© Journal of Accessibility and Design for All (JACCES), Volume 14, Issue 2, 2024, ISSN: 2013-7087
https://doi.org/10.17411/jacces.v14i2.470

Experimental study about 3D printed tactile symbols for tactile maps and blind users.

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Received: 2023-05-08 | Accepted: 2024-03-06 | Published: 2024-11-11

Abstract: The aim of this paper is to determine whether certain volumetric tactile symbols (3D) have a level of tactile recognition similar to those of low relief (2D). This study evaluates a sample of 3D volumetric symbols produced by means of 3D printing for use in tactile maps. An experimental test was conducted on a group of 26 totally blind users with different levels of experience in tactile exploration. Part of the experiment involved analysing the percentage of correct answers as a dependent variable and the volume in the shape of the tactile symbols (3D vs. 2D) as the experimental stimulus. The results obtained indicate that volumetric symbols have a high level of tactile recognition. In addition, the study shows some of the possibilities that are emerging in the design of tactile maps and models with the development of new techniques such as 3D Printing (3DP). The inclusion of 3DP within the field of tactile map design is leading to a reassessment of some of the basic principles of tangible graphic design, such as using only two-dimensional graphic elements to produce tangible graphics. Other categories of design elements such as volumetric design elements (3D) can now be included. This opens up a range of possibilities in the field of tactile maps, providing the designer and/or the Mobility Instructor with a wider range of variations in shape from which to design or select a set of symbols for use in tactile maps.

Keywords: visual impairment, blind, inclusive design, 3D printing, tactile map.

1. Introduction

This section describes the objective and the research question, and the background considered in the study. Specifically, the background deals with the design and use of tactile maps, some studies on tactile symbols on relief maps, the importance of tactile experience in the use of this type of maps and some works that have discussed the production of tactile maps or tactile scale models using 3D printing.

1.1. Objective and research question

The objective of this work is to determine whether certain volumetric tactile symbols (3D) have a level of tactile recognition similar to that of low relief ones (2D), these latter being the most commonly employed in the design and use of inclusive tactile maps.

The research question is: Do volumetric symbols extend the range of the current set of tactile symbols?

1.2. Background

Tactile maps, as tangible graphic resources, are a group of devices that rely on relief to convey graphic information. Tactile symbols are usually used within this sort of product and are normally employed with their corresponding legends. These devices help the visually impaired understand features of the environment around them using the sense of touch.

The morphological design elements used when designing tactile maps and symbols for visually impaired users are points, lines, and areas (Amick, Corcoran, Hering, Nousanen, 2002; Bentzen, Marston, 2010; Edman, 1992). As a result of using these design elements, typical of 2D graphics, the tactile symbols that are utilized today in tangible graphics have a low relief, normally translated from an original 2D format.

However, since 3D design came into being, a fourth group of elements, volumetric elements (Wong, 1993) such as basic prisms, could be added. These are commonly used in product design and architecture (Ching, 2007) but are not normally used in the design process of tactile maps, partly due to difficulties stemming from the traditional production systems, i.e., microencapsulation and thermoforming (Rowel, Ungar, 2003).

1.2.1. Design and use of tactile maps

Ergonomics, which is also centred on the study of human interaction with displays, among other things, shows how it is possible to use volumetric shapes to reach good results in terms of tactile discrimination (Sanders, 1993). Anthropometry shows us data for designing this sort of element in harmony with human interaction (Pleasant, Haslegrave, 2006). This is the case, for example, of the controls of an airplane, which should be easily distinguishable and discriminable, among other factors, by touch in order to avoid human errors while pilots are using them (Sanders, 1993; Self, Van Erp, Eriksson, Elliot, 2008).

In the field of tactile maps, it is important to point out some previous studies closely linked to this one, such as that conducted by Sandra Jehoel, Paul T. Sowden, Simon Ungar and Annette Sterr on elevation in tactile maps (Jehoel, Sowden, Ungar, Sterr, 2009). According to the results of this study, the minimum range of elevation for identifying a tactile symbol using the sense of touch is 0.04-0.08 mm. However, the use of tactile contrast, for example height or texture contrasts, is one of the most important recommendations when designing an efficient tactile map (Nolan, Morris, 1971), regardless of the cost involved.

Regarding use, the main beneficiaries of this type of maps are the blind and visually impaired, although with a correct design which includes relief elements, colour contrast, braille code, large text, etc., a tactile symbol or map can generally be understood by almost all users.

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https://doi.org/10.17411/jacces.v14i2.470

Some of the most important factors to be considered when designing this sort of product for the blind are:

Firstly, always adopt simple solutions in the design process (Amick et al., 2002; Edman, 1992), since touch is less sensitive than sight (Schiff, Foulke, 1982).

Secondly, user familiarity with tactile graphics, i.e., previous tactile experience (See Section 1.3.3), because reading a tactile map requires certain skills and knowledge of exploration strategies (Lillo-Jover, 2008; Rowell, Ungar, 2003).

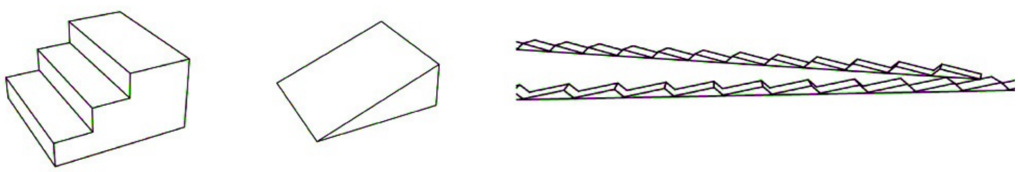
Finally, it is important to mention the role played by haptic memory in totally blind users when it comes to exploring tangible graphics (Millar, Al-Attar, 2003). This sort of memory works sequentially and requires the use of design elements that are easy to recognize and memorize through touch. In contrast, visual memory is simultaneous.

