A Refreshable Tactile Display Effectively Supports Cognitive Mapping Followed by Orientation and Mobility Tasks

A Comparative Multi-modal Study Involving Blind and Low-vision Participants

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ABSTRACT

We investigate the role of refreshable tactile display in supporting the learning of cognitive maps, followed by actual exploration of a real environment that matches that map. We test both blind and low-vision persons and compare displaying maps in three information modes: with a pin array matrix, with raised paper and with verbal descriptions. We find that the pin matrix leads to a better way of externalizing a cognitive map and reduces the performance gap between blind and low-vision people. The entire evaluation is performed by participants in autonomy and suggests that refreshable tactile displays may be used to train blind persons in orientation and mobility tasks.

CCS CONCEPTS

• CCS → Human-centered computing → Accessibility → Accessibility technologies

KEYWORDS

Haptic rendering; Assistive Technology; Visual Impairment; Blindness; Tactile Graphics; Pin Array Matrix; Orientation and Mobility; Navigation; Externalization; Cognitive Mapping; Refreshable Braille Display

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1 Introduction

Navigation is an ability that mainly relies on visual inspection of the environment. As such, this capability can be impaired in people with visual impairment [19]. For instance, blind persons might have difficulties in estimating distances [6] and inferring spatial relationships in large spaces [8]. Furthermore, they tend to use *route-like* and not *survey* representations [14, 16]. The former representations are egocentric while the latter are allocentric because they are based on a *bird's eye* view, independent from the observer [22]. Importantly, egocentric representations are often associated with lower navigation performance compared to allocentric representations [2]. The preference for route-like representations might depend on the way blind persons acquire spatial information. Since they cannot use sight, they form spatial representations, known also as spatial cognitive maps, in a serial fashion through the senses of touch, audition and kinesthetic information [15, 16]. However, blind persons are in principle able to develop and use survey representations and, when they do it, their spatial performance can be similar to that achieved by sighted persons [23].

As sighted persons do, blind individuals can form spatial cognitive maps through the direct exploration of the environment and/or using spatial maps. Tactile maps are largely employed in orientation and mobility activities because they show a global representation of an environment while including only essential spatial information [5, 7, 27]. Standard tactile maps are produced using swell or Thermoform paper. Although these maps are proven to be useful in mobility activities [2, 13, 24–27], they unfortunately show several limitations. The production process of maps is complex, time consuming and expensive; information is static, i.e. cannot change over time, nor cannot be taylored to user needs.

Another approach to provide spatial information takes advantage of verbal descriptions. This method does not require to access special printers and raised paper and it can contain much more information than a printed map. However, verbal descriptions may include complex or unknown concepts and also imprecisions [1].

To date, no commercially widespread instruments exist that translate digital maps into tactile (or audio-tactile) representations. Therefore, the lack of accessible solutions for tactile graphics widens the gap between blind and sighted people in the

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touchscreen information era, where ‘touchscreen’ is a practically ill-posed term since any commercial touchscreen requires vision.

In the last decades, electronics maps have been built to overcome the limitations of classical tactile maps [9, 17]. Refreshable tactile displays, in particular pin-arrays matrices, represent one kind of electronic maps. They are composed of arrays of pins, called ‘taxels’ (i.e. the tactile equivalent of the pixels) that can be raised or lowered under computer control [28]. Pioneering works have shown that a pin array matrix (PAM) can be effective in orientation and mobility tasks in blind persons [4, 10, 12, 21, 30, 31]. However, little studies aimed at comparing the effectiveness of pin array maps to standard paper and verbal description methods.

Zeng, Miao and Weber [29] compared pin array and paper maps and found that participants’ accuracy and speediness in learning the two kinds of maps and their ability to make pre-journey routes were similar when using the two methods. However, they did not compare tactile maps with verbal descriptions. Furthemore, they did not test the actual navigation performance that followed knowledge acquisition obtained from the map.

Another recent study compared audio-tactile and verbal descriptions and found that, when using the first method blind users were more accurate both in map comprehension and points of interest localization in the real environment [18]. However, the authors did not include standard paper maps in their comparison.

Our study is aimed at comparing the three conditions described above, i.e. 1. A tactile condition with raised paper, 2. A tactile condition with a PAM 3. A verbal-only description. We compared them both in terms of accuracy when building a cognitive map and accuracy when actually navigating in the real environment represented by the map.

