Three-dimensional tactile symbols produced by 3D Printing: Improving the process of memorizing a tactile map key

Jaume Gual[AQ1]
Universitat Jaume I, Spain

Marina Puyuelo
Universitat Politècnica de València, Spain

Joaquim Lloveras
Universitat Politècnica de Catalunya, Spain

Abstract[AQ2]

The aim of this article is to determine whether the process of memorizing a tactile map key, or legend, can be improved by including three-dimensional (3D) symbols produced by means of 3D Printing. The method used in this study involved asking a group of 20 volunteers with different profiles to memorize eight tactile symbols from two keys, each of which had different characteristics: Key 2 included 3D tactile symbols and Key 1 had only two-dimensional (2D) tactile symbols. Results show statistically significant differences between the two keys. Use of Key 2 yielded a 48.72% reduction in the number of errors compared to Key 1 ($N = 20$, p-value = .014). These data show that combining 3D with flat relief symbols (2D) improves the process of memorizing a tactile key because the 3D attributes can be distinguished from the 2D features by touch. For practitioners, this article provides data about the possibilities of 3D Printing applied to tactile maps, keys, and symbols.

Keywords

Tactile key, tactile map, tactile symbol, visual impairment

Objective

The aim of this article is to analyse whether including three-dimensional (3D) symbols in the key of a tactile map enables users to improve their ability to memorize it. With this objective in mind, the researchers compared two different legends: one in which the symbols were arranged in a

Corresponding author: [AQ3]

Jaume Gual, Departamento de Ingeniería de Sistemas Industriales y Diseño, Universitat Jaume I, Campus Riu Sec s/n, 12071, Castelló, Spain.
Email: jgual@esid.uji.es

specific way by grouping them separately according to whether they displayed 3D or 2D tactile attributes, while the other key used only 2D symbols positioned at random.

In addition, this study also intends to analyse the data obtained about different user profiles and haptic reading strategies employed in the process of memorizing keys, as well as the possibilities offered by 3D Printing for producing tactile maps and symbols for the visually impaired.

Introduction

In this study, a new type of tactile symbols, 3D symbols, have been tested to determine how easy or difficult it is to memorize them. In keeping with the objective of this study, in this introduction, four fundamental pillars should be noted: (1) the importance of the activity of memorization, haptic memory, and short-term memory for blind users (Millar & Al-Attar, 2003) as a means to store the information provided by symbols; (2) the role of previous experience with tangible graphics (Graven, 2003) in exploring a tactile device efficiently; (3) the possibility of using the Gestalt principle of grouping by shape similarity (Todorovic, 2008) as a strategy to improve the amount of data stored through touch; and (4) the possibilities of 3D Printing as a new system to produce tactile maps and tangible symbols based on 3D shapes such as basic prisms, that is, using 3D design criteria.

Tactile maps, keys, and symbols: their use and design requirements

Tactile maps are commonly used to teach graphic concepts to visually impaired persons. In fact, Orientation and Mobility Instructors (OMI) commonly use relief mobility maps in mobility training lessons to improve the ability of the visually impaired to orientate themselves because this sort of tactile device allows blind users to build their own cognitive map of an environment or even to consult them in situ while they are following an itinerary.

In addition, this sort of maps contain different types of symbols (Image 1), as occurs with visual ones, but in the case of tactile maps these symbols are produced in relief so that they can be perceived by the sense of touch and stored in memory. The standardization of tactile symbols is a long-standing demand claimed by stakeholders, although unfortunately today there are still no international standards, even after holding a number of meetings such as in the First European Symposium on Tactual Town Maps for the Blind in Brussels in 1983 (European Symposium on Tactual Town Maps for the Blind, 1983).

It is also worth noting that these symbols are normally contextualized in a key as a list of items (symbols, abbreviations, etc.) related to certain features on the map with their corresponding explanation. According to Rowell and Ungar's (2005) studies on users' preferences regarding tactile maps, the key is the most important of the complementary elements accompanying such maps.

A user of a tactile map can normally memorize the symbols of a key before using it, but s/he may also need to refer back to it while actually exploring a map. However, anticipation is essential for a visually impaired person (Madrazo & Solorzano, 2003) because it improves interaction with the map, so less time is needed to read and understand it. Therefore, to improve anticipation it is necessary to enhance the process of memorizing the elements of the map, especially the key.
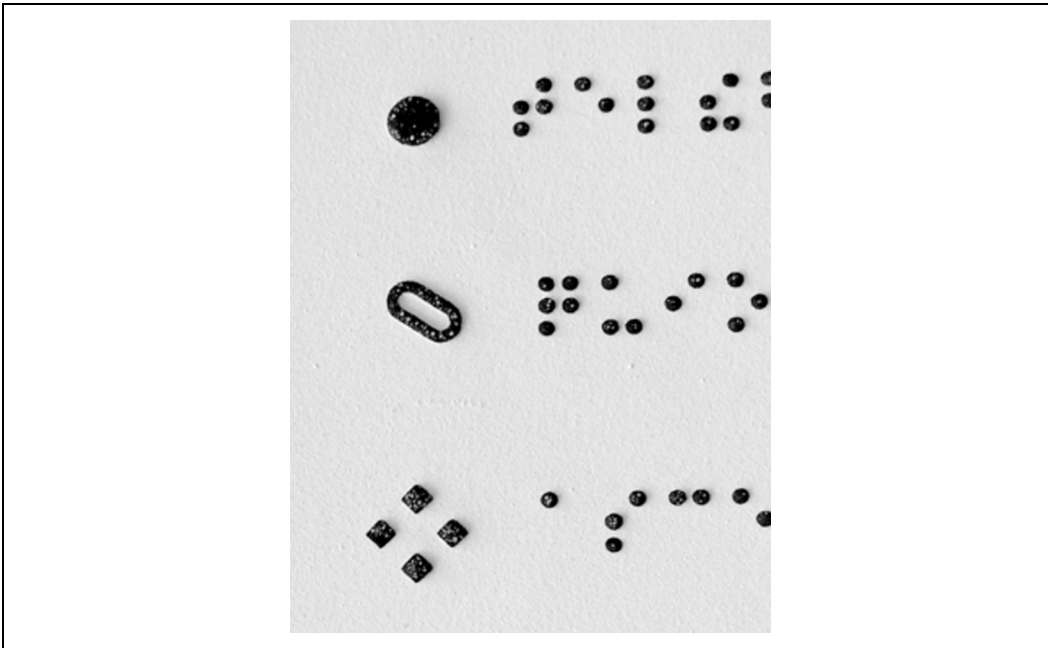
Image 1. Image with three-point symbols (2D) currently used in tactile keys (Edman, 1992) and their explanation in Braille. These symbols were produced using microencapsulation, the result being a shape with a flat relief and an elevation of around 0.5 mm.