1.2.2. Tactile symbols on relief maps

The symbology of tactile maps has been widely studied from disciplines such as Cartography (Perkins, 2002; Rener, 1993; Rowell, Ungar, 2003). The factors of recognition, legibility, memorizing and discrimination of symbols have also been examined in a number of studies in order to verify the usability of these types of products and their efficient use for maps (Berlá, 1982; Gill, James, 1972; Gual, Puyuelo, Lloveras, 2014; Lambert, Lederman, 1989). One of the criteria for accepting a symbol as efficient for tactile recognition is that no symbol with an error rate of more than 5% should be recommended for use on tactile maps (Amick et al., 2002).

Volumetric symbology has not received much attention in the literature, although the work of Don McCallum, Simon Ungar and Sandra Jehoel should be mentioned. In this work, the authors analysed different kinds of directional symbols with a certain amount of relief. The results in this case were ambiguous, since the use of some 3D shapes yielded a modest increase in the level of agreement of 'up' for symbols intended to show stairs (McCallun, Ungar, Jehoel, 2006). This last study was the starting point for the current one. In addition to the stairs symbol, represented as a miniature stairway with three steps, this study also included a group of volumetric symbols with a variation in height or cross-sectional profile, such as ramps or lines with a saw-tooth surface profile (Figure 1), which allows users to perceive a feeling of roughness or smoothness depending on the direction of the line traced by the finger. In this study this direction was detected quite clearly, although there was no consistent interpretation by all participants. However, users could be trained or instructed to interpret the directional information in a specific way (McCallun et al., 2006).

Figure 1. Images of some of the tactile symbols tested in the study by McCallum, Ungar and Jehoel. From left to right, the miniature stair symbol, the ramp, and the saw-tooth line profile.



In addition, standardization of tactile symbols is a goal sought by all those involved, although this is proving to be a complicated issue given the difficulty in reaching efficient agreements.

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Notable efforts have been made, however, such as those proposed at the International Conference on Mobility Maps in Nottingham in 1972 (Perkins, 2002; James, 1982).

Nowadays the selection of the symbol and its relationship with the content of a tactile map depends on the criteria of the designers, who have access to a wide variety of design recommendations supported by empirical evidence (ADON, 1986; Edman, 1992; Gill, James, 1972; Goodrick, 1987; Hinton, 1996; Rener, 1993). Thus, the designer's role is to select the appropriate symbols, which are easily recognizable and distinguishable to the touch, in order to represent specific meanings.

1.2.3. Tactile experience

As it was mentioned above, it is important to mention the previous tactile experience of each user for reading efficiently a tactile phenomenon, this familiarity depends fundamentally on the training received by the people using the map (Lillo-Jover, 2008; Rowell, Ungar 2003). For example, using two hands to explore a tactile map allows blind users to recognize the information offered by a tactile product more accurately and effectively than using only one, as shown by Perkins and Gardiner in their study (Perkins, Gardiner, 2003).

1.2.4. 3D Printing (3DP) to produce tactile maps and models

Traditionally, studies of symbols have focused on the possibilities of microencapsulated manufacturing systems and/or thermoforming (Rowell, Ungar, 2003), while the new Additive Manufacturing (also known as 3D Printing) techniques offer a wide range of possibilities to address this phenomenon (Kordon, 2002). These last techniques allow us to design and produce a new type of tactile symbol by using CAD tools and the geometric possibilities offered by them. Nevertheless, we consider this aspect to be poorly developed due to the technical limitations of the traditional manufacturing processes of thermoforming and microencapsulation, which are not able to reproduce some of the more complex geometries.

The novelty of this work lies in the use of an empirical study to test the feasibility of integrating a new category of symbols, namely volumetric tactile symbols (3D), into the current ones, whose shape is associated with three main design elements – points, lines, and areas – and are therefore characterized by a low relief format.

3D printing (3DP) is used to manufacture volumetric symbols, since it can produce more complex geometries, provide more edge resolution in the shapes than can be achieved with traditional methods (Chua, Leong, Lim, 2003) and can also include colour in the final model. This technique is not yet fully integrated as a tool for the production of evaluation models, prototypes, or even as a final product in the field of tactile map design, although some studies support an increasingly common use of the technique in the design of maps and its possibilities for tactile models. For example, researchers at Palacky University in Olomouc (Czech Republic) have analysed the use of 3DP technology for producing tactile maps with Geographic Information System (GIS) to improve the understanding of spatial orientation and movement of blind persons (Voženílek, Kozáková, Šťávová, Ludíková, Růžičková, Finková, 2009). In addition, the study by Gual was focused on improving urban orientation for the blind, using tactile maps based on 3DP to improve the understanding of some urban landmarks (Gual, Puyuelo, Lloveras, 2011).