A second aim is comparing the ability in using the three methods by visually impaired persons with varying levels of visual ability (i.e. blind vs low vision).

2 Methods

2.1 Participants

Thirty-three participants (sixteen totally blind and seventeen very low vision) were recruited by the Chiossone Foundation in Genoa. Age range of participants was 12-61 years. All participants were naïve to the experiment and none had a cognitive impairment that could influence performance in the tasks. The participants’ family gave informed consent in compliance with the Declaration of Helsinki. The experimental protocol was approved by the local Ethics Committees. Two experimenters and one orientation and mobility practitioner assisted the participants during the tasks.

2.2 Materials

Three maps of a room were drawn using both a PAM named Hyperbraille and swell paper (see Figure 1). The Hyperbraille is a multiline Braille display provided by Metec AG. It is composed by an array of 30 by 32 taxels. The distance between taxels is 2.5 mm and they can raise at about 0.7 mm. The display was connected via USB to a standard laptop and controlled by the software PadDraw, Matlab and Psychtoolbox 3 [3, 11].

2.2.1 Stimuli. The participants had to explore the three tactile maps, that showed the main characteristics of the room (i.e. walls, doors, windows) and the location of two objects: a small square, representing a little table and a reversed “U” symbol representing a chair.

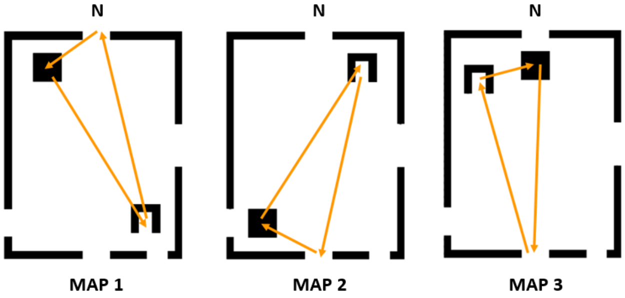


Figure 1: Tactile maps on swell paper. The corresponding maps with the PAM had similar content and size (7.8 cm X 6 cm). The arrows (not present in the real maps) show examples of the order of the targets that participants had to reach.

2.2.2 Map externalization. After the exploration, participants had to reconstruct the map of the room using a set of standard LEGO bricks (see Figure 2). The LEGO elements that participants had to position correctly to build the room were six: four walls and two objects (see Figure 2).

2.2.3 Post-navigation questionnaire. At the end of each navigation task participants had to answer to the following questionnaire using a 10-points scale (from 1 = not at all, to 10 = very much).

Table 1: Post-navigation questionnaire

Item #	Question
1	How much efficient did you find the map presentation modality?
2	How much precise were you during the building task?
3	How mentally demanding was the task?
4	How physically demanding was the task?
5	How much precise were you in pointing to the targets?
6	How much precise were you in reaching the target positions?
7	How much effort did you put to achieve this performance level?
8	How much fast you were during the tasks?

9	How much did you feel obliged to do the task quickly?
10	How much did you feel insecure, discouraged, irritated, stressed or bored?

2.3 Procedure

All participants with residual sight were blindfolded to avoid visual inspection of the material and the room. Then, they wore a hat on which three infrared markers were fixed to capture head movements and other six markers were fixed on other body locations (two on the shoulder, one on the chest, one on the hand and two on the feet) to capture all the body movements using a system of ten infrared cameras (VICON system). The experiment comprised three phases (see Figure 2): 1) acquisition of the spatial map; 2) building of the spatial map using LEGO bricks; 3) navigation task in the real room.

