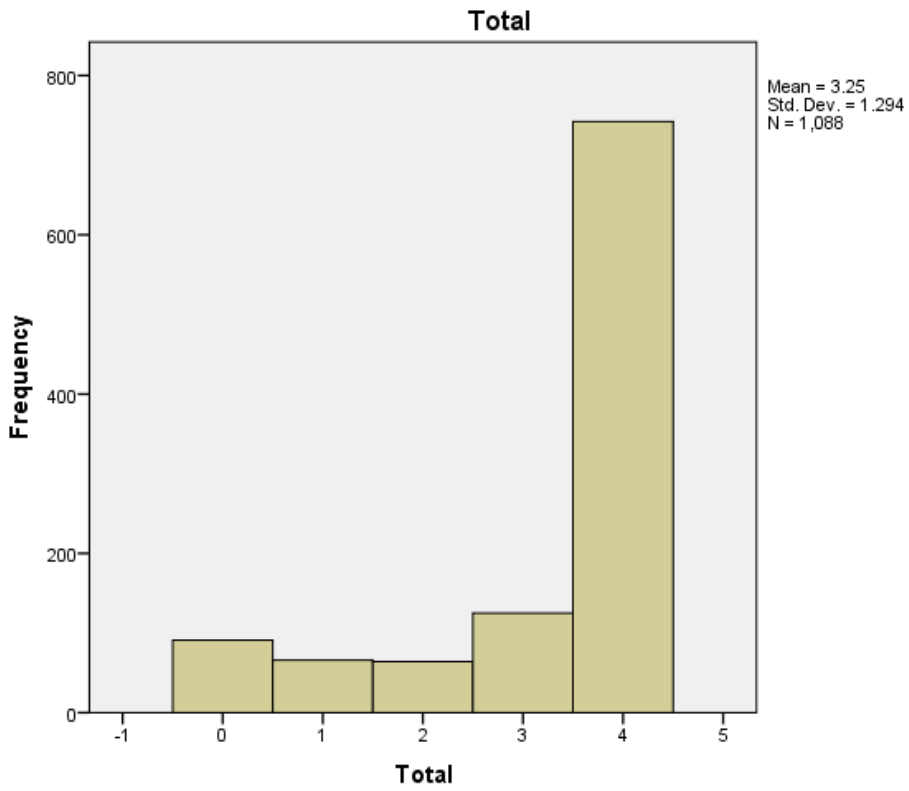

Figure 2. Graphical presentation of the successes during haptic exploration

From the above it can be conjectured that generally the participants performed high scores in detection and discrimination during all matching activities between the stimulus test and the target set (68.2% regarding four successes towards 8.4% for 0 successes). Hence, it seems that the first measurements of the present study confirmed the outcomes of Martos' et al. (2021). Nevertheless, at this part of the analysis, it was decided to examine the discriminability and detectability of the embossed lines and squares not only regarding the variable of scoring but also regarding the variable of time taken to conduct all trials towards scoring.

The mean values of the time spent in the trials depending on the score are presented in Table 4.

Table 4. Total time spent in trials towards scoring.

	N	Mean	Std. Deviation	Std. Error
0	91	49.45	29.620	3.105
1	66	53.36	34.653	4.266
2	64	49.38	32.264	4.033
3	125	40.49	24.217	2.175
4	742	35.80	22.740	.836
Total	1088	39.35	25.683	.780

In turn, a one-way analysis of variance (ANOVA) was conducted to compare variances between participants' scoring during the trials and time spent for the corresponding trials. There was a statistical significance at the $p<.05$ level in total time spent for the different clusters of successes [$F (4, 1080) = 15.215$, $p = .000$].

Based on the above, it may be argued, that the participants that scored high (3 or 4) performed the tasks in a significantly quicker time than participants who scored low (0, 1 or 2). This means that if we set a cutoff time for the completion of a trial and disregard the rest then we could achieve better results. According to the research design the same pattern of trials was followed with all stimuli for embossed lines and squares at two levels of densities (10dpi vs 20dpi). In essence, the focus was put on the interaction between surface (embossed line vs embossed square) and resolution (10dpi vs 20dpi) on the proportion of successful responses. Repetition did not have any effect and at first inspection, neither did the surface (see Table 5).

Table 5. Statistics in repetition trials (lines vs squares & 10dpi vs 20dpi)

	Surface	N	Mean	Std. Deviation	Std. Error Mean
Percent	Lines	544	80.74	32.226	1.382
	Squares	544	81.80	32.501	1.393
	Resolution				
	10dpi	544	84.38	31.526	1.352
	20dpi	544	78.17	32.897	1.410

However, a difference was noticed between the two resolutions (10dpi vs 20dpi). When conducting a one-way between-subject effects it was found that at lower resolution (10dpi), the proportion of successes was significantly higher than at 20dpi. Table 6 depicts the whole picture.