Moreover, the production of tactile scale-models through this system of manufacturing seems to be an appropriate way to manufacture this sort of device for the sense of touch. Celani and Milan, from the State University of Campinas in Brazil, obtained good results in their experiments with tactile scale-models and blind users. The scale-models were very helpful for spatial orientation, but also highlighted the importance of other variables in improving human interaction with these products. These factors were the type of blindness, previous knowledge of the space, and previous experience with tactile maps and scale-models (Celani, Milan, 2007). Finally, it is worth noting the study by Voigt and Martens, from Vienna University of Technology in Austria, who worked with 3D printing techniques to produce architectural scale-models to help blind users to recognize environmental features more efficiently. Among other aspects the models improved the cognitive maps for blind and partially sighted people of the architectural phenomena in terms of better recognize spatial elements and their relationships, subspaces, and possible spatial sequences (Voigt, Martens, 2006).

2. Methodology

The following is a description of the methodology of the study, mainly the main characteristics of the sample used in this study, the tactile symbols selected, the material and its design and production characteristics, and the tasks and protocol of the experimental part of the work. The methodology used was experimental and the data obtained were quantitative and it was analysed from an inferential statistical perspective.

2.1. Subjects

The experimental test was conducted on a group of 26 totally blind users (13 congenitally blind and 13 adventitiously blind) with ages ranging between 26 and 80 (Table 1). The subjects participated voluntarily in the experiment and provided written informed consent.

Table 1: Segmented profiles of the subjects in the sample used in the experiment.

Totally blind	Mean age	Expert users	Some experienced users	No experienced users
26	51.19 (SD 12.56)	13	7	6

Regarding the tactile experience factor (see Section 1.2.3), that is, the degree of knowledge of techniques or strategies of haptic reading of any type of tangible graphic and braille code, the sample contained:

- 13 expert users; these were users who regularly used tactile graphics and braille code in their daily life or job, an example of which are those who had received special training in the past to learn how to explore a tangible graphic effectively. They were subjects such as educators of blind children who need to explain, for example, graphical concepts in subjects like maths or geography to their blind students in their classes, as well as passionate lovers of the adapted cultural exhibitions who were used to exploring relief materials when they visit these cultural events.

- 7 users with some experience (usually of reading braille, but only occasionally tactile graphics).
- 6 users with no experience of tactile devices, that is, users whose first experience with tactile devices was in the above-mentioned experiment, and they did not know or use braille code.

Figure 2. Image of the four target symbols. From left to right: a. *Circumference "O" 2D stimulus; b. Arrowhead 2D stimulus; c. Pyramid 3D stimulus; d. Ring 3D stimulus.*

a b c d

Table 2. Dimensions of the four target symbols.

Symbol	Circumference "O" 2D stimulus	Arrowhead 2D stimulus	Pyramid 3D stimulus	Ring 3D stimulus
Exterior diameter	7.0 mm	-	-	6.5 mm
Interior diameter	5.0 mm	-	-	5.6 mm
Height	2.0 mm	1.2 mm	7.5 mm	6.0 mm
Inner height	1.0 mm	-	-	-
Angle	-	70º	-	-
Length of outer lines	-	7.0 mm	-	-
Line thickness	-	2.0 mm	-	-
Square base	-	-	5.5 x 5.5 mm	-
Ring 3D stimulus	-	-	-	-
Depth	-	-	-	2.5 mm

2.2. Target symbols

Four "target" symbols were studied and evaluated, two of them with a two-dimensional attribute relief (2D), like extruded surfaces, and the other two volumetric (3D), hereafter referred to as circumference "O" (2D), arrowhead "V" (2D), pyramid (3D) and ring (3D) (Figure 2, Table 2). These symbols could be used, for example, as specific points or even directional symbols on a tactile map. The reason for selecting these symbols was, on the one hand, that the symbols chosen in 2D (circumference “O” and arrowhead “V”) were two of the most commonly used on tactile maps and mentioned in several studies (Bentzen, Marston, 2010; Edman, 1992; Goodrick, 1987; Jehoel, McCallum, Rowell, Ungar, 2005; Lockwood, 1995; Meihoefer, 1969; NMCA, 1985; Nolan, Morris, 1971; Rener, 1993), generally with good results. On the other hand, the volumetric symbols (3D: pyramid and ring) were selected on the basis of previous studies. In these pilot studies, the subjects in an experiment were stimulated with volumetric (3D) and 2D shapes and had to recognize a set of 80 tactile symbols. The results of this experiment showed that the pyramid and ring tactile symbols obtained a high level of tactile recognition (Gual, Puyuelo, Lloveras, 2012), which created good expectations for further studies.

2.3. Material

The main material used in this study was a set of eight test cards distributed with other tactile symbols arranged in a table of 4 columns by 5 rows (Figures 3, 4).

All material used was produced using polychrome 3DP equipment (Z-Corb 510, CMYK and 24 bits colour).

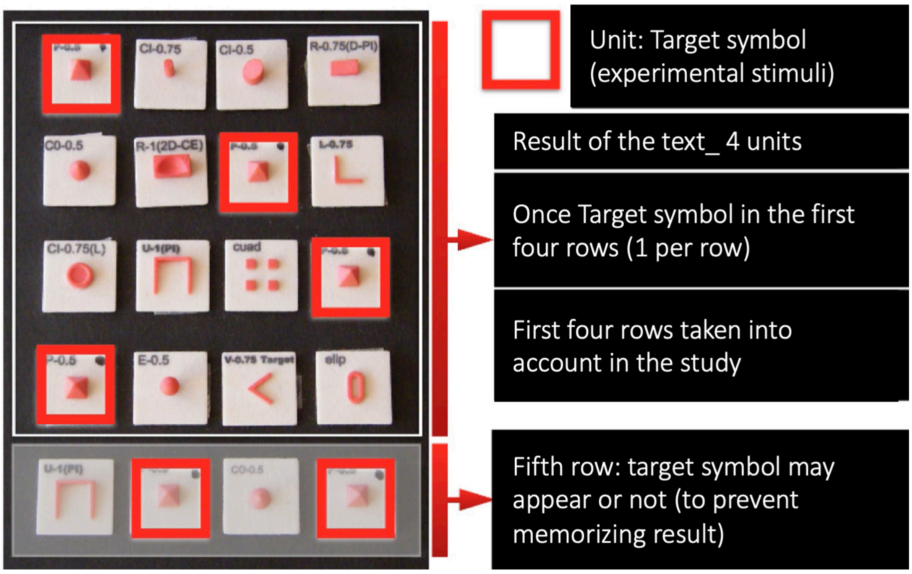
Prior to the experiment, an introductory test card was carried out in order to teach the tasks to each user.