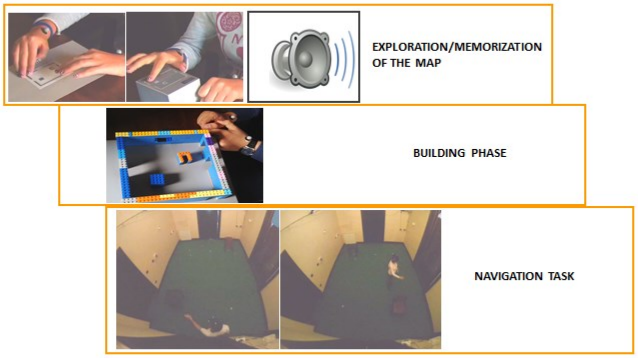


Figure 2: Timeline of the experiment

In the first phase, participants acquired the spatial maps using each of the three conditions in different sessions (PAM, PAPER and VERBAL) in counterbalanced order. The presentation of the map included also information about a navigation task, in which the participants had to reach three targets in a specific order (e.g. table first, then chair, finally the exit door). The spatial information was provided using two different sensory modalities (touch and audition) that were differently involved in the three different conditions.

For instance, swell paper maps included also some speech synthesis describing the map legend. Table 2 shows the kind of sensory information provided in each condition.

Table 2: Kind of sensory information given in the three conditions (T=tactile, A=acoustic)

Condition	Room description	Furniture description	Task description
PAPER	T	A	A
PAM	A (sequential, synced with T)	T	A
VERBAL	A (sequential)	A	A

The table shows that the three conditions differ only in the modality that describes the room and the furniture.

Specifically, the participant was put in a scenario where ideally no external rehabilitators were available and learning had to be achieved in autonomy. Therefore, the room description was given with speech synthesis when the technology allowed it, i.e. in VERBAL and PAM conditions. The PAPER condition allows instead a tactile legend on paper. However, the furniture description was given verbally with PAPER (and not with a Braille legend) because we recruited very low vision participant who are infrequently Braille readers. The PAM condition, instead, allowed to display spatial information sequentially (e.g. the furniture after the room walls), therefore minimizing ambiguity, and did not need audio. Finally, since the description of the task did not have to influence our metrics it was provided verbally in all the conditions.

After the acquisition phase, participants had to reconstruct the map of the room using the LEGO bricks. At the end of the externalization, an experimenter took a picture of the reconstruction. No feedback about their reconstruction performance was given to participants.

Finally, participants performed the navigation task. The orientation and mobility practitioner accompanied the participant to the entrance door. Participants were firstly asked to point with their index fingers of the dominant hand to the expected location of the first object. Then, they had to reach it. From that position, they had to point to the second object and so on, following the order received during the first phase, until they reached the exit door.

At the end of the navigation, participants completed the post-navigation questionnaire. All the three phases described above were repeated for all the conditions (PAM, PAPER, VERBAL) in counterbalanced order across participants. Motion capture data were acquired and the whole experiment was video recorded.

2.4 Experimental variables

Independent variables: a) condition (PAM, PAPER, VERBAL); b) degree of visual disability (blind, very low vision).

For the dependent variables, in the externalization phase we assigned one point for each component placed in the correct position (maximum = six points). LEGO accuracy was the sum of all percentage scores achieved by participants. We also measured the reconstruction time. For the navigation phase, we measured:

a) the navigation time

b) the length of the path in meters

c) the pointing error

d) the number of targets the participants were able to reach

e) a performance index calculating the ratio between reaching accuracy of targets and path length.

Using these metrics it was possible to disambiguate between two kinds of navigation strategies: i) walking without maintaining any trajectory looking for objects; ii) walking towards the desired object having a good representation of its position in the room.

3 Results

3.1 General effect of condition

In a first analysis, we investigated whether the condition modulates the performance in the different phases of the study. To do so, we merged the blind and the low vision groups and we ran Friedman analyses for each phase of the study. We found that condition did not modulate participant performance in any task. Since the different conditions differed also for the kind of sensory modality involved, e.g. in the PAPER and in the PAM conditions both touch and audition were stimulated, we subtracted the performance achieved by participants in the VERBAL condition from the performances obtained in the PAPER and in the PAM conditions. After this normalization, we compared the scores of each dependent variable in each phase of the study.

3.1.1 Externalization performance. We found that the normalized accuracy score was higher in the PAM than in the PAPER condition when externalizing with LEGO (t=51, p<.05, see Figure 3). No differences were observed in LEGO reconstruction time. Therefore, the participants were more accurate in externalizing a map when it was memorized beforehand with a pin array matrix compared to raised paper.

