Tactile Symbol Discrimination on a Small Pin-array Display

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ABSTRACT

Pin-array displays are a promising technology that allow to display visual information with touch, a crucial issue for blind and partially sighted users. Such displays are programmable, therefore can considerably increase, vary and tailor the amount of information as compared to common embossed paper and, beyond Braille, they allow to display graphics. Due to a shortage in establishing which ideal resolution allows to understand simple graphical concepts, we evaluated the discriminability of tactile symbols at different resolutions and complexity levels in blind, blindfolded low-vision and sighted participants. We report no differences in discrimination accuracy between tactile symbols organized in 3x3 as compared to 4x4 arrays. A metric based on search and discrimination speed in blind and in low-vision participants does not change at different resolutions, whereas in sighted participants it significantly increases when resolution increases. We suggest possible guidelines in designing dictionaries of low-resolution tactile symbols. Our results can help designers, ergonomists and rehabilitators to develop usable human-machine interfaces with tactual symbol coding.

KEYWORDS

Haptic rendering; Assistive Technology; Visual Impairment; Blindness; Tactile Symbols; Tactile Discrimination; Tactile Graphics; Braille displays; Pin array displays; Shape discrimination

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1 INTRODUCTION

The skin is the largest sense organ in our body, roughly 2 m^2 in the average male [16]. Despite of this, human-machine interfaces have traditionally neglected the possibility of delivering graphical information through touch [5, 22]. This limit is especially relevant if we consider the needs of the visually impaired community, for which large area tactile displays would make the digital world more accessible. In the last years, pin-array displays designed to improve the quality of life of visually impaired people have been developed. These devices attempt to present information that is generally organized as small pin-shaped actuators, named *taxels* as they can be considered the tactile equivalent of the pixel [6]. Applications of these devices span from text reading to tactile graphics [30]. Unfortunately, these prototypes rarely have become commercial. One of the reasons is that large-area tactile displays that are big enough to display graphical information such as maps and scientific content are extremely expensive to date. This huge cost is mainly due to the large number of individually assembled components required to develop such devices. Particularly, cost grows exponentially when organizing pins in two-dimensional arrays.

This technical limitation introduces the need of defining a set of tactile symbols, which are big enough to be correctly perceived and discriminated but small enough to be represented within a small tactile display. In addition, using small symbols introduces constraints in stimulus complexity which is a factor that has been shown to affect tactile recognition performance [14]. For instance, Tu et al. [23] found that the contours of tactile shapes with a closed series of edges such as grapes and caps took longer times to be recognized. Similarly, Ng and Chan [18] found that tactile symbols with smaller number of edges were recognized significantly faster than those with more edges. Tactile displays of small dimensions may also require a small space between symbols. Guidelines recommend a widely varying range of separation distance of 2.3mm (i.e. the dot spacing in a single Braille character) to 8 mm between symbols [1, 2, 20] in order to ensure that the gap between map features can be well perceived. Psychophysical measures of tactile acuity of the fingertip in humans showed thresholds for detecting separate tactile features (such as points or lines) in the range of 0.87-2.36 mm, depending on the task employed, age of participants and so on [4, 13, 17]. These features could be detected at an elevation of 0.85 µm [12] when the pins have a very high stiffness. Previous studies on tactile picture identification used mainly raised-line drawings of common objects [8, 9, 19] which are usually depicted at big scales, i.e. in the order of centimeters. On the other hand, most studies investigating abstract symbols discriminability compared only pairs of adjacent symbols [e.g. 6, 15]. This task cannot be compared to reading a tactile map [10, 11] in which different symbols are generally distributed over a larger area. In these real-life situations, the map reader will spend time travelling from one symbol to another and is likely to encounter several other symbols while doing so.