Table 6. Tests of between-subject effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	28770.106[a]	3	9590.035	9.373	.000	.025
Intercept	7186563.074	1	7186563.074	7024.293	.000	.866
Surface	303.883	1	303.883	.297	.586	.000
Resolution	10469.324	1	10469.324	10.233	.001	.009
Surface * Resolution	17996.898	1	17996.898	17.591	.000	.016
Error	1109041.820	1084	1023.101			
Total	8324375.000	1088				
Corrected Total	1137811.926	1087				

a. R Squared = .025 (Adjusted R Squared = .023)

Also, the effect of surface was qualified through its interaction effect with resolution (see Figure 3).

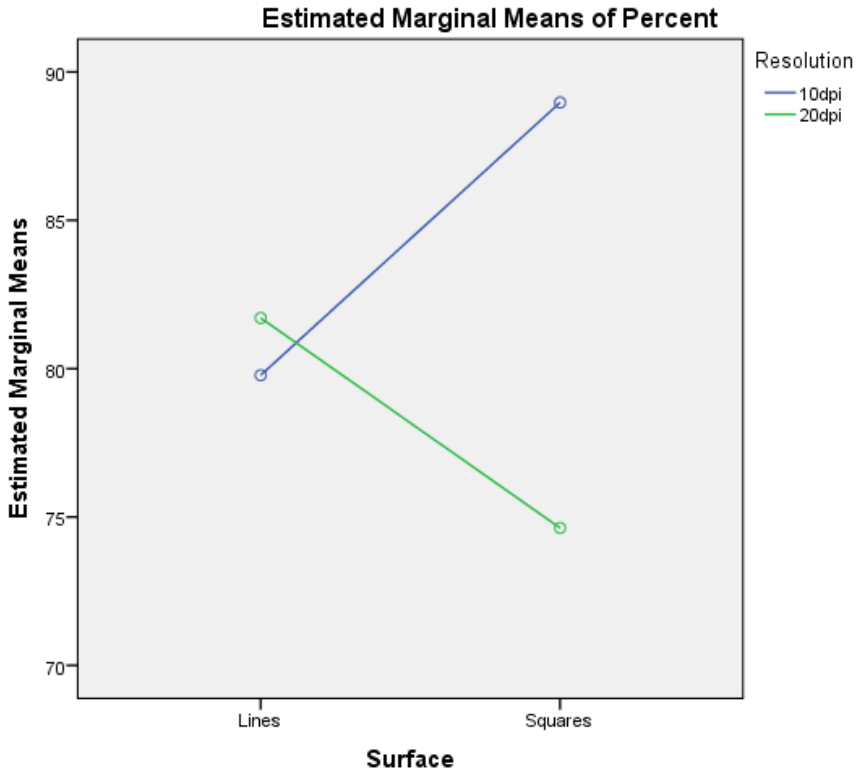

Figure 3. Resolutions vs Surfaces

To conclude, lines had roughly the same success proportion at the two resolutions (10dpi vs 20dpi). However, squares had a significantly greater success proportion at 10dpi than at 20dpi. In fact, squares were better than lines at 10 dpi but worse than lines at 20 dpi.

3.2 Regarding Research Question 2

The second research question deals with issues of haptic perception and accuracy. It was decided to tackle it by using confusion matrices, which combine “actual" and "predicted" classes of an algorithm or a performance. All participants provided four responses for each experimental trial. Hence, the model which was developed in the context of this study was a classifier of four. The participant’s success rate (SR) during each experimental trial varied from zero to four (or from 0% to 100%, in percentage form). The success rate (SR) was considered the primary dependent variable, and according to the study's experimental design, it was repeated 16 times (2 stimulus types x 2 dot densities x 4 heights/see Table 1). Hence, the dependent variable of the success proportion was subjected to a 2X2X4 repeated-measures analysis of variance.

Tables 7, 8, 9, and 10 constitute confusion matrices of the response height versus the stimulus height in terms of lines at 10 and 20 dpi respectively and in terms of squares at 10 and 20 dpi, respectively.

Table 7. Matching outcomes for 10dpi embossed dotted lines [test stimuli (rows) vs target stimuli (columns)].