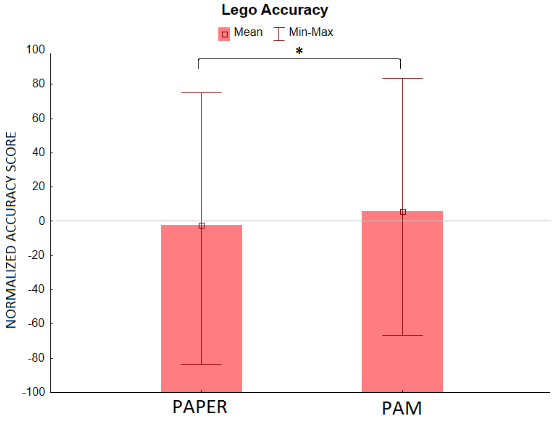


Figure 3: Mean and min-max values of accuracy in building task following PAPER and PAM acquisition normalized by VERBAL condition (SEM reported). *, p<.05.

3.1.2 Navigation performance. No differences were observed in the navigation task variables.

3.1.3 Post-navigation survey. We found an effect of condition on participants' judgments about the efficiency of the kind of map (χ^2 (2, N= 33) = 23, p< .01). The judged efficiency of PAPER was significantly higher than the efficiency of VERBAL (p<.01, see Figure 4). The efficiency of PAM condition was significantly higher than the efficiency of VERBAL (p<.01). Finally, the efficiency of PAPER was significantly lower than the efficiency of PAM condition (p<.05). Furthermore, the self-evaluation about accuracy achieved in building task in VERBAL was significantly lower than PAPER (p<.05) and PAM condition (p<.05, see Figure 4).

Therefore, participants found that the pin array matrix led to better performance compared to the other conditions.

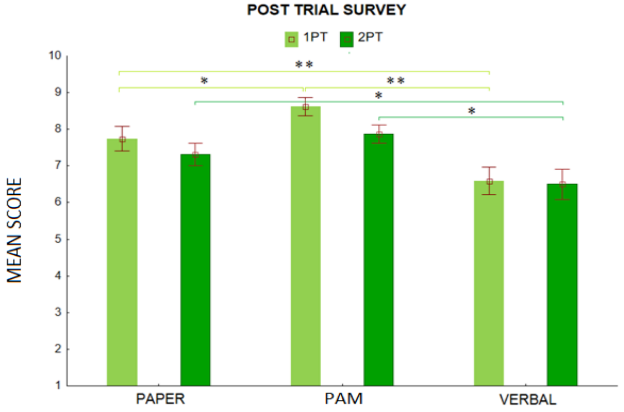


Figure 4: Mean participants' judgements about technology efficiency (item 1) and self-evaluation of performance in building task (item 2) (SEM reported). *, p<.05, **, p<.01

3.2 Interaction between condition and level of visual disability

3.2.1 Externalization performance. We did not find an interaction when considering LEGO building accuracy. For the reconstruction time, low vision participants were significantly faster than blind subjects (U = 53, p<.05, see Figure 5). Therefore, the use of PAPER widened the gap linked to disability, while PAM did not.

3.2.2 Navigation performance. We found an interaction between condition and visual disability level only in the reaching accuracy variable. Indeed, low vision participants obtained an higher score than blind in the VERBAL condition (U = 67, p<.05, see Figure 6). Therefore, a significant difficulty to transform VERBAL descriptions into egocentric representations was linked to an higher level of visual disability, while this did not happen when information was given with a PAM.

3.2.3 Post-navigation questionnaire. No interaction between condition and visual disability level was observed in the questionnaire.

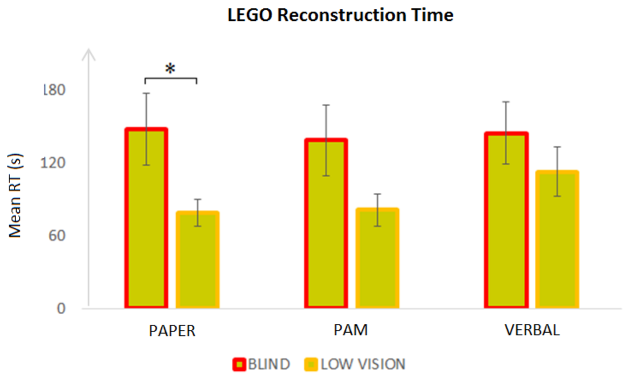


Figure 5: Mean reconstruction time in LEGO building following the three different map acquisition conditions (PAPER, PAM and VERBAL) in low vision and blind participants (SEM reported). *, p<.05.