Finally, if tactile graphics must be derived from Braille pins, then an appropriate set of symbols – different than Braille letters - needs to be found. Ideally, such set of symbols will have minimal requirements in terms of resolution (unlike paper-based symbols, all pin-based symbols are discrete) and performance (is a set understandable? Can symbols be discriminated from each other?). However, such set of symbols does not exist yet and there is very little research towards the definition of standards in tactile graphics. For example in [24] understandable cardinal symbols are derived on a pin array with Braille-spaced dots.

In the quest for a suitable dictionary of abstract tactile symbols, in this study we attempted to evaluate the usability of two sets of symbols with varying shape complexity (within set) and resolution/dimension (across sets) on a pin-array Braille display. As evaluation metric, we defined usability both in terms of accuracy in matching tactile symbols and in terms of symbol identification speed, as done in [21]. The final goal is to identify a set of usable and non-ambiguous tactile symbols that can be used by engineers, designers and rehabilitation practitioners in representing tactile maps and diagrams on small-size tactile displays. Another aim of this study is to find out how the degree of visual ability influences symbol usability. To do so, we tested a group of totally blind, a group of low vision and a group of sighted participants.

2 METHODS

2.1 Participants

Sixty-one participants (19 blind, 20 low vision and 22 sighted) took part in this study. Their ages ranged from 12 to 61 years, with a mean age of 24.5 years. All sighted participants reported having normal or corrected-to-normal vision. All participants declared no conditions affecting tactile perception. The experiment complied with the declaration of Helsinki and all participants gave prior consent. The experiment was approved by the local ethical committee.

2.2 Materials

The experiment was performed using a pin-array display (see Figure 1A) named Hyperbraille. It is a multi-line Braille display provided by Metec AG, composed by an array of 30 by 32 pins and a screen refresh rate capability of 5Hz [24]. The display area is composed by a large number of assembled pins, from novel vertical cells (each cell has 2 by 5 pins) at a standard equidistant resolution of 2.5 mm for each pin. Each pin could raise about 0.7 mm. On the top of the cells there is a capacitive layer (2 sensors per cell). The device was connected via USB cable to a standard PC and controlled by PadDraw, a graphical interface written in C++ developed at Geomobile GmbH, Germany, within the scope of the EU project BlindPAD (www.blindpad.eu), and piloted by a Matlab R2013 script that made us of Psychtoolbox 3.0.11 [3, 15].

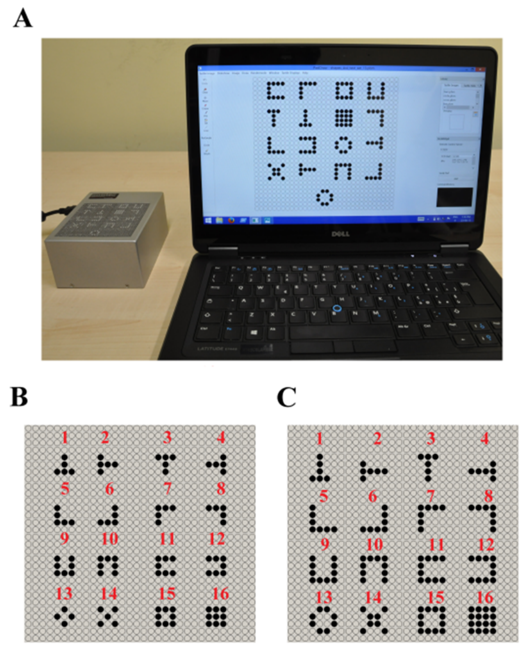

Figure 1: (A) Experimental setup with the Hyperbraille on the left side and the PC running the script and the graphical interface on the right side. The picture shows an example of trial with a circle-like symbol as target. (B) 3x3 and (C) 4x4 set of tactile symbols. Red numbers identify tactile symbols.