Consequently, as some manuals and guides on tangible graphics mention with regard to the design requirements, the tactile symbols of a key should be clearly distinguishable from each other in order to make them easier to memorize (Edman, 1992; Gardiner & Perkins, 2002; Rowell & Ungar, 2003b). According to William Schiff, some tactile factors that can facilitate this process of discriminating between symbols have to do with the size, shape, and contrast attributes. Thus, if we wish to design a comprehensive tactile key, we must use symbols of a suitable size, simple shapes, and contrasted symbols, that is, symbols with differentiable features in terms of height, texture, or the concavity/convexity of the relief (Gardiner & Perkins, 2002; Nolan & Morris, 1971).

Some considerations about memory and perceptual organization

Hence, as we have observed, using a tactile map key involves the use of 'short-term working memory' that allows users to store a number of data or features about a map through different tactile stimuli, including those concerning the symbols. Mental storage capacity is a controversial issue in cognitive psychology. Miller (1956), for example, highlighted the process of grouping items together as a mental mechanism to form units in order to organize and store more information. Other researchers have later shown that it is possible to improve memory performance when items are grouped into mental lists of units organized under some similar pattern (Broadbent, 1975; Ryan, 1969).

Yet, the principles of grouping in Gestalt psychology tell us that, in the visual domain, the individual elements of a group tend to be perceived as units if they have similar features such as shape, size, colour, texture, lighting, and so forth (Todorovic, 2008). These principles are,

therefore, important to know how users memorize individual elements of information, for example, the list of symbols on a legend in a rational way. This can only be accomplished, however, if the stimuli allow for a reasonably easy interpretation of the different attributes of the shape of a symbol. These similar elements are finally perceived as unitary groups of items instead of a large array of individual ones, which in turn makes it easier to memorize them.

If we ask about the validity of these visual principles in the haptic sphere, however, some authors such as Alberto Gallace and Charles Spence (2011) argue that the same principles governing the sense of sight or hearing also govern the sense of touch. In fact, some experimental results indicate that the principles of similarity do apply in the same way to both visual and haptic groupings (Chang, Nesbitt, & Wilkins, 2007).

However, the haptic memory that blind persons use to interact with a tactile map has a considerable shortcoming in comparison with visual memory, namely, a poorer capacity to process information. Specifically, during tactile reading, haptic memory works sequentially, since it is necessary to explore the tactile device step by step. Visual memory, in contrast, is simultaneous and can recognize more information at a single glance (Millar & Al-Attar, 2003). Generally, less time and effort are needed to understand a visual phenomenon than a tactile one. Nevertheless, according to Millar's (1999) studies on tactile memory, the use of haptic memory can reach the same levels of efficiency as vision when tasks are related to memorizing shapes, distances, directions, or locations.

The influence of haptic reading strategies to gather tactile information

Conversely, certain haptic reading strategies are essential for the successful understanding and use of these tactile devices. As the Royal National Institute of Blind People (RNIB) mentions, one good basic practice is to scan a tactile map with more than one hand and/or finger (Cryer & Gunn, 2008). Employing this haptic strategy enables users to establish an optimum interaction with a tactile device as long as the information it offers is correctly encoded (Blades, Ungar, & Spencer, 2010; Lillo-Jover, 1992; Perkins & Gardiner, 2003). Generally, blind users assimilate these gestures through their personal experience as part of their own individual learning process. Hence, the accuracy of tactile recognition varies in relation to the subject's prior accumulated perceptual experience and there are in fact remarkable differences from one subject to another. This is the case of the congenitally blind, who have more haptic experience than the late adventitiously blind because among other things, they tend to have been using Braille and tactile devices for a longer time. In contrast, the congenitally blind have no long-term visual experience or visual cues with which to build a mental image of the tactile stimuli. Graven's (2003) studies concluded that the overall shape of objects exposed to the memory of blind persons by visual and haptic cues are recognized better by subjects who have visual and tactile experience, that is, the adventitiously blind.

Design of tactile map symbols: two-dimensional and three-dimensional elements

As indicated in many publications, the design of tactile maps is the result of combining three types of symbols (Image 2) from (2D) graphic design (Bentzen & Marston, 2010; Edman, 1992; Trevelyan, 1986).