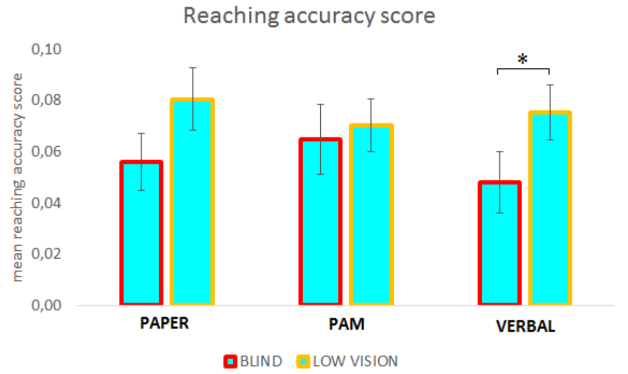


Figure 6: Mean normalized reaching accuracy score in low vision and blind participants for each condition (SEM reported). *, p<.05.

3.3 Effect of level of visual disability

3.3.1 Externalization performance. Results show blind and low vision obtained a similar level of accuracy in LEGO building (U = 1135; p>.05, see Figure 7), that was on average 72%. However, low vision were significantly faster than blind participants in building the LEGO (U = 533.5, p<.01).

3.3.2 Navigation performance

3.3.2.1 Pointing. As a first surprising result, the level of visual disability did not modulate the error pointing score, but did modulate indeed the reaching accuracy score (U = 972, p<.01, see Figure 7). This strong effect might be mostly due to how differently VERBAL descriptions affect the two groups (see Figure 6).

3.3.2.2 Path length. Low vision covered shorter paths than blind participants (U=894, p<.05, see Figure 8). Instead, the two groups did not differ in terms of navigation time (U=907, p>.05).

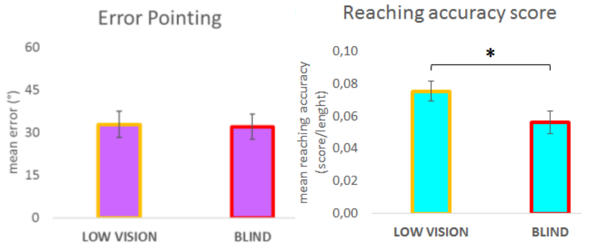


Figure 7: Left: Mean pointing error during the navigation in low vision and blind participants. Right: Mean of the ratio between raw reaching accuracy and path length covered by participants in the navigation task (SEM reported). *, p<.05.

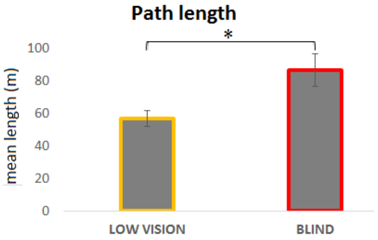


Figure 8: Mean path length in meters covered by low vision and blind participants in the navigation task (SEM reported). *, p<.05.

Therefore, blind participants explored more extensively the real room, possibly at a slightly higher speed pace.

3.3.3 Post-navigation questionnaire. The only item in which we found a significant difference between groups concerned the amount of effort employed by participants to perform the navigation task (item 7). Low vision gave a higher score than blind participants (U=583, p<.05, see Figure 9).

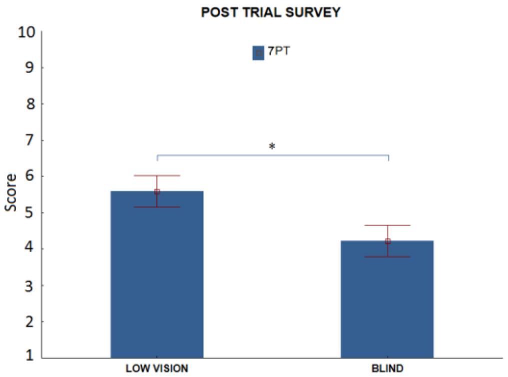
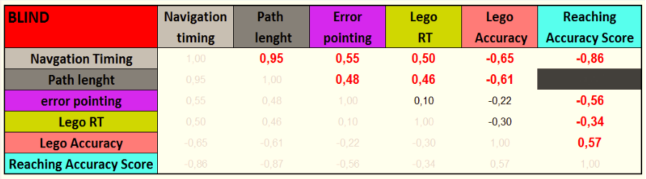


Figure 9: Mean amount of effort declared by low vision and blind participants during navigation task (SEM reported). *, p<.05.