Two sets of tactile symbols were prepared. Both sets were composed by 16 different symbols. In the 3x3 set, each symbol was inscribed in a 3x3 taxel array (see Figure 1B). In the 4x4 set, each symbol was inscribed in a 4x4 taxel array (see Figure 1C). The size of 3x3 symbols was about 5.5 x 5.5 mm with an inter-symbol distance of 8 mm. Inter-row distance was 5.5 mm. The size of 4x4 symbols was around 8 x 8 mm with an inter-symbol distance of 8 mm. Inter-row distance was ~3 mm. Four category of symbols were created; targets 1-4 were "T-shaped", symbols 5-8 were "L-shaped", targets 9-12 were "U-shaped", while symbols 13-16 had all point symmetry ("O-shaped"). As is observable in Fig. 1B and 1C, the two sets of symbols differed mainly for targets dimensions. The position of the symbols in each trial was pseudo-randomized.

2.3 Procedure

All but blind participants were blindfolded before the task. Participants were given verbal instructions at the beginning of the experiment, that started with a learning phase in which subjects familiarized with the tactile symbols before the task. Subjects were comfortably seated at a table in a silent room and were asked to explore haptically the set of tactile symbols. When they felt accustomed, they performed a search task. In each trial, one tactile target was shown at the bottom of the tactile display, under the entire set of symbols (see Figure 1A) . The position of the 16 symbols in each trial was pseudo-randomized to avoid that the participant could remember their position and to avoid that the symbol position could influence our metric (especially on speed). Subjects were asked to touch it and to find the matching figure presented above it, by exploring the tactile screen with their dominant hand. They were asked to do the task as quickly and accurately as possible but response accuracy was stressed. For each trial the participants had to respond by touching/indicating their selected target on the device with their index finger in association with a verbal response. The task was repeated for all 16 tactile targets composing the set of symbols. After a few minutes break, the participants repeated the task with the other set. The order of sets (3x3 and 4x4) was counterbalanced across participants to compensate for learning effects. We recorded response accuracy and response speed. We collected a total of 1952 responses (61 participants x 16 tactile symbols x 2 sets). We then analyzed response accuracy and response speed in terms of tactile symbol, set and visual impairment. Finally, we investigated the relationship between response accuracy and speed.

3 RESULTS

Since accuracy and response time (RT) data were not normally distributed according to Shapiro-Wilk normality tests, we performed non-parametric tests. Particularly, we performed a Friedman ANOVA for each set including the tactile symbol as factor. Whenever required, we used Wilcoxon signed rank tests as post-hoc analyses. As for between groups statistics, we performed Kruskal-Wallis ANOVAs followed, whenever required, by Mann-Whitney tests as post-hoc analyses.

3.1 Blind

3.1.1 Accuracy

Overall, blind participants recognized the two sets of symbols equally well (accuracy for the 3x3 set: 90.5%; accuracy for the 4x4 set: 93.8%, p = .22).
As for the 3x3 set, no statistical differences in symbols recognition emerged (chi-squared = 15.28, p = .43). Symbol 6 was always correctly recognized whereas symbols 3 and 14 were the symbols more difficult to be recognized (accuracy = 78.9%).
Fig. 2 shows recognition accuracy for the two set of symbols in the blind. Note as L-shaped and U-shaped categories were the better identified, whereas accuracy was worse for O-shaped symbols.

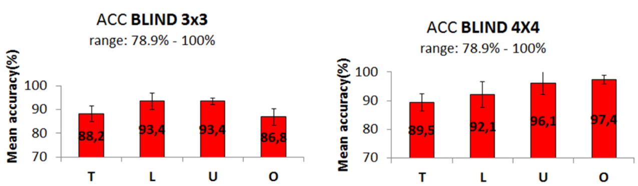

Figure 2: Accuracies for blind participants

Fig. 3 shows the confusion matrix for each set in the blind. Note as T symbols were confused with L symbols five times. O symbols were the targets that generated more mistakes with an equal distribution of within- and between- errors. Interestingly, T symbols and O symbols were never confused as well as U symbols and L symbols, suggesting that these specific combinations can be safely used without worrying about possible recognition mistakes.

3x3

	T	L	U	O
T	2	5	2	0
L	3	2	0	0
U	1	0	2	2
O	0	2	3	5

4x4

	T	L	U	O
T	6	2	0	0
L	3	3	0	0
U	0	0	2	1
O	0	0	1	1

Figure 3: Confusion matrix for blind participants. The correct responses were subtracted from the diagonal.