It should be remarked that these three types of symbols belong to the 2D domain and are commonly used in tangible graphics (Bertin, 1981; Edman, 1992). However, a fourth set of
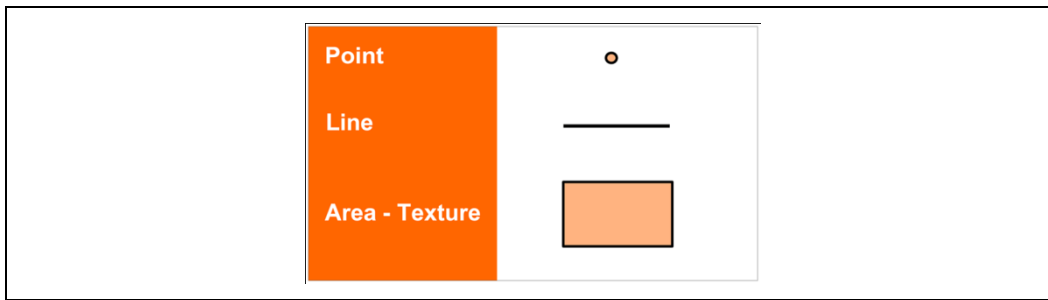
Image 2. The three types of conceptual symbols used in (2D) graphic design and tactile maps. Any graphic phenomena can be drawn by designers using these three elements.
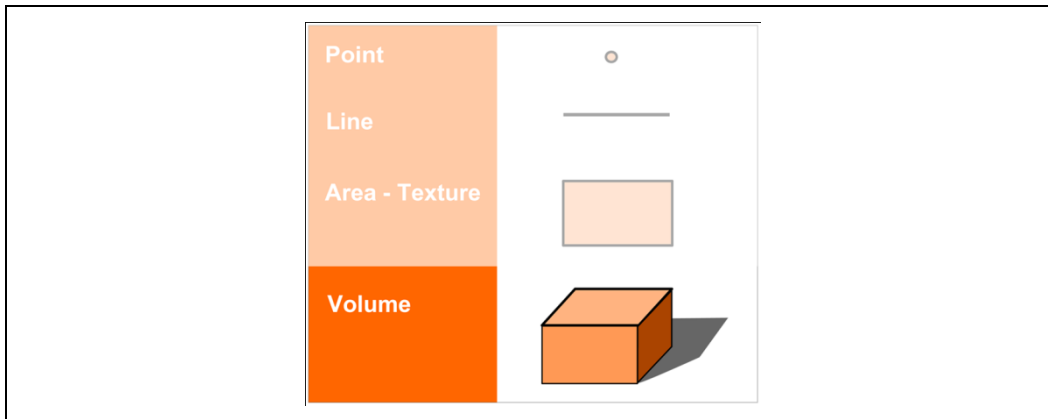

Image 3. Conceptual framework of the four elements used in architecture and (3D) product design. In this case, a rectangular prism represents the volumetric design elements that could be used as volumetric tactile symbols.

symbols should also be mentioned, namely, volumetric elements (3D symbols), which are usually presented as basic prisms (Image 3) and are commonly used as design elements in fields such as architecture and/or product design (Ching, 2007; Wong, 1993). Yet, these 3D symbols are seldom used in designing tangible graphics, due to the fact that cartographers and mobility instructors prefer to design tactile devices under 2D graphical criteria, instead of using 3D criteria, or a combination of both (2D/3D). This is probably because the most common production systems, as we will see in the following paragraphs, cannot reproduce certain volumetric figures (3D criteria).

Hence, it is necessary to mention certain aspects and requirements of traditional techniques for producing tactile maps and symbols so that they can be compared with a new and competitive alternative within the Rapid Prototyping techniques, here 3D Printing, which allows mapmakers to use 2D and also 3D design criteria.

Traditionally, the most usual methods of producing tactile maps and symbols are microencapsulation (Image 1) and thermoforming (Image 4) (Rowell & Ungar, 2003a). The first of these two methods of production, microencapsulation, uses a special material called swell paper as a substrate. This has a composition based on microcapsules of alcohol that react with heat and black ink, the result of the reaction being an elevation (vertical height) of about 0.5 mm (Jehoel et al., 2005) of the black parts of the map: lines, textures, and so on.
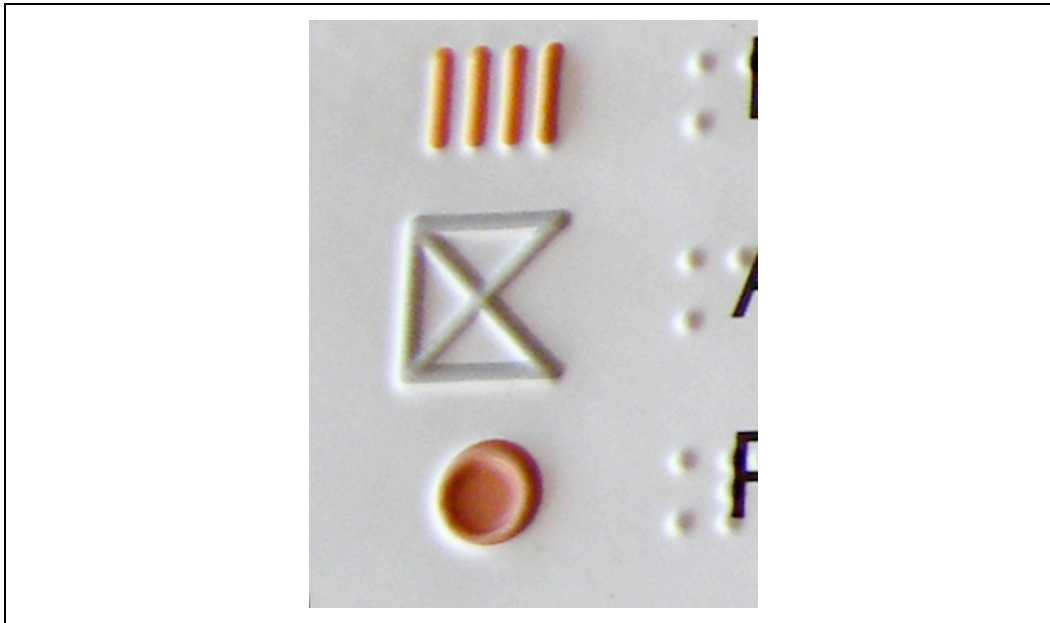
Image 4. Example of typical tactile symbols (2D) produced using thermoforming.