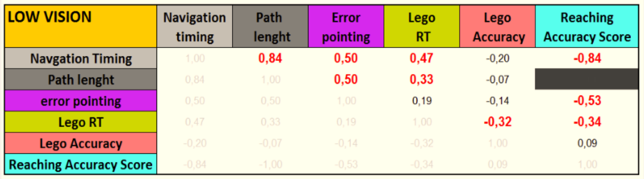
3.4 Correlations between different scores

We correlated the performance scores we collected during the building and navigation tasks using Spearman correlations. In the blind (see Table 3), we found that higher level of accuracy reached during the building phase (LEGO Accuracy) had a positive correlation with the level of performance reached during the navigation phase (reaching accuracy score). Furthermore, participants who achieved a good performance during the building phase covered shorter paths during the navigation phase (path length) and were faster to perform the navigation task (navigation time). Participants that were accurate during the pointing phase (error pointing) covered shorter paths and employed less time.

Table 3: Spearman correlation coefficients table. Red values indicate a significant correlation (p<.05).



BLIND	**Navigation timing**	**Path lenght**	**Error pointing**	**Lego RT**	**Lego Accuracy**	**Reaching Accuracy Score**
Navgation Timing	1,00	**0,95**	**0,55**	**0,50**	**-0,65**	**-0,86**
Path lenght	0,95	1,00	**0,48**	**0,46**	**-0,61**	[redacted]
error pointing	0,55	0,48	1,00	0,10	-0,22	**-0,56**
Lego RT	0,50	0,46	0,10	1,00	-0,30	**-0,34**
Lego Accuracy	-0,65	-0,61	-0,22	-0,30	1,00	**0,57**
Reaching Accuracy Score	-0,86	-0,87	-0,56	-0,34	0,57	1,00



LOW VISION	**Navigation timing**	**Path lenght**	**Error pointing**	**Lego RT**	**Lego Accuracy**	**Reaching Accuracy Score**
Navgation Timing	1,00	**0,84**	**0,50**	**0,47**	-0,20	**-0,84**
Path lenght	0,84	1,00	**0,50**	**0,33**	-0,07	[redacted]
error pointing	0,50	0,50	1,00	0,19	-0,14	**-0,53**
Lego RT	0,47	0,33	0,19	1,00	**-0,32**	**-0,34**
Lego Accuracy	-0,20	-0,07	-0,14	-0,32	1,00	0,09
Reaching Accuracy Score	-0,84	-1,00	-0,53	-0,34	0,09	1,00

In low vision participants, we found that participants that were accurate during the pointing phase (error pointing) and during reaching object phase (reaching accuracy score) covered shorter paths and were faster to accomplish the navigation task. We also found a correlation between LEGO scores and LEGO reconstruction time. In particular, participants that achieved higher accuracy score (LEGO accuracy) were faster to complete the building task. The two groups mostly behaved similarly but for the role of externalization: good externalization scores predict the performance in the real room in the blind, while such link cannot be observed in low vision.