As for the 4x4 set, a statistical difference in accuracy between symbols emerged (chi-squared = 26.7, p = .03). Symbols 3,6,7,13 and 15 were always correctly recognized whereas the most difficult symbol to be discriminated was the symbol 5 (78.9%).
When considering categories, the O and U symbols were the better discriminated (see Fig. 2), whereas accuracy was worse for T symbols.
The confusion matrix shows that T symbols generated six within-category errors. On the other hand, they were never confused with U and O symbols. Similarly, L symbols were never confused with U and O symbols.

3.1.2 Response time

Also for RTs, no significant differences emerged between sets (3x3 = 16.9s, 4x4 = 17s; p = .89).
As for the 3x3 set, we found a significant effect of tactile symbols on response speed (chi-squared = 28.5, P = .02). Particularly, RT for symbol 16, 7 and 11 were the fastest (11.3, 13 and 13s, respectively), while RT for symbols 8 and 3 were the slowest (20.1 and 21.5s, respectively).
Fig. 4 shows RT for each symbol category. Note as O symbols were the fastest recognized and the T symbols the slowest recognized.

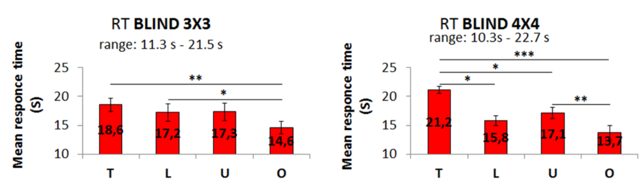

Figure 4: Response times for blind participants

3.2 Low vision

3.2.1 Accuracy

Also low vision participants recognized the two sets of symbols equally well (3x3 = 81.6%, 4x4 = 87.5%, p = .08).
As for the 3x3 set, the symbol type had a significant effect on accuracy (chi-squared = 28.6, p = 0.02). The symbol 8 was always correctly recognized whereas the symbol 2 was the worst recognized (65%).

Fig. 5 shows that L and U symbols were the better recognized, whereas T symbols were more difficulty recognized.

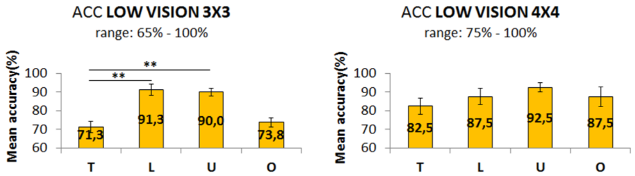

Figure 5: Accuracies for low-vision participants

Fig. 6 shows how T symbols generated ten within-errors and thirteen between-errors. In particular, they were confused with L symbols. O symbols generated ten within-errors and eleven between errors. In particular, they were confused with U symbols. T symbols were never confused with U symbols. U symbols were never confused with L symbols. L symbols and O symbols were never confused with each other.

3x3

	T	L	U	O
T	10	12	0	1
L	3	3	1	0
U	1	0	3	4
O	3	0	8	10

4x4

	T	L	U	O
T	4	8	1	1
L	3	5	2	0
U	0	1	5	0
O	1	0	0	9

Figure 6: Confusion matrices for low-vision participants. The correct responses were subtracted from the diagonal.

As for the 4x4 set, the symbol type had only a marginal effect on accuracy (chi-squared = 24.2, p = 0.06).
The symbol 16 was always correctly recognized whereas symbols 2,3 and 13 generated more errors (75%).
Fig. 5 shows that U symbols tended to be better recognized whereas T symbols got the lowest accuracy.
U symbols generated mainly within errors, while T symbols were mostly confused with L symbols (Fig. 6). Note as L and O symbols were never confused with each other as well as O and U symbols. Finally, U symbols were never confused with T symbols.