A second and quite popular alternative method used to produce tactile maps is thermoforming. A thin film of thermoplastic polymer is placed on a model (master piece or mould) to reproduce the final shape (Image 4), usually by applying pressure under a vacuum and heat. The elevation commonly used in a thermoformed tactile map is around 1 mm (Jehoel et al., 2005).

The accuracy and the control of the relief, radius, and chamfers of both systems are notable weak points that could be understood as limitations for tactile mapmakers and designers.

New possibilities through 3D Printing. One possible alternative to these systems, however, is 3D Printing, which affords designers an accurate control over the geometry and colour, as well as an almost limitless control over the elevation of the symbols. The first step involved in applying this method is to prepare a 3D Computer Aided Design file that can be sent to the 3D printer, which will produce a rigid and, therefore, non-portable, but nevertheless durable and accurate map.

Some earlier studies in this field produced tactile maps or models using Rapid Prototyping techniques, focusing especially on the application of tactile models, as is the case of Voigt or Milan within the field of tactile architectural scale models (Celani & Milan, 2007; Voigt & Martens, 2006), or Skawinski et al. (1994), who used stereolithography to produce 3D tactile models of molecules for blind scientists and students. In addition, there are also studies referring to tactile maps (Gual, Puyuelo, Lloveras, & Merino, 2012; Voženílek et al., 2009) and tactile graphics (Zhang, Richardson, Surana, Dwornik, & Schmidt, 1996), as well as the possibility of using 3D tactile symbols (Image 5) with a high-contrast elevation that allows visually impaired users to distinguish them from 2D symbols (Gual, Puyuelo, & Lloveras, 2011, 2012).
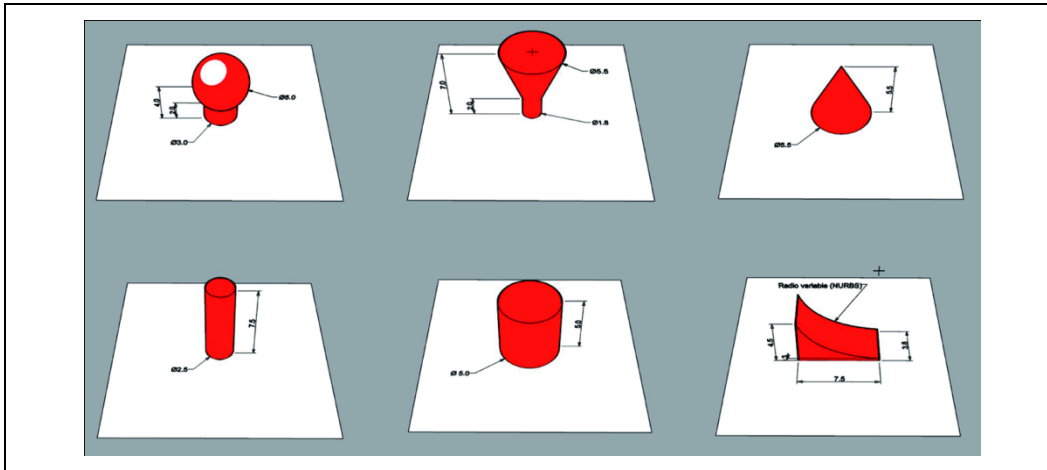
Image 5. Image with a sample of 3D tactile symbols.

Methodology

This research followed the tenets of ethical research involving human subjects and all the subjects participated in the experiment voluntarily and gave their written informed consent. They were recruited from different organizations in Barcelona and Spain, such as *Organización Nacional de Ciegos Españoles* (ONCE), *Associació de Discapacitats Visuals de Catalunya B1 B2 B3*, and *Associació Catalana per a la Integració del Cec* (ACIC).

Before going on, it should be pointed out that this study has two noteworthy limitations, one of which is the small size of the sample of visually impaired persons that was used in it. In fact, sighted participants were added, on the one hand, due to the difficulty in recruiting an optimum sample of blind participants and, on the other hand, bearing in mind the premise that these participants can provide information about non-experienced users. Employing a sample with sighted (blindfolded) subjects is quite common practice in studies where visually impaired persons are involved, as can be confirmed by some previous studies (Jehoel et al., 2005; McCallum, Ungar, & Jehoel, 2006; Millar & Al-Attar, 2003). Second, the set of 3D tactile symbols (only four) tested in the study was very small (Image 7), due to time restraints that made it more difficult to perform a reasonable test in terms of duration, especially when memorizing is the central activity in the tasks and participants need to have rested. These two limitations could affect the consistency of the results and the conclusion.