On each test card there are different types of symbols (Figure 4), including the target symbols (experimental stimuli) that are the object of this study.

These are randomly distributed, but always appear once in the first four rows, so that there are always four target symbols in the first four rows. In the fifth and last row more target symbols may or may not be shown randomly, following a similar method to that used by Sandra Jehoel, Simon Ungar, Don McCallum and Jonathan Rowell for the evaluation of substrates of tactile maps (Jehoel et al., 2005). In this way, the fifth row prevents participants from memorizing the number of symbols per test, i.e. four. Thus, for this study, only the results of the first four rows were considered (Figure 4).

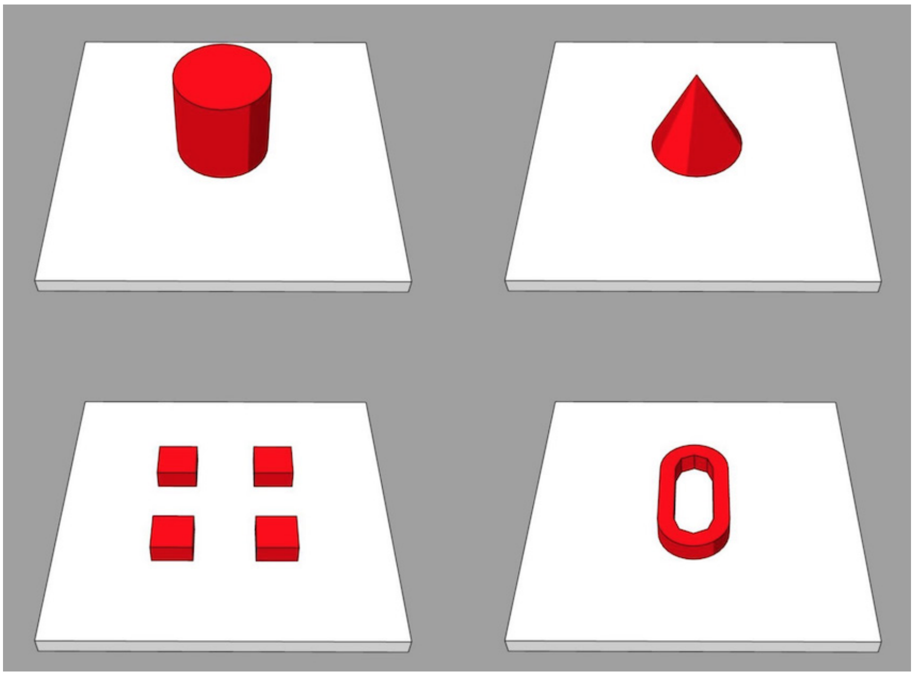
Figure 3. Subject from the experiment doing a task while using one of the eight cards of the study.

Figure 4. Sample of one of the eight test cards used in the study.



Other symbols with different characteristics such as ellipses, squares, "U-shapes", cones, cylinders, etc. (Figure 5) were used on the test card¸ randomly distributed along with the target symbols. Some of these symbols have been designed taking into account 3D attributes in the shape and others were selected according to a clear representation of 2D attributes.

Figure 5: Image of some of the symbols used along with target symbols on the test card. The symbols at the top follow the shape of basic prisms (3D attributes) such as a cylinder or cone, while the symbols below are two extruded surfaces that follow 2D shapes with relief. Those in the first group have a greater height contrast than the ones in the second.



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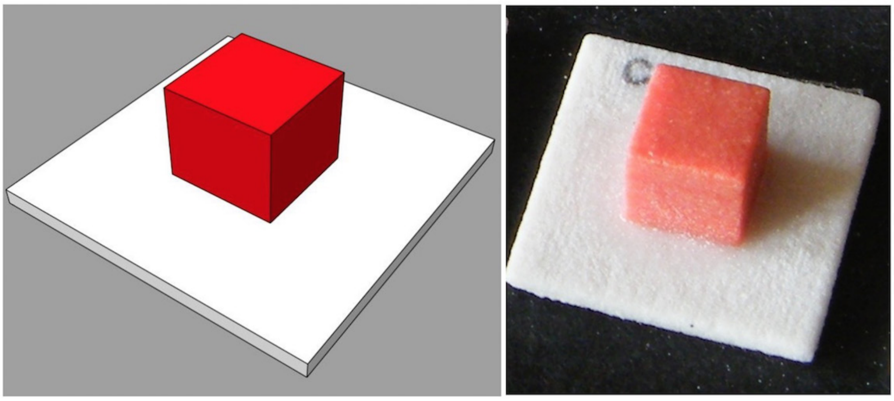
https://doi.org/10.17411/jacces.v14i2.470

Figure 6: Image of the geometry of a cube designed by means of CAD techniques (left) and the same cube printed by means of 3DP (right). This simple shape could be a good design element to be recognized by touch if given the correct size because, among other reasons, it is simple.