3.2.2 Response time

Also in low vision, no significant differences emerged between sets (25.9s for both sets; p = .94).
As for the 3x3 set, the tactile symbol had a significant effect on RT (chi-squared = 29.1, p = 0.02). Particularly, RTs for symbols 16 and 8 were the fastest (18.1s and 20.8s, respectively) whereas RTs for symbols 14 and 12 were the slowest (34.9s and 35.4s, respectively).
Fig. 7 shows RTs for each category. L symbols were the faster recognized whereas T and U symbols needed more time to be recognized.

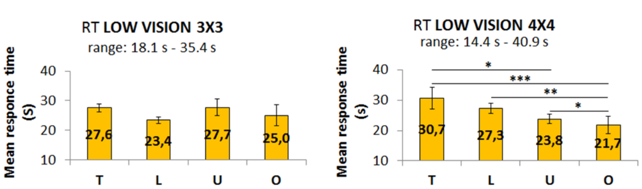

Figure 7: Response times for low-vision participants

Also in case of the 4x4 set, the symbol had a significant effect on RT (chi-squared = 47.6, p = 0.005). Symbols 16 and 12 were the fastest (14.4s and 19.9s, respectively) and symbols 4, 6 and 2 were the slowest recognized (30.3s, 30.6s and 40.9s, respectively).
As for the symbol category, O symbols were the fastest and T symbols were the slowest recognized (see Fig. 7).

3.3 Sighted

3.3.1 Accuracy

As it happened in visually impaired participants, sighted recognized equally well the two sets of symbols (3x3 = 90.1%, 4x4 = 91.8%, p = .67).
As for the 3x3 set, the tactile symbol had an effect on accuracy (chi-squared = 27.5, p = 0.03). Symbols 5 and 8 were always correctly matched whereas symbols 2 and 14 were recognized with more difficulty (72.7%).
Fig. 8 shows recognition accuracy for each symbol category in the sighted. L and U symbols were the best recognized whereas the percentage of mistakes was higher for T and O symbols.

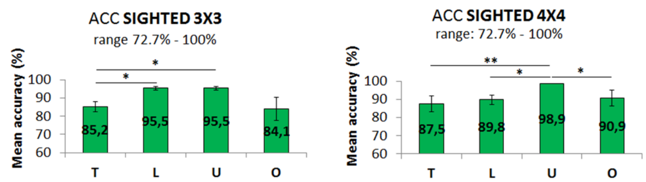

Figure 8: Accuracies for sighted participants

While U symbols generated only within category mistakes, L symbols were three times confused with T symbols (Fig. 9). Most of the mistakes with T symbols were confusion with L symbols. On the contrary, O symbols were mostly confused with other symbols of the same category.
As for the optimal combinations, L and O symbols were never confused with each other. U symbols were never confused with T, L and O symbols.

3x3

	T	L	U	O
T	4	7	1	1
L	3	0	1	0
U	0	0	4	0
O	3	0	2	9

4x4

	T	L	U	O
T	2	6	2	1
L	3	3	3	0
U	0	0	0	1
O	1	0	1	6

Figure 9: Confusion matrices for sighted participants. The correct responses were subtracted from the diagonal.

Also for the 4x4 set, the tactile symbol had an effect on accuracy (chi-squared = 31.3, p = 0.008). Symbols 10, 11, 12, 13 and 16 were always correctly identified whereas the most difficult symbol was the number 15 (72.7%).
U symbols were the better identified while the T symbols collected the larger number of mistakes (Fig. 8).
L and O symbols were never confused with each other. U symbols were never confused with T, L and other L symbols (Fig. 9).