Sample

A group of 20 subjects (7 men and 13 women) took part in this experiment: 10 totally blind persons, 4 partially sighted users, and 6 sighted participants (Table 1). The average age of participants was 45.15 ($SD = 16.64$), ranging from 25 to 74 years. They are adults that could potentially use a tactile map to try to follow a route on their own. Low-vision and sighted participants performed the tasks blindfolded in order to ensure the study would focus only on the tactile aspects without the intervention of any other mode of perception.

With regard to the degree of previous knowledge of haptic reading strategies, among the 10 totally blind participants in this experiment there were

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

Participants		N
Totally blind	Congenitally blind (experts)	6
	Adventitiously blind	4
Partially sighted		4
Sighted		6
Total		20
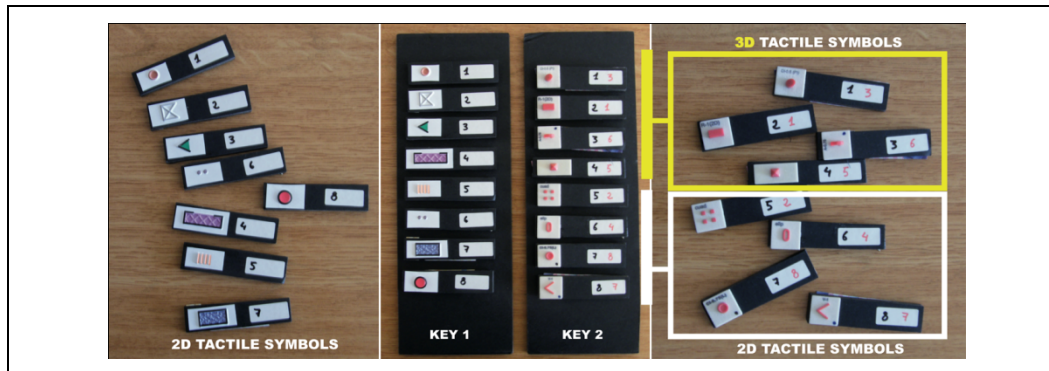
Image 6. Image of the two keys used in the study.
On the left, Key 1; on the right, Key 2.
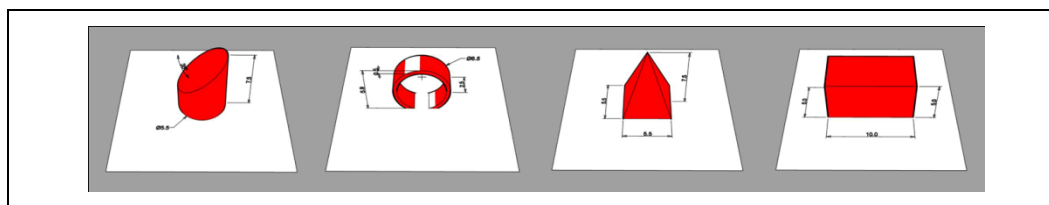
Image 7. Image with the four selected symbols (3D tactile symbols) used in this study.

- six congenitally blind expert users, who use tangible graphics on a regular basis.
- four who have no previous experience with this type of tactile devices, although they read Braille. These participants were adventitiously blind.

Material used in the study: recording

Two templates with tactile symbol keys were used in this study (Image 6), both with eight symbols but without any explanation. Key 1, with tactile symbols commonly used on real (2D) maps, was designed under 2D (graphic) criteria and produced by means of thermoforming. Conversely, Key 2, produced by 3D Printing, included two blocks of four symbols grouped in units according to their type of morphology: the first four symbols following 3D design criteria (Image 7), and the last four symbols in 2D, similar to those used in Key 1. The symbols were not related to any particular meaning, but were ordered from one to eight, starting from the top with one.

The tasks to be carried out in the experiment were recorded using digital video and the results (errors) were later obtained by carefully viewing the videos.

Table 2. Mean in the experiment for both legends and the whole sample, including blindfolded sighted participants.<mark>[AQ22]</mark>

	N	Mean of errors	Mean number of symbols memorized	SD
KEY 1 (2D symbols)	20	**1.95**	6.05	2.012
KEY 2 (2D/3D symbols)	20	**1.00**	7.00	1.376

The information obtained from the participants was processed using statistical data processing software IBM® SPSS® Statistics Version 21 (IBM Corp) and G*Power Version 3.1.2. Data did not follow a normal distribution, so non-parametric tests were used to analyse them, namely, the Wilcoxon *T*-test (when it was necessary to compare paired groups of dependent data) and the Mann–Whitney *U*-test, when independent data were compared ($\alpha = .05$).

Tasks and procedure

The aim of the experiment was to evaluate the process of memorizing tactile symbols belonging to two different keys following different memorization strategies: one memorizing symbols by shapes and the other decided freely by each participant.

The task conducted was one that is commonly employed in the use of tactile maps: the memorization of the symbols of the key to a map. Participants had to remember both legends, first one and then, after being given some time to rest, the other.

The experiment was carried out as follows: each participant was given the templates with the two keys, one at a time, which had been selected at random to ensure that the order effect would not affect the results of the experiment. First, participants had to memorize the order in which the symbols appeared in the key, from top to bottom, from first to eighth. Once the order had been memorized, the researcher gave them the symbols that they had tried to memorize in the key, one by one, a second time. These were presented at random, until all eight symbols in the key had been listed. When the participants touched the symbols provided by the researcher for the second time, they had to state what place each symbol occupied in the key they had memorized. Subjects had to remember both keys, and the errors committed by each participant were measured for each key.