4 Discussion

Our results confirm the effective role of pin array matrices (PAM) in the construction and memorization of cognitive maps when vision problems occur. Our study has two main novelties. First of all, it compares three different information modalities in two groups of different levels of visual disability. Secondly, the quality of cognitive mapping is scored along with scores of the quality of the actual exploration. In particular, the use of pin array matrices to learn digital maps with touch objectively facilitates a subsequent reconstruction with physical means (i.e. LEGO bricks) more than what traditional raised paper can do. This is reflected by subjective judgments which also confirm how verbal descriptions are suboptimal, in agreement with Papadopoulos [18]. Interestingly, the use of pin arrays does not create a gap between blind and low vision people according to two performance metrics. On the contrary, the gap is evident when learning maps with verbal means (blind people are worse than low vision) or when reconstructing maps after using paper (low vision people are faster). The 'inclusive' effect of pin arrays seems not be due to ceiling effects, since blind people tend to improve their performance in the room. Regardless of the information modality, the fact that (blindfolded) low-vision people outperform blind persons in a reaching task is not new, but the fact that blind persons can point to targets in a room, merely after having studied them on a map, with similar accuracy than low-vision fellows seems surprising. In fact, people with residual vision dispose of daily reference points to refine pointing abilities over time, while blind persons can only infer their location with non-visual information (e.g. sounds and air motion). The overall higher path length and the lower declared amount of effort of blind persons are non-surprising results because they are consistent with an occasional tendency of blind persons in underestimating the difficulty in spatial tasks [32]. Finally, the correlation between our different metrics suggest that only in blind persons an effective externalization performance could hint a similarly effective navigation performance. This last result can be important in rehabilitation, where predicting the outcome of time-consuming practices can be of great value. One limitation of this work is its non-longitudinal nature, caused by the relatively long sessions (each participant sustained all the three conditions). However, involving more than thirty participants allowed us to positively evaluate pin array matrices as a technology that can substitute raised paper at least in the preparation and execution of orientation and mobility exercises. Although rehabilitation practitioners were involved at all stages of the protocol, we emphasize that during our experiments blind and low-vision people attempted to achieve all the tasks with minimal external assistance. Therefore, the scope of our results extends to home-based scenarios, where tactile graphics can be used to help blind persons to autonomously train their spatial abilities.

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REFERENCES

[1] Bentzen, B.L. 1997. Orientation aids. *Foundations of orientation and mobility*. B.B. Blash et al., eds. AFB Press.

[2] Bentzen, B.L. 1972. Production and Testing of an Orientation and Travel Map for Visually Handicapped Persons. *New Outlook for the Blind*. (1972).

[3] Brainard, D.H. 1997. The Psychophysics Toolbox. *Spatial Vision*. 10, 4 (Jan. 1997), 433–436. DOI:https://doi.org/10.1163/156856897X00357.

[4] Brayda, L. et al. 2018. Updated Tactile Feedback with a Pin Array Matrix Helps Blind People to Reduce Self-Location Errors. *Micromachines*. 9, 7 (2018), 351. DOI:https://doi.org/10.3390/mi9070351.

[5] Cattaneo, Z. et al. 2008. Imagery and spatial processes in blindness and visual impairment. *Neuroscience and biobehavioral reviews*. 32, 8 (Oct. 2008), 1346–60. DOI:https://doi.org/10.1016/j.neubiorev.2008.05.002.

[6] Gaunet, F. and Thinus-Blanc, C. 1996. Early-Blind Subjects' Spatial Abilities in the Locomotor Space: Exploratory Strategies and Reaction-to-Change Performance. *Perception*. 25, 8 (Aug. 1996), 967–981. DOI:https://doi.org/10.1068/p250967.

[7] Golledge, R.G. 1991. Tactual strip maps as navigational aids. *Journal of Visual Impairment & Blindness*. 85, 7 (1991), 296–301.

[8] Herman, J.F. et al. 1983. Cognitive mapping in blind people: Acquisition of spatial relationships in a large-scale environment. *Journal of Visual Impairment & Blindness*. 77, 4 (1983), 161–166.

[9] Hyperbraille: The project.: 2019. *http://hyperbraille.de/project/*.

[10] Ivanchev, M. et al. 2014. Pre-journey Visualization of Travel Routes for the Blind on Refreshable Interactive Tactile Displays. Springer, Cham. 81–88.

[11] Kleiner, M. et al. 2007. What's new in Psychtoolbox-3? *Perception ECVP Abstract Supplement*. 36 (2007).

[12] Leo, F. et al. 2019. Blind Persons Get Improved Sense of Orientation and Mobility in Large Outdoor Spaces by Means of a Tactile Pin-Array Matrix. *CHI'19 Workshop on Hacking Blind Navigation* (Glasgow, Scotland, 2019).

[13] Leonard, J.A. and Newman, R.C. 1967. Spatial Orientation in the Blind. *Nature*. 215, 5108 (Sep. 1967), 1413–1414. DOI:https://doi.org/10.1038/2151413a0.

[14] Millar, S. 1994. *Understanding and Representing Space: Theory and Evidence From Studies with Blind and Sighted Children*. Oxford University Press UK.