2.4. Design and production of the symbols evaluated

To produce these types of symbols, basically two steps have to be followed. The first is to be able to use CAD software, which helps the designer to conceptualize the virtual-digital shape (geometry) in 3D in the form of a closed polysurface (solid). Conceptual design programs such as Blender, Sketch up, Rhinoceros, AutoCAD or Inspire Studio could be used to model the 3D shapes and, for experts, advanced CAD software like Catia or Solidworks can also be used. These applications always have a specific command for building basic prisms. Once the geometry has been modelled in any CAD file format, it must be exported (within the CAD program) to the STL file format in order to obtain a new file with the same type of solid but now polygonised (i.e. having a closed polysurface). In this stage, the CAD program normally prompts the user as to the different options available with which to adjust the final geometry; this may involve, for example, specifying the number of polygons, but usually the default options are sufficient. In any case, STL is a very common file format supported by several CAD programs and 3D printers, and most of these CAD programs and 3D printers are quite intuitive to use.

The second step is the physical production of the 3D virtual geometry. It is necessary to use some of the multiple 3D Printing techniques for this, including Fused Deposition Modelling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS) and 3D Printing (3DP-Binder Jetting). In the case of this project, the researchers used 3DP-Binder Jetting, which produces physical models using fine dust combined with small droplets of glue to produce polychrome pieces. The reason for using this technique is due to the possibility of including in the final design a wide range of colours (CMYK colours), which makes possible the production of inclusive tactile maps for people with low vision. In addition, using this technique, some complex geometries, such as the ring in Table 2 used in this study, do not require support material to be removed in a subsequent post-processing stage, which facilitates their production. Finally, the excess material can be reused again, reducing waste, and thus extending its life cycle.

In any event, using this method allows 3D shapes to be produced almost without limitation, and it can be applied to several areas such as this case, i.e., to propose different ways to manufacture tactile symbols, maps, or tangible graphs. As mentioned earlier, the 3D symbols selected in this experiment are only a proposal of the researchers based on previous studies (Gual, et al., 2011; Gual et al., 2012; Gual et al., 2014), but the use of CAD software and 3DP equipment makes it possible to design any geometry capable of being recognized by the sense of touch (Figure 6).

2.5. Tasks, procedure and description of the variables and experimental stimulus

In this study, the different cards containing the different tests (a total of eight test cards) were shown one by one, randomly, and sequentially to each participant until the eight test cards had been completed. The task to be conducted consisted in the recognition of a target symbol through the sense of touch, its memorization and subsequent localization on the relevant test card. Users were asked to count the number of target symbols recognized through the sense of touch on each of the test cards and to feel the symbols row by row using their fingers, going from left to right and from top to bottom, as if they were reading Braille. Before beginning the experiment with the eight test cards, the researcher used a draft sample, not employed during the experiment, so the participants could practise. Once the participants understood the tasks to be conducted, the complete experiment of eight test cards was carried out. So, participants had to identify the target symbols and explain them orally to the researchers when they found them; the experimenters recorded the correct or wrong answers (see Section 2.3. for further information about the structure of the test cards employed during the experiment; Figure 4). The experiment was recorded using digital video and the statistics were analysed using statistics data software (IBM SPSS Statistics 21 and G*Power 3.1.2).

The dependent variable to be measured was the correct answer rate, the units chosen to do this being the percentage of correct answers given by the subjects during the experiment. In addition, it was measured the average number of errors committed per participant, according to his previous tactile experience.

The types of error that can occur in recognizing tactile symbols are:

- Error in reading: it was not recognized although it was touched.
- False hits: it was confused with other symbols, because of a similar shape or other causes.

The experimental stimulus taken into account was the volume (3D vs. 2D) of the shape of the tactile symbols. Thus, in this article the results are shown as follows:

- First, the percentage of correct answers for target symbols: low relief (“V” (2D) or “O” (2D)) and volumetric symbols in 3D (ring and pyramid; see Section 3.1, Table 3). Also, it was measured the type of errors per user (See Section 2.5).
- Second, the differences between the use of the symbols depending on the previous experience of participants with tactile maps and haptic reading strategies (see Section 3.2, Table 4).

3. Results

The following section shows the results obtained in the experiment carried out from basically two points of view, i.e., on the one hand, from the data collected from the dependent variable (2D vs. 3D volume) and, on the other hand, from the previous experience of the participating subjects.

These are original data from this work, some of which have a certain statistical significance.

3.1. Depending on the experimental stimulus: volume (3D vs. 2D) of the shape of the tactile symbol

As can be seen in Table 3, data indicate that, in the dependent variable, the highest percentage of correct answers was for a volumetric symbol (pyramid, 99,03 %), one with 3D attributes, while the symbol with the lowest percentage of correct answers was the "V" or arrowhead (2D, 93,26%).

The first point to note, in this analysis, is that all symbols were read fairly well, that is, with a high level of correct answers (more than 90%). However, under a criterion such as that put forward by Nancy S. Amick, Jane M. Corcoran, Sally Hering, Diane Nousanen (Amick et al., 2002), which assumes that if the symbols are correctly perceived in 95% of cases, they can be used in the design of a tactile map, only two of the symbols analysed, the pyramid (3D, 99,03%) and the "O" (2D, 96,15%), can be guaranteed to function properly on a tactile map. The Friedman test shows that these data are statistically significant ($N = 208$; p value $= 0.017$; $\alpha = 0.05$).