Finally, it should be mentioned that the researcher provided short instructions on how to perform the tasks. Most importantly, for the memorization of Key 2, the researcher suggested the possibility of using a strategy to memorize the symbols of the legend for different groups, since the display order criterion meant that the first four (Number 1–4) were 3D, while the rest (Number 5–8) were those in 2D. Thus, in line with the theory, certain principles of memorization and perceptual organization were considered (Broadbent, 1975; Chang et al., 2007; Gallace & Spence, 2011; Ryan, 1969; Todorovic, 2008).

Results

Total sample results

As shown in Table 2, the average error obtained in Key 2 (3D/2D) for all the participants, including the sighted ones, was 1.00 (*SD* 2.02) versus 1.95 (*SD* 1.28) for Key 1 (2D), with a total error reduction of 48.72% for Key 2. Seen from another perspective, after the 20 participants had attempted the task, the average score for Key 1 was 75.62% and for Key 2 it was 87.50%. This represents a *mean* number of memorized symbols, out of the eight symbols in each legend, of

6.05 for Key 1 and 7.00 for Key 2. These results are remarkable, since the *p*-value is .014 (Wilcoxon T-test) with a power of 0.73.

Visually impaired persons' results

However, if the analysis of the results is focused only on the visually impaired persons, that is to say on totally blind and low-vision subjects (Table 3), the *mean of the errors* is 2.14 (*SD* 2.07) in memorizing Key 1 and 1.29 (*SD* 1.54) for Key 2. Therefore, the key that included 3D symbols obtained fewer memorization errors than the control legend (Key 1) – in fact, 39.72% fewer mistakes were produced. This represents a *mean* of 5.86 over eight tactile symbols memorized in the first legend versus the *mean* of 6.71 for the second legend with height contrast between the groups of symbols.**[AQ4]** The Wilcoxon *T*-test showed a *p*-value of .058.

In the *mean of errors* obtained by the four low-vision subjects (Table 4), they registered a 50% reduction in the number of errors in memorizing Key 2 with respect to Key 1 (3.00 [*SD* 2.45] vs 1.50 [*SD* 1.91]). Thus, the results obtained were similar to the data shown above with the total sample of visually impaired participants. The *mean* number of memorized symbols obtained was 5.00 using Key 1 and 6.05 when the same group of participants performed the same tasks with Key 2. Even with this reduction in the mean number of errors, the statistical tests indicated that these differences are not significant.

In contrast, the totally blind participants in the experiment obtained similar results in both keys (1.80 [*SD* 1.93] in Key 1 and 1.20 [*SD* 1.48] in Key 2) with a minimum difference of errors between keys (Table 5). Thus, there was only a 33.33% reduction in the number of errors, and with fewer memorization errors than partially sighted subjects (1.80 vs 3.00 in Key 1 and 1.20 vs 1.50 in Key 2). The *mean* numbers of symbols memorized when they had to remember the tactile symbols of both keys were very similar: 6.20 for Key 1 and 6.80 for Key 2. These differences are not statically significant.

Results for the totally blind according to their level in reading strategies

Turning to look at the results obtained in the use of tactile devices when only totally blind participants were considered and depending on their previous experience with tangible graphics, it can be observed that experienced (congenitally) blind participants obtained an average of 1.00 (*SD* 1.01) for Key 1 and 0.33 (*SD* 0.82) for Key 2 (Tables 6 and 7). Non-experienced adventitiously blind users were the group with the worst results in both cases, 3.00 (*SD* 2.45) for Key 1 and 2.50 (*SD* 1.29) for Key 2. Better results were obtained for Key 2 from both groups of blind users, with a 16.67% reduction in errors in the memorization process in non-experienced blind users and 67.00% in experienced blind users. In any case, a more precise statistical analysis shows that these reductions in errors are not statistically significant between legends. However, significant differences were found within keys, especially between non-experienced and experienced users in Key 2, with a high effect size and power (Mann–Whitney *U* test: *p*-value = .017; effect size = 2.00 and power = 2.01). In addition, a high effect size (1.05) was also found among the participants for Key 1 (2D symbols), although without enough power (*p*-value = .094; power = 0.42) to determine statistical differences.

The *mean* numbers of symbols memorized by haptic memory for experienced users who regularly use tactile devices were 7.00 for Key 1 and 7.67 for Key 2. Similar results were, therefore, obtained with both legends. Yet, non-experienced adventitiously blind participants obtained a *mean* of 5.00 in Key 1 and 5.50 on memorizing the symbols in Key 2.**[AQ5]**

Table 3. Mean and standard deviation of errors of the results excluding sighted participants.

	N	Mean of errors	Mean number of symbols memorized	SD
KEY 1 (2D symbols)	14	**2.14**	5.86	2.070
KEY 2 (2D/3D symbols)	14	**1.29**	6.71	1.541

Table 4. Mean and standard deviation of errors committed in the experiment by partially sighted participants.

Partially sighted participants	N	Mean of errors	Mean number of symbols memorized	SD
KEY 1 (2D symbols)	4	3.00	5.00	2.449
KEY 2 (2D/3D symbols)	4	1.50	6.50	1.915

Table 5. Mean and standard deviation of errors committed in the experiment by blind participants.

Blind participants	N	Mean of errors	Mean number of symbols memorized	SD
KEY 1 (2D symbols)	10	1.80	6.20	1.932
KEY 2 (2D/3D symbols)	10	1.20	6.80	1.476

Table 6. Mean and standard deviation of errors committed in the experiment only by blind participants in Key 1, comprising only 2D tactile symbols.