[15] Millar, S. 1994. *Understanding and Representing SpaceTheory and Evidence from Studies with Blind and Sighted Children*. Oxford University Press.

[16] Noordzij, M.L. et al. 2006. The influence of visual experience on the ability to form spatial mental models based on route and survey descriptions. *Cognition*. 100, 2 (2006), 321–342. DOI:https://doi.org/10.1016/j.cognition.2005.05.006.

[17] O'Modhrain, S. et al. 2015. Designing media for visually-impaired users of refreshable touch displays: Possibilities and pitfalls. *IEEE Transactions on Haptics*. 8, 3 (2015), 248–257. DOI:https://doi.org/10.1109/TOH.2015.2466231.

[18] Papadopoulos, K. et al. 2017. Orientation and mobility aids for individuals with blindness: Verbal description vs. audio-tactile map. *Assistive Technology*. 00, 00 (2017), 1–10. DOI:https://doi.org/10.1080/10400435.2017.1307879.

[19] Pasqualotto, A. and Proulx, M.J. 2012. The role of visual experience for the neural basis of spatial cognition. *Neuroscience and Biobehavioral Reviews*. 36, 4 (2012), 1179–1187. DOI:https://doi.org/10.1016/j.neubiorev.2012.01.008.

[20] Schmidt, S. et al. 2013. Spatial representations in blind people: The role of strategies and mobility skills. *Acta Psychologica*. 142, 1 (2013), 43–50. DOI:https://doi.org/10.1016/j.actpsy.2012.11.010.

[21] Schmitz, B. and Ertl, T. 2012. Interactively Displaying Maps on a Tactile Graphics Display. *SKALID 2012-Spatial Knowledge Acquisition with Limited Information Displays: 13* (2012).

[22] Taylor, H.A. and Tversky, B. 1992. Spatial mental models derived from survey and route descriptions. *Journal of Memory and Language*. 31, 2 (Apr. 1992), 261–292. DOI:https://doi.org/10.1016/0749-596X(92)90014-O.

[23] Tinti, C. et al. 2006. Visual experience is not necessary for efficient survey spatial cognition: evidence from blindness. *Quarterly journal of experimental psychology*. 59, 7 (2006), 1306–1328. DOI:https://doi.org/10.1080/17470210500214275.

[24] Ungar, S. et al. 1994. Can visually impaired children use tactile maps to estimate directions? *Journal of Visual Impairment & Blindness*. 88, 3 (1994), 221–233.

[25] Ungar, S. et al. 1997. Teaching visually impaired children to make distance judgments from a tactile map. *Journal of Visual Impairment & Blindness*. 91, (1997), 163–174.

[26] Ungar, S. et al. 1996. The construction of cognitive maps by children with visual impairment. *The Construction of Cognitive maps*. 32, 1951 (1996), 247–273. DOI:https://doi.org/10.1007/978-0-585-33485-1.

[27] Ungar, S. et al. 1993. The role of tactile maps in mobility training. *British Journal of Visual Impairment*. 11, 2 (Jul. 1993), 59–61. DOI:https://doi.org/10.1177/026461969301100205.

[28] Wall, S.A. and Brewster, S. 2006. Sensory substitution using tactile pin arrays: Human factors, technology and applications. *Signal Processing*. 86, 12 (Dec. 2006), 3674–3695. DOI:https://doi.org/10.1016/J.SIGPRO.2006.02.048.

[29] Zeng, L. et al. 2014. Interactive Audio-haptic Map Explorer on a Tactile Display. *Interacting with Computers*. 27, 4 (2014), 413–429. DOI:https://doi.org/10.1093/iwc/iwu006.

[30] Zeng, L. and Weber, G. 2012. ATMap: Annotated Tactile Maps for the Visually Impaired. Springer, Berlin, Heidelberg. 290–298.

[31] Zeng, L. and Weber, G. 2010. Audio-Haptic Browser for a Geographical Information System. Springer, Berlin, Heidelberg. 466–473.

[32] Memeo, M., & Brayda, L. (2016, July). How geometrical descriptors help to build cognitive maps of solid geometry with a 3DOF tactile mouse. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications* (pp. 75-85). Springer, Cham.