On performing an in-depth exploration of the data obtained in the study, it is possible to appreciate a high level of tactile recognition for the pyramid symbol: this new volumetric symbol obtained a rate of almost 100% of correct answers in the experiment.

Table 3. Percentage of correct answers depending on the symbol analysed.

Name of symbol	Type of stimulus	N*	Frequency of correct answers	Percentage
V	2D	208	194	93.26%
O	2D	208	200	96.15%
PYRAMID	3D	208	206	99.03%
RING	3D	208	195	93.80%

**N = 26 participants x 4 symbols/card x 2 cards/symbol=208.*

Finally, if the dependent variables are analysed based on the type of errors per user (see Section 2.5), i.e., errors in reading and false hits, comparing 2D vs. 3D stimuli:

- The average number of errors in reading tactile symbols in 3D was 0.73 (SD 0.96), while in 2D the average was 0.81 (SD 0.98).
- The average number of false hits for tactile symbols in 3D was 0.11 (SD 0.32), while in 2D the average was 0.38 (SD 0.80).

Although both differences between groups of symbols show better results in tactile recognition for 3D symbols, these differences are not statistically significant. So, the ratios of errors indicate a similar pattern between different types of volumes (3D vs. 2D) of the shape of the tactile symbols (experimental stimulus).

Table 4. Number of correct answers, total errors and percentage of correct answers depending on the type of symbols and the level of experience of the participants.

Type of symbol	Type of stimulus	No experience	Some experience	Experienced
V Correct Answers	2D	29	65	100
V Errors	2D	3	7	4
V, Percentage of correct answers	2D	89.65%	89.23%	96.00%
O Correct Answers	2D	32	68	100
O Errors	2D	0	4	4
O, Percentage of correct answers	2D	100%	94.12%	96.00%
Pyramid Correct Answers	3D	30	72	104
Pyramid Errors	3D	2	0	0
Pyramid, Percentage of correct answers	3D	93.33%	100%	100%
Ring Correct Answers	3D	29	70	96
Ring Errors	3D	3	2	8
Ring, Percentage of correct answers	3D	89.65%	98.57%	91.66%

3.2. Depending on the participants' previous experience

The data collected according to the type of symbol and the previous experience of the users (Table 4) show that experienced and some experienced participants, surprisingly, made no mistakes during the experiment when they performed the tasks with the Pyramid symbol. In addition, experienced participants perceived the “O” and “V” symbol with a 96 % of correct answers and less than 95% when they tested the Ring symbol (91,66%).

On the other hand, the seven subjects with only some experience using tactile maps obtained a 98,57% of correct answers when they performed the tasks with the Ring symbol, and they obtained a percentage of correct answers of 89,23% for “V” symbol and 94,12% for “O” symbol.

Additionally, the participants of the experiment with no experience made no mistakes using the “O” symbol, while the rest of the symbols (“V”, Pyramid and Ring) were perceived with a range of correct answers below 95%.

The difference of correct answers within the group of 3D stimuli is statistically significant (p value = 0.04) and there were no significant differences between Errors in Reading and False Hits attending the profile of users.

Summarizing the best results of the experiment under the point of view of each symbols V, O and Pyramid symbols were well distinguished for experienced users (96%, 96% and 100%

of corrects answers), Pyramid and Ring symbols were easily distinguished when users had some experience (100% and 98,57 % of correct answers), and "O" symbol was perfectly perceived by no experienced subjects (100% of correct answers).

4. Discussion and Implications

In the following, the data are discussed from an analytical and critical perspective, trying to link the aspects addressed in the introduction, mainly with the literature mentioned in this section.

Finally, some considerations regarding the production of this type of tactile symbols are also described and discussed in this section.

4.1. Experiment

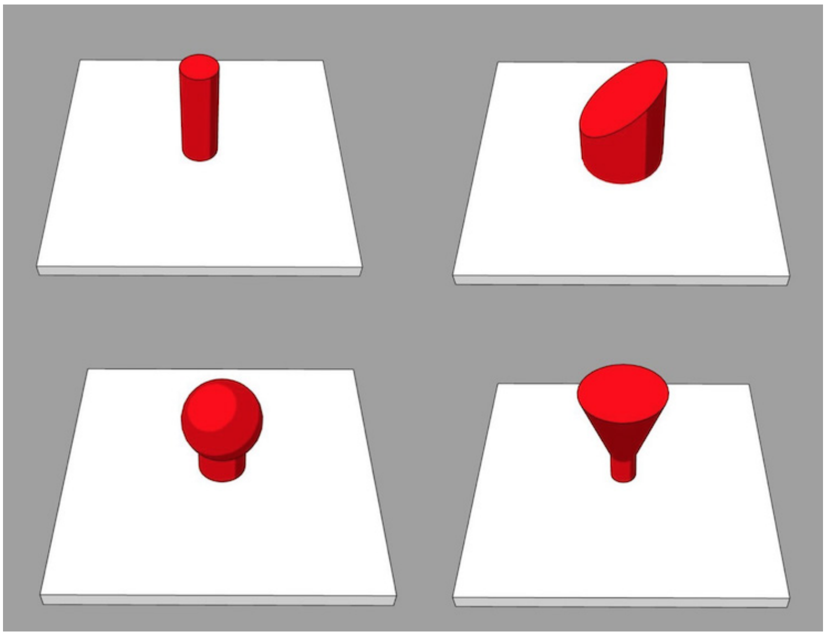
In general, taking into account the percentage of correct answers (dependent variable) for symbols in 3D compared with those in 2D, we can state that volumetric tactile symbols (3D), and more specifically the ones studied here (pyramid and ring), seem good elements to extend the range of the current set of tactile symbols, specifically Pyramid symbol. This last type of symbol considers only two-dimensional design elements. In contrast, those proposed here in 3D consider volumetric design elements (Ching, 2007; Wong, 1993).