	Personal skills	N	Mean of errors	Mean number of symbols memorized	SD	Statistical data
Key 1 (2D symbols)	Non-experienced	4	3.00	5.00	2.449	p-value = .094
	Experienced	6	1.00	7.00	1.095	Power = 0.42 Effect size = 1.054

Table 7. Mean and standard deviation of errors committed in the experiment only by blind participants in Key 2, comprising 2D and 3D tactile symbols.

	Personal skills	N	Mean of errors	Mean number of symbols memorized	SD	Statistical data
Key 2 (2D/3D symbols)	Non-experienced	4	2.50	5.50	1.291	p-value = .017
	Experienced	6	0.33	7.67	0.816	Power = 2.01 Effect size = 2.00

Discussion

Previous experience and memory implications

The data obtained in this study show that in all the cases tested in the experiment (Tables 2 to 7), the memorization of Key 2 (2D/3D) produced better results than Key 1 (2D). Therefore, the main

finding of the study is that data were more positive in the process of memorizing the symbols of Key 2, that is, the legend that used a combination of 2D and 3D tactile symbols.

After analysing the data in detail, only the case within Key 2 can be considered statistically significant when the profiles of experienced users were compared with those of non-experienced ones (Section 'Results for the totally blind according to their level in reading strategies'; Table 7). In this particular case, the experienced participants performed the task with good results in terms of memorization (*Mean* of 7.67/8 in experienced subjects vs 5.50/8 in non-experienced subjects). The statistical data, therefore, show a high power and effect size (p-value < .05, power = 2.01; effect size = 2.00).

In addition, when all the sample was taken into account in the analysis, that is, including the sighted participants in the experiment (Table 2), the results obtained show a p-value < .05, with a power that is almost high enough to be considered statically significant (0.73).

Hence, the study does not strictly confirm any differences between legends beyond some isolated results like the two cases mentioned earlier. Even so, the generally good positive performance of Key 2 indicates that with a bigger sample significant differences are likely to be obtained in further research. This can be claimed because in all the cases in this study Key 2 obtained a reduction in the number of errors with respect to Key 1, sometimes with a difference of 50% between the two legends (Table 4).

In any case, as the present study has shown, the experienced subjects benefited most from using Key 2 with respect to Key 1 (Section 'Results for the totally blind according to their level in reading strategies'). This group of users improved the memorization process on two different levels (Tables 6 and 7): between keys (67% reduction in errors) and within Key 2 (with a high power and effect size). These improvements are probably due to their regular contact with this sort of tactile devices, this previous experience including familiarization with the tactile symbols (Millar, 1999; Millar & Al-Attar, 2003) to be able to explore a tactile map correctly. Consequently, it can be supposed that the congenitally blind (experienced subjects) have developed some skills, such as anticipation (Madrazo & Solorzano, 2003) for haptic interaction, more than the adventitiously blind, low-vision and sighted (blindfolded) participants in the experiment.

Hence, in contrast to Graven's (2003) results concerning the recognition of the object's overall shape by visually impaired persons, the effect of the tactile experience, according to the present results, was greater than the effect of the combination of mental images and tactile information, as reflected by the better results obtained by the congenitally blind subjects. The reason, beyond the accumulated experience of some participants, could be explained by taking into account the different materials employed in the two studies. Graven used raised-line drawings of concrete figures such as a car, face, or cup, among others, while in the present experiment only simple abstract shapes were used. Participants in this experiment with a visual memory such as the sighted, partially sighted, and adventitiously blind could not, therefore, build up a strong mental image of an abstract shape through visual memory to reinforce their haptic perception.

In any case, the results with the most experienced participants confirm previous studies with regard to the better accuracy and efficiency of the tactile information acquired when users employ reading strategies on a tactile device, provided that it has been correctly designed following the haptic requirements (Blades et al., 2010; Lillo-Jover, 1992; Perkins & Gardiner, 2003). This means, among other things, that it was designed following principles of simplicity and using tactile attributes that highlight the contrast (Nolan & Morris, 1971), as in the case of Key 2 with 3D basic prisms with height contrasts and 2D shapes with little height contrast. The

competing 2D key (Key 1), in contrast, did not use contrasting heights between groups of symbols.

It is also worth noting that the experienced subjects in the experiment normally performed the task using both hands as a technique to scan a tactile map, following some of the recommendations of the RNIB (Cryer & Gunn, 2008). Non-experienced subjects, however, did not take advantage of the full potential of a systematic way of scanning because, among other reasons, they did not have any previous experience with a tactile key and performed the task by intuitive gestures that normally did not include the use of several fingers or both hands.

Perceptual organization

Beyond the subjects' previous experience in tactile reading strategies and with haptic memory, it should be mentioned that the better results may have been produced in Key 2 because participants were able to group the tactile symbols in this second legend into two differentiated blocks (2D vs 3D), following the strategy indicated by the researchers during the course of the experiment. In Key 2 participants could, therefore, make an association between tactile symbols in order to organize them into two units of four symbols with similar characteristics, which would lead to improved memorization in terms of short-term memory and mental storage capacity (Broadbent, 1975; Miller, 1956; Ryan, 1969). At the same time, they could also follow the possibilities offered by Gestalt principles of grouping (Todorovic, 2008) and the premise that both the sense of sight or hearing and the haptic sphere are governed by the same principles (Gallace & Spence, 2011), particularly in displays, as in the experiment conducted by Chang et al. (2007).