		Response Dot Height (RDH)				Total
		DH1	DH2	DH3	DH4	
Stimulus Dot Height (SDH)	DH1	230 (84.6%)	42 (15.4%)	0 (0.0%)	0 (0.0%)	272
	DH2	5 (1.8%)	263 (96.7%)	4 (1.5%)	0 (0.0%)	272
	DH3	0 (0.0%)	8 (2.9%)	243 (89.3%)	21 (7.7%)	272
	DH4	0 (0.0%)	0 (0.0%)	140 (51.5%)	132 (48.5%)	272
Total		235	313	387	153	1088

Table 8. Matching outcomes for 20dpi embossed dotted lines [test stimuli (rows) vs target stimuli (columns)].

		Response Dot Height (RDH)				Total
		DH1	DH2	DH3	DH4	
Stimulus Dot Height (SDH)	DH1	223 (82.0%)	48 (17.6%)	1 (0.4%)	0 (0.0%)	272
	DH2	13 (4.8%)	252 (92.6%)	7 (2.6%)	0 (0.0%)	272
	DH3	0 (0.0%)	13 (4.8%)	227 (83.5%)	32 (11.8%)	272
	DH4	0 (0.0%)	1 (0.4%)	84 (30.9%)	187 (68.8%)	272
Total		236	314	319	219	1088

Table 9. Matching outcomes for 10dpi embossed dotted square areas [test stimuli (rows) vs target stimuli (columns)].

		Response Dot Height (RDH)				Total
		DH1	DH2	DH3	DH4	
Stimulus Dot Height (SDH)	DH1	254 (93.4%)	18 (6.6%)	0 (0.0%)	0 (0.0%)	272
	DH2	2 (0.7%)	270 (99.3%)	0 (0.0%)	0 (0.0%)	272
	DH3	2 (0.7%)	10 (3.7%)	240 (88.2%)	20 (7.4%)	272
	DH4	0 (0.0%)	0 (0.0%)	68 (25.0%)	204 (75.0%)	272
Total		258	298	308	224	1088

Table 10. Matching outcomes for 20dpi embossed dotted square areas [test stimuli (rows) vs target stimuli (columns)].

		Response Dot Height (RDH)				Total
		DH1	DH2	DH3	DH4	
Stimulus Dot Height (SDH)	DH1	258 (94.9%)	12 (4.4%)	0 (0.0%)	2 (0.7%)	272
	DH2	34 (12.5%)	230 (84.6%)	7 (2.6%)	1 (0.4%)	272
	DH3	1 (0.4%)	98 (36.0%)	152 (55.9%)	21 (7.7%)	272
	DH4	3 (1.1%)	16 (5.9%)	81 (29.8%)	172 (63.2%)	272
Total		296	356	240	196	1088

All above four confusion matrices (Tables 7, 8, 9, & 10), described responses heights vs stimulus heights per density and per surface. The accuracy was found to be high especially for DH2 (Dot Height 2). The following Table 11 shows the overall confusion matrix of the response height versus the stimulus heights. The overall accuracy was (3537= 965+1015+862+695)/4352=81.3%, but as the Table 11 shows this was not evenly distributed among the different stimulus heights. The best accuracy is observed for the stimulus DH2 (SDH2, 93.3%), having only 1.8% of wrong response dot heights 3 or 4 (RDH2 or RDH4) and 5.0% wrong response dot height 1 (RDH1). Quite satisfactory was the accuracy for stimulus dot height 1 (88.7%), however it was significantly less than for stimulus DH2 (Difference 4.6%, 95% CI 2.1%-7.1%, $p<0.01$). This is due to a significantly larger dispersion of SDH1-RDH2 misidentifications (11.0%) than of SDH2-RDH1 misidentifications (5.0%).

Table 11. Confusion matrix of the response dot height versus the stimulus dot heights.

		Response Dot Height (RDH)				Total
		DH1	DH2	DH3	DH4	
Stimulus Dot Height (SDH)	DH1	**965 (88.7%)**	120 (11.0%)	1 (0.1%)	2 (0.2%)	1088
	DH2	54 (5.0%)	**1015 (93.3%)**	18 (1.7%)	1 (0.1%)	1088
	DH3	3 (0.3%)	129 (11.9%)	**862 (79.2%)**	94 (8.6%)	1088
	DH4	3 (0.3%)	17 (1.6%)	373 (34.3%)	**695 (63.9%)**	1088
Total		1025	1281	1254	792	4352

The accuracy for the stimulus DH3 evidenced a very significant drop to 79.2% ($p<0.001$), with SDH3-RDH2 misidentifications being somewhat larger (11.9%) than SDH3-RDH4 misidentifications (8.6%, $p<0.05$). A further significant drop ($p<0.001$) was evidenced for the accuracy for the stimulus DH4 (63.9%) with practically all the misidentifications belonging to SDH4-RDH3 (34.3%), which is by far the misidentification that stands out. The above results and the way that the information was revealed through confusion matrices may show an innovative way to the construction of a stimulus models that would have very high accuracy.