3.3.2 Response time

In the sighted, RT for the 3x3 set was significantly higher than RT for the 4x4 set (55s vs 47s, p <.001).
The tactile symbol had a significant effect on RT both in 3x3 and 4x4 set (both p's < .001). As for 3x3 set, symbols 5, 16 e 9 were the fastest recognized (27.7 s, 35.6 s and 37 s, respectively) while symbols 3, 2 and 14 were the slowest (69.4 s, 71 s and 89 s).
When considering symbol category, L symbols were the fastest recognized (Fig. 10), whereas T symbols were the slowest.
As for the 4x4 set, symbols 16 and 11 were the fastest identified (28.3 s and 37.1s, respectively), while symbols 8, 1 and 6 needed longer times to be recognized (56 s, 64.1 s, 64.2, respectively).
When considering symbol category, U symbols were the fastest recognized (Fig. 10), whereas T symbols were the slowest.

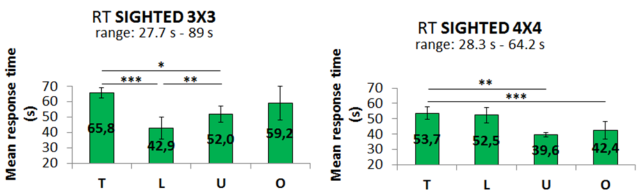

Figure 10: Reaction times for sighted participants

3.4 Group comparisons

3.4.1 Accuracy

The level of visual ability had an effect on recognition accuracy both in the 3x3 (H = 14.7, p = .0006) and 4x4 set (H = 7.8, p = .02). As for the 3x3 set, low vision accuracy (81.6%) was significantly lower than blind (90.5%, p = .001) and sighted accuracy (90.1%, p = .002). For the 4x4 set, low vision performance (87.5%) was significantly lower than blind performance (93.8%, p = .008).
Fig. 11 shows the comparison between groups for each symbol category in the two sets. For the 3x3 set, the accuracy of the low vision participants was lower for symbols T and O. Group differences were reduced in the 4x4 set (see Fig. 11).

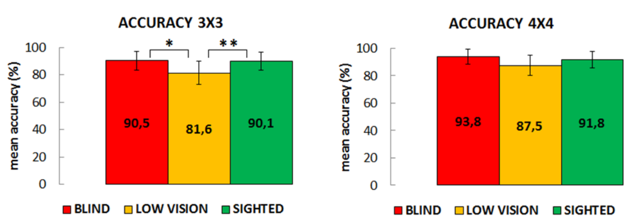

Figure 11: Accuracies: comparison among groups

3.4.2 Response time

The level of visual ability had an effect also on response times both in the 3x3 (H = 9.9, p = .001) and 4x4 set (H = 37.1, p = .001). As for the 3x3 set, blind participants (16.9s) were faster than low vision (25.9s, p < .001) and sighted (55s, p < .001). Low vision were faster than sighted (p < .001).
We observed the same trend in the 4x4 set. Blind participants (17s) were faster than low vision (25.9s, p < .001) and sighted (47s, p < .001). Low vision were faster than sighted (p < .001).
This trend was the same for all the symbols categories in both sets (see Fig. 12).

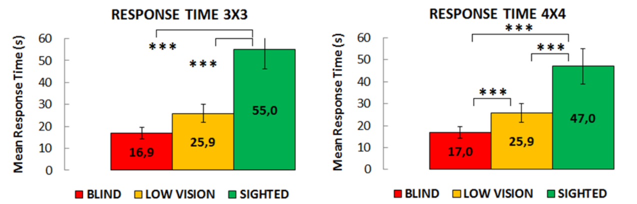

Figure 12: Response times: comparison among groups

4 DISCUSSION

In this work we studied the influence of resolution and complexity of pin-base tactile symbols on discrimination accuracy and response time. This study clarifies that a tactile dictionary can be presented on a Braille-spaced graphical display, with accuracies that are in general higher than 90% regardless of visual disability and with almost no training. We tentatively derive a set of design rules that might be of help for designers and rehabilitation practitioners:

- Both 3x3 and 4x4 resolutions seem appropriate to define a tactile dictionary
- L-shaped and U-shaped symbols are preferred with 3x3 resolution. O-shaped should be avoided.
- O-shaped symbols can be safely considered in 4x4 symbols
- A slower learning curve should be expected if the person has a residual vision