Design requirements: 2D plus 3D

Another important point in the study is related with the design strategy used for tactile maps and symbols. The two groups of symbols in Key 2 were based on different design criteria: first, those in 3D in the form of basic prisms were designed following the knowledge accumulated in product design and architecture (Ching, 2007; Gual et al., 2011; Gual, Puyuelo, & Lloveras, 2012; Wong, 1993), and the second, those in 2D were based on (2D) graphic design criteria, as regularly mentioned in the current literature on tactile maps (Bentzen & Marston, 2010; Bertin, 1981; Edman, 1992; Trevelyan, 1986). The consequence was that the use of a combination of groups of symbols with different design criteria in the second legend made tactile discrimination among the shapes of the symbols more effective than with the use of just 2D design criteria. In contrast, Key 1 did not have enough cues to allow symbols to be discriminated, for example, by height contrast or by groups.

Therefore, in the researchers' opinion, breaking the tendency to use only 2D symbols (raised points, lines, and areas-textures), as tactile mapmakers tend to do today (Bentzen & Marston, 2010; Bertin, 1981; Edman, 1992; Trevelyan, 1986), while at the same time incorporating 3D geometries could probably open up new possibilities to improve these maps targeted for use by visually impaired persons. Among other things, these enhancements would include access to a wider range of tactile stimuli in order to distinguish the different features (3D vs 2D) of a map, as in the present study with tactile legends. Likewise, mapmakers would also have access to a wider range of both 2D and 3D symbols from which to select the most appropriate solution for a tactile map.

3D Printing versus traditional systems for producing tactile maps

One last important point, beyond the assumption that a tactile map or legend would be enhanced by including 3D symbols, would be the production of this sort of tactile symbols, particularly in terms of the possibilities the use of rapid prototyping systems offers mapmakers (Chua, Leong, & Lim, 2003; Zhang et al., 1996). As some previous studies have shown, the application of this emergent system of production offers a wide range of possibilities (Celani & Milan, 2007; Gual, Puyuelo, Lloveras, & Merino, 2012; Skawinski et al., 1994; Voigt & Martens, 2006; Voženílek et al., 2009).

The results of this study have shown a possible new application of 3D Printing to tactile legends, by taking advantage of the possibility of producing complex geometries with enough elevation to accentuate the effect of the differences in height between the symbols of the key so that they can be detected by the fingertips and remembered through their specific shape–volume attributes. The performance of the competing production system used in Key 1, the thermoforming technique that is quite commonly used by mapmakers (Jehoel et al., 2005; Rowell & Ungar, 2003a), was poorer than that of Key 2 produced with 3D Printing. In contrast, the other system commonly used to produce tactile maps, that is, microencapsulation, although not tested in this experiment, has notable limitations with regard to the elevation of the elements on the map (Jehoel et al., 2005) and their geometry, both of which are critical aspects when it comes to designing an acceptable tactile map (Gardiner & Perkins, 2002; Nolan & Morris, 1971).

Conclusion

The data from the experiment show that there is an improvement in the discrimination of tactile symbols when participants use a combination of haptic memory and their previous experience with tangible graphics to remember the order of a group of eight symbols in a key which displays 3D and 2D symbols together. However, this only occurs provided that the 3D symbols are introduced and distributed in this legend following a criterion that arranges them into groups according to the contrasts between their shape and height. By so doing, advantage is taken of the benefits provided by considerations on short-term memory (Broadbent, 1975; Ryan, 1969; Miller, 1956) and perceptual organization theories, such as the Gestalt principles of grouping by shape similarities (Todorovic, 2008). Accordingly, after analysing the data from the experiment, the researchers can conclude that including 3D symbols in the key of a tactile map could enable users to improve the process of memorizing it.

Thus, when it comes to using tactile symbols, it is possible for an OMI to select 3D tactile symbols and combine them with the current ones in 2D if the production process and purpose of the map allows it. Including volumetric symbols in a key, as an additional category of tactile symbols (Ching, 2007; Wong, 1993), therefore, accentuates the shape contrast and makes it easier to discriminate symbols using the sense of touch than using only the three types of symbols mentioned above in the literature on tactile maps (point, line, and areas-textures) (Bentzen & Marston, 2010; Bertin, 1981; Edman, 1992; Trevelyan, 1986).

On another level, the fact that there could be differences between different blind users according to their previous experience with tactile devices and tactile reading strategies seems to have been confirmed, following previous studies that emphasize the importance of the reading strategies and accumulated experience in exploring a tactile device (Blades et al., 2010; Cryer & Gunn, 2008; Lillo-Jover, 1992; Perkins & Gardiner, 2003).

Furthermore, we should mention the possibilities yet to be explored in the use of Rapid Prototyping systems in the field of tactile maps. As shown in this study and other previous works

(Celani & Milan, 2007; Gual et al., 2011; Gual, Puyuelo, & Lloveras, 2012; Skawinski et al., 1994; Voigt & Martens, 2006; Zhang et al., 1996), specialists in the field (tactile mapmakers, OMIs, cartographers, designers of tactile maps etc.,) should expand and exploit the advantages of the emerging development of Rapid Prototyping, since the results obtained by this system reached at least the same level of efficiency as the traditional methods of production.

Finally, the aim of the work presented here is not to put forward a set of standard tactile symbols like the symbols proposed, for example, in past meetings (European Symposium on Tactual Town Maps for the Blind, 1983), but even so the positive results obtained with 3D symbols should be taken into account, in the researchers' opinion, in new proposals in the future. This study, therefore, provides a starting point for researchers and learners who want to know more about the possibilities of 3D Printing applied to a tactile map, in this case to a tactile key. Likewise, it also highlights new areas for further research, such as the design of a new set of tactile symbols taking into account the possibilities of volumetric shapes.

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