4. Discussion and Conclusions

The present study was a follow up of the research conducted by Martos et al. (2021), attempting to go a little bit further. More specifically, the present research aimed to investigate furthermore issues of discriminability and detectability amongst the prevailed four dot heights (i. e. DH1, DH2, DH3 and DH4) which were traced in Martos et al. (2021). The results revealed that the embossed lines had approximately the same success proportion at the two resolutions (10dpi vs 20dpi), whereas squares had significantly greater success proportion at 10dpi than at 20dpi. It seemed that, according to the participants' responses, squares were better than lines at 10dpi but worse than lines at 20dpi. Also, the present study examined issues of haptic perception and accuracy via confusion matrices, and it was found that the accuracy was high especially for DH2 and quite satisfactory for stimulus DH1 (88.7%), however the latter was significantly less accurate than the former (i.e. stimulus DH2). What seems to be extremely important is the fact that confusion matrices may constitute a valid medium to construct stimulus haptic models of very high accuracy when participants who are blind explore embossed material by active touch.

Specialized technological advances, such as embossers coupled with computer generated raised-line tactile graphics have become more commonly used because they are faster and less expensive to produce than the cut-and-paste graphics for thermoform production (Pather, 2014). According to Vieira et al. (2022), embossing is a functional and strategic process which requires input from the end users. In our case the end users are individuals with vision disability. Tools and methods which trace and examine combinations of dot elevation and dot density in order to maximize haptic perception and conceptualization are considered to be very important in inclusive education and in the assistive technology industry as well. As Arroyo et al. (2020) emphasized, all implementations of assistive technology, such as embossers, should be incorporated in educational settings, work environments, and/or home, for this, they need to be simple, noiseless, low-cost,

effective and, easy to maintain/repair. It may be argued that the present study constitutes an input to the construction of a braille embosser prototype in order to meet the above contemporary challenges. Mukhiddinov and Kim (2021), after an extensive literature review of the tactile graphics creation, have ended up with similar outcomes emphasizing that:

> "Researchers working on this topic have not collaborated with blind and visually impaired individuals. Thus, many science-based solutions have remained theoretical without reaching the production stage. Despite the development of Assistive Technology algorithms for many years, methods for creating tactile graphics have mostly used traditional methods. Hence, it is crucial to create custom datasets to develop machine-learning models. Considering the increasing number of blind and visually impaired people in the world, it is essential to expand the range of Assistive Technology that assists them in receiving quality education" (p.24)

It may be argued that the inferences of the present work can influence the redesign of educational material and pedagogy for students with blindness by contributing to the development of a standardized set of symbols or to the development of custom datasets with associated meanings and using them for book annotation or indicating the genre and the very meaning of a graphic or an image, avoiding the pitfall of complex "visually correct" images. Nevertheless, it has to be mentioned that from an educational point of view, research has recognized the significance of detailed and good tactile embossed graphics in blind students' effective education. For example, having reached a good level of tactile embossed graphics through vector graphics format, students with vision disability, on the one hand, can develop very good tactile skills getting a robust understanding about the content of their study, and on the other, can feel independent during the learning process since the assistance from sighted persons will become very limited (Gardner, 2002). A relevant quote from Gardner's work is presented below:

> At some future time, when graphics are presented as properly created Scalable Vector Graphic files, graphical information will be usable by people with print disabilities without any assistance by a sighted person (p.503)

It is evident that IT applications have a significant influence on the transcription of reading materials into alternative formats, such as embossed content, for people with vision disability. In addition, the rapid and specialized advancement of IT information technology in today's modern society is empowering the element of social integration (Argyropoulos & Ravenscroft, 2020; Wei et al., 2022). It is crucial to bear in mind that there are many interrelated issues in education and IT advancements, such as access, new approaches to literacy, privacy (GDPR), commercialization, etc., which have come to the fore bringing big promises but risks as well (Burbules, 2018). What is needed now is better assessment and more targeted interventions in educational settings to support inclusion and social integration effectively.

Limitations of the Study

The number of study participants may be considered small because of the low incidence of vision disability and cost of the experimental process. It may also be considered as one of the limitations of the present study the fact that the execution of the experiments was a time-consuming process.

Data availability

The data that support the findings of this study are available from the committee of the National and Kapodistrian University of Athens, but restrictions apply to the availability of these data, which were used under written consent from the participants for the current study are not publicly available. The data are, however, available from the authors upon reasonable request and with the participants' permission and the committee of the National and Kapodistrian University of Athens.

Declarations of interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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