In fact, a first finding concerns a possible optimal set of usable tactile symbols. "L-shaped" and "U-shaped" symbols appeared to be the easiest to be recognized, regardless of visual disability, especially if compared to "T-shaped" symbols. We hypothesize that this happened because L- and U-shaped had a simplest geometrical shape, with two taxels protruding at least in two locations in the figure. The two legs of the L and the first and third leg of a U seemed more markedly perceivable, unlike the T. Even though familiarity is known as an important factor affecting tactile picture perception [see 8, for a review], a relationship with a possible visual reminiscence of the Latin alphabet has to be excluded, since "T-shaped" symbols corresponded to worse performance. The "T-shaped" may have failed because of their horizontal/vertical edges protruding only by 1 pin from the other vertical/horizontal edge. This may have tricked participants, that also confused the four T-shaped symbols with each other and with other symbols. However, this result complies with previous findings [18] in that our best symbols had only either two or three edges. Therefore, tactile symbols with simple geometry and few edges seem the best to constitute a tactile dictionary when using a small-size tactile display.
The O-shaped symbols were most likely too small. However, when dealing with 4x4 symbols, the O-shaped were clearly less ambiguous, as apparent from the remarkably slower response times. This happened independently on visual disability.

A second finding is that that discrimination is not influenced by resolution, at least at the tested sizes. On the contrary, resolution affected response time. Participants response time was indeed faster as symbols resolution increased. This can be explained by the different amount of discrete information for tactile symbols. In fact, 3x3 symbols are depicted by a number of pins between 4 and 9, while 4x4 symbols employ between 6 and 16 pins, meaning an average of 45% of additional information. However, such additional information only helps in being faster, but not in being more accurate. This may be in part due to a ceiling effect, since on average both discrimination performance are beyond 90%. Therefore, larger tactile symbols may be preferable, although more resolutions should be considered to reinforce this finding.

This is not the first study that presents low-resolution tactile symbols. Crossan and Brewster used single edges on a 4x4 pin-based tactile display [25] with blind participants, but did not evaluate a dictionary because symbols were edges of virtual objects in a bimanual navigation task; Tahir [26] used a single 2x4 braille cell with only 7 symbols with the different purpose of pointing to digital information with a remote control; Ziat [28] studied tactile zoom, but the idea was to manipulate the zoom factor, with a constant display size.
Pietrzak [27] used size as a factor for the design of tactile icons and found that a subset of navigational symbols containing L-shaped symbols mixed with I-shaped symbols was easier to discriminate if it was presented as a 4x4 symbols rather than a 3x3. They did not recruit persons with visual impairment however. Yet, their results on sighted subjects comply with ours, since L-shaped were found to be better than other symbols. However, with sighted subjects we found U-shaped symbols (not considered in [27]) to be significantly better than any other category.

One limitation of our study is that we did not consider higher resolutions. We expect higher resolutions to increase the accuracy level and decrease the response time. Our discrimination scores are already quite high with 3x3 and 4x4 symbols: given that no time limit was given to the participants, we probably would have incurred into ceiling effects with 5x5 symbols and more. Also, we could have not displayed 16 symbols with higher resolutions on a 30x32 display, therefore the experimental manipulation could have made the comparison among resolutions tricky. In another study [29], we have considered 6x6 symbols shaped as crosses and shown that they can be the basis for increasing spatial learning skills in blind children and adolescents.

A last novel aspect of our study is that, unlike previous literature, we did not attach semantics to our tactile symbols (such as cardinal points or features of a map during navigation), nor we suggested to name the symbols in a way defined by the experimenter. In this sense, our study is unbiased towards an application and can be applied in general. Our study clarifies that already 3x3 and 4x4 symbols are effective enough to be distinguished in dynamic tactile maps and drawings. We have shown that to find a suitable dictionary of discrete pin-based tactile symbols, resolution seems not a major factor for performance, while it affects discrimination time of tactile symbols. Our study helps with standardization of tactile graphics, which is a paramount requirement for visually impaired computer users.

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