Of the 4 symbols evaluated, the pyramid (3D) and "O" (2D) display a very high rate of success in reading, which shows that they could be used on tactile maps following the criteria proposed by Amick and colleagues (Amick et al. 2002). In addition, following the results of the group of 3D symbols, it seems reasonable to trust in this sort of elements to design a tactile map or simply a tactile device, because the rate of correct answers in this experiment was higher than that obtained in the group of 2D symbols which have been mentioned or used with good results in several studies (Bentzen, Marston, 2010; Edman, 1992; Goodrick, 1987; Jehoel et al., 2005; Lockwood, 1995; NMCA, 1985; Nolan, Morris, 1971; Rener, 1993) and there was a similar pattern of tactile recognition during the experiment between the different stimuli.

On the other hand, following the results of this experiment, the group of blind users with some experience regarding tactile exploration could benefit from the inclusion, in tactile graphics, of this type of volumetric shapes because they obtained good results when they explored the Pyramid and Ring symbols. Under the perspective of experienced users, in this experiment, they obtained a good range of results testing the tactile cards except for the Ring symbol, which it was perceived with a lower percentage of correct answers than the rest of the analysed symbols.

Probably, users with some experience have a minimum level of haptic exploration to learn or memorize (haptic memory) quickly, by the sense of touch, a different type of tactile elements that requires new tactile techniques to be recognized by fingers because they present 3D attributes. Meanwhile, experts' users, in our opinion, are influenced by their previous learned strategies to read a common tactile map in relief (2D - 2,5D). For users non experts, the process of learning any of the two types of stimuli, 3D or 2D, should not present difference at first, although they obtained no mistakes when they explored the "O" symbol, which is very simple and suitable for the sense of touch.

Figure 7. Some volumetric symbols for possible use as symbols in tactile maps. They are configured from the use of basic prisms (3D).



The novelty of this study lies in the positive results for the pyramid and ring symbols (3D), which were surprisingly at the same level as a symbol as simple and consolidated as "O" (Lockwood, 1995; Meihoefer, 1969). At this point it is especially important to highlight the good results obtained using the pyramid symbol. Therefore, it is worthwhile continuing this line of research – already initiated by Don McCallum and his colleagues – with the analysis of some symbols with volumetric attributes (James, 1992) (Figure 1). This opens the door to the study of other 3D symbol shapes (Figures 6 and 7), such as spheres, cones, or regular prisms in order to discern, among other factors, the degree of recognition, tactile discrimination, texture and size to be used on tactile maps.

The selection of a group of symbols that are recognizable to the touch and distinguishable from each other is one of the critical points in the design of tactile maps. Including 3D symbols in the production of tactile maps or any tangible graphic could improve the usability of these devices, thus benefiting Orientation and Mobility Instructors, educators, rehabilitation professionals and others in the field, because they would be able to combine graphic design elements (2D elements) with volumetric elements to design tangible graphics. The results of the experiment presented here open up the possibility of using distinguishable 3D elements for the sense of touch for any conceivable use, such as employing volumetric symbols (with the greatest elevation) to indicate specific elements on the maps that require quick and easy localization and positioning using a significant abstract shape. Example uses include the case of some of the information items that designers tend to employ in the conceptualization of tactile maps to be understood by end users: information desk, “you are here” or lifts on plans of the inside of buildings; traffic lights or telephone booths on urban maps; capitals of countries, cities and villages in geographic and themed maps; and vertex, centre points or cross points in tactile graphics for teaching maths or any other tactile graphic information for blind students.

In accordance with the results of this study, 3D symbols such as the pyramid or ring can be introduced as tactile representation elements because they are clearly recognizable and are seldom confused with symbols in low relief (2D), thus slightly improving the usability of these devices.

4.2. The 3D printing (3DP) considerations and implications

Producing a 3D symbol is not really a problem with production systems such as 3DP, and even certain symbols like the pyramid, among others, could also be reproduced in thermoforming (Figure 8). To make a 3D printed pyramid like the one employed in this experiment (Figure 9), firstly its geometry was modelled using Rhinoceros CAD software (height=7.5 mm; sides of the square base=5.5 mm) and NURBS (Non-Uniform Rational B-Splines) surfaces. This program, like most similar applications, has a specific command in its Solid menu to (digitally) make pyramids or any other basic prism easily. Once the pyramid had been modelled it was exported to the STL file format and sent directly to the 3D Printer (see also Section 2.3.), which finally produced the model in a few minutes. The precision of this technique is greater than competing systems, and once the model has been designed its flexibility allows mapmakers to quickly introduce changes into the geometry in order to reprint a new version, which is very interesting in the evaluation stages.

Figure 8. A draft of pyramid symbols (3D) produced with thermoforming.

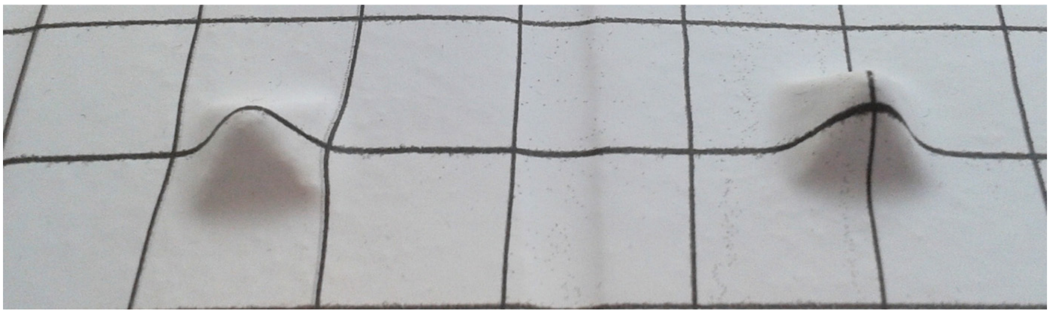
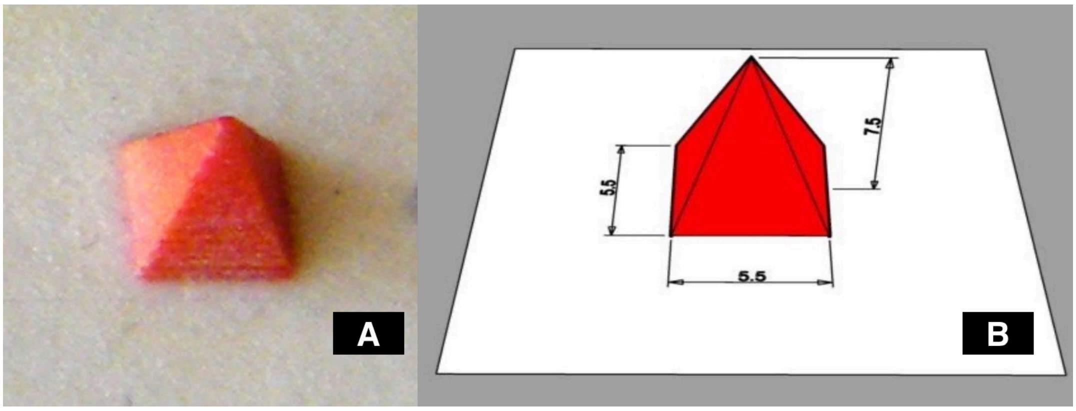


Figure 9. The pyramid symbol used in the experiment. The edges between surfaces show greater precision in the geometry of the shape than the thermoforming sample shown in the previous figure (A). Measurements of the pyramid tactile symbol (B).



Thus, 3D Printing has been used in several contexts with successful results, such as in the area of tactile maps and scale-models for the blind (Voženílek et al., 2009). This fact should encourage researchers to follow this thread of investigation because the use of 3DP makes it possible to design tactile maps that were previously unthinkable with other systems of production such as thermoform or microencapsulation (Rowell, Ungar, 2003). Examples of such maps include tactile maps with volumetric attributes that are easy to recognize by touch, thereby improving their usability. In any case, further research for evaluating 3D tactile symbols should be done, following a similar methodology, but with a bigger sample of subjects to increase data quality.

5. Conclusions

In view of the results and the analysis of the data obtained in this experiment, on one hand, 3D symbols could be incorporated into the set of symbols in 2D because they have, at least, similar results in terms of tactile recognition and discrimination, and some symbols such as the pyramid even seem to obtain better ratios than the 2D ones used today.

On the other hand, the inclusion of 3D tactile symbols in tactile maps seems that can benefit those blind users who have little experience and they do not have a strong influence from the common strategies of tactile exploration as experts' users who have mechanical gestures learned to explore a typical tactile map.

Thus, the researchers consider that 3D symbols could be good elements of design for extending the range of the current set of symbols, in this way answering the research question proposed in this work. This may make it necessary to reconsider the theoretical framework so as to think in both volumetric and two-dimensional terms when designing elements for tactile maps.

The idea of evaluating this type of symbols arises in parallel with the incorporation into the state of the art of new manufacturing process capable to produce three dimensional shapes quickly and easily. This work shows a first approach to how to take advantage of the tactile attributes of three-dimensional shapes to use them in tactile maps. Although some research has been conducted in this idea (McCallum et al., 2006), the nature of the volumetric attributes for the tactile sense, and for designing tactile symbols for improving the use of tactile maps, has not been studied sufficiently.

In any case, using 3DP for tactile maps seems a good choice given the possibilities for reproducing, among other things, colour for low-vision users and accurate complex geometries suitable for tactile perception. Although it must be recognized that the rapid prototyping techniques Fused Deposition Modeling (FDM) or the equivalent of Fused Filament Fabrication (FFM) are currently more popular, and they have lower cost than the one used in this study.

The possibilities of 3D Printing techniques applied to tactile maps for blind users should be more exploited by the community of researchers, and experiments like the one presented here are only a first step to show how we can improve these devices through the new production techniques of Additive Manufacturing. Some studies using 3D symbols applied to real tactile maps (3D printed) support this thesis with encouraging results and implications (Gual et al., 2015).

Finally, this study opens a door to the design of and research into new volumetric symbols with a size, texture and form suited to the sense of touch for use on tactile maps.

6. Acknowledgments

The work reported here is a part of a research project supported by the public institution Generalitat Valenciana (Spain) under grant GV/2021/084.

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How to cite this article

Gual Ortí, J., Puyuelo Cazorla, M., Lloveras Macia, J., Amat Cozar, J. (2024). Experimental study about 3D printed tactile symbols for tactile maps and blind users. Journal of Accessibility and Design for All, 14(2), 16-34. https://doi.org/10.17411/jacces.v14i2.470

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