

Similarity of Blind and Sighted Subjects When Constructing Maps with Small-Area Tactile Displays: Performance, Behavioral and Subjective Aspects

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Abstract. Conveying spatial information to visually impaired people is possible by leveraging residual tactile abilities. It is still unclear how to effectively evaluate mental map construction beyond performance-based metrics. Here we use a minimalistic mouse-shaped tactile device to display tactile virtual objects. We study how task complexity and visual deprivation influence behavioral, subjective and performance variables both in blind and sighted subjects. Complexity shows to be a factor equally affecting both groups. As well we show that performance, amount of acquired information and subjective judgments of task difficulty do not depend on visual deprivation. Results can help with technological solutions in rehabilitation programs for impaired individuals.

Keywords: Haptics · Visually impaired · Assistive device · Behavior · Cognitive load · Performance

1 Introduction

Haptic feedback has shown to be useful to compensate the lack of visual information when acquiring spatial content [1]: it is indeed possible to teach blind subjects tactile maps of unknown environments [2]. Technological solutions mostly relying on tactile feedback exist, e.g. large-area displays, to be used with both hands [3]: here displayed spatial information is exhaustive at the price of bulky and costly devices. Alternatively, one can rely less on touch, but more on proprioception and motion, through small-area displays [4]: here the resemblance of tactile maps to their real counterparts is lower, however with reasonable device dimensions and costs. Since using small-area tactile displays possibly requires more effort for potentially future users, assessing the efficacy of such systems is crucial in the context of Orientation and Mobility (O&M) and, more generally, in rehabilitation scenarios. To this aim, mapping ability is generally only evaluated with simple

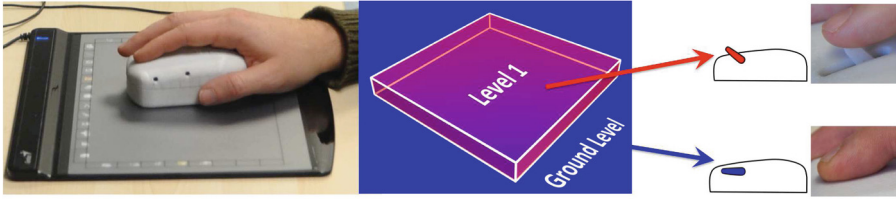


Fig. 1. TActile Mouser operating principle. Left: TAMO moved on the positioning tablet; Center: when the finger is on top of the virtual object, the lever rises at Level 1, otherwise it lowers to Ground Level. Right: finger-lever contact.

scores, coming from questionnaires, error rates or execution times [5]. However, this does not clarify *how* and with *how much effort* a map is actually built. In fact, most studies have focused on current spatial abilities (competence) rather than on potential, probably missing possible improvements in rehabilitation training. Assessing tactile displays can be difficult due to possible mismatches between subjects' perceived and real stimuli [6]. Involving behavioral and performance variables may help [7], also comparing real and virtual explored objects [5]. Previous works encoded task difficulty as velocity of stimuli presentation, but it was not a significant factor when presenting Braille dots as a sequence of serialized temporal stimuli [8], meaning that the relations between task difficulty, performance and the required mental effort to construct the map are not obvious. Nor it is clear whether early rather than *de novo* blind subjects would equally benefit from tactile displays, i.e. if tactile information should be calibrated on the amount of vision loss. We have proposed a haptic mouse-shaped device capable of delivering simple tactile maps of virtual objects and we have shown that blind and sighted subjects qualitatively exhibit similar exploration strategies [9]. In this work we quantitatively compare two groups of blind and sighted subjects - considered as a model of *de novo* blind subjects - in terms of performance, amount of acquired information and cognitive load. We answer to the following research questions. When asked to construct virtual maps with touch:

1. Are blind and sighted subjects comparable when considering measures of performance, cognitive load and information acquisition?
2. How much task difficulty, as compared to visual deprivation, modulates these variables?
3. Are these possible modulations linked to an at least partially successful mental map construction?

2 Experimental Setup and Protocol

The TActile Mouser (TAMO) is a minimalistic device aimed at getting 3D virtual maps through the sense of touch (see Fig. 1), see [10] for details. 15 blind subjects with age 34 ± 12 (range: 20–62 years) and 15 blindfolded sighted subjects, with

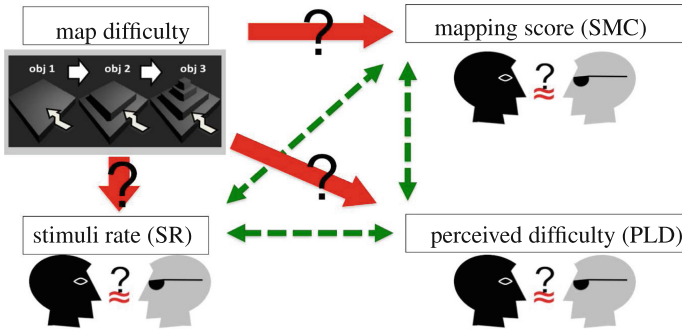


Fig. 2. Methodology: blind and sighted subjects freely explore three virtual environments, of which we measure the effect (red continuous arrows) on performance, cognitive load and information acquisition. We investigate relations between these variables (green dashed arrows) (Color figure online).

age 33 ± 8 (range: 20–46 years) participated in the study. The two groups were matched both for gender (6 female and 9 male) and for age ($t(14) = 0.33$, $P = 75 * 10^{-2}$). Approval by the local ethics research committee and a written informed consent according to the declaration of Helsinki were obtained. All subjects were right-handed. The degree of visual impairment was assessed by the Istituto David Chiossone, who also selected the sample: of the 15 blind subjects, 6 were completely blind, 7 were severely visually impaired and 2 had residual sight. Subjects subsequently explored with TAMO the top-view tactile maps of three, gradually more complex virtual objects (top-left of Fig. 2), namely *obj1*, *obj2*, *obj3*. The aim was to allow construction of a cognitive map in a constrained amount of time: subjects explored each object 10 times, each time for 10 s. Every trial started and stopped with two distinct sounds and was preceded and followed by 10 s of rest. A 2 min pause was induced in-between object explorations. At the end of 10 consecutive explorations of each virtual object, subjects filled the following questionnaires:

- Please rate the difficulty you perceived in constructing the map on a 1–10 scale (higher rates correspond to higher difficulties).
- Please answer these four questions: 1. “How many objects did you identify on the tablet?” (correct answer for all objects: “one”); 2. “Apart from the ground level, how many other different levels did you detect?” (correct answer: “one”, “two”, “four” respectively); 3. “What was the contour of each level?” (correct answer: “a square for each level”); 4. “Where were levels located with respect to each other and with respect to the center of the tablet?” (correct answer: “concentric and in the center”). We assigned 1 point to each correct answer, 0 otherwise.

The following dependent variables were considered: the Perceived Levels of Difficulty (PLD), a *subjective measure* of cognitive load due to map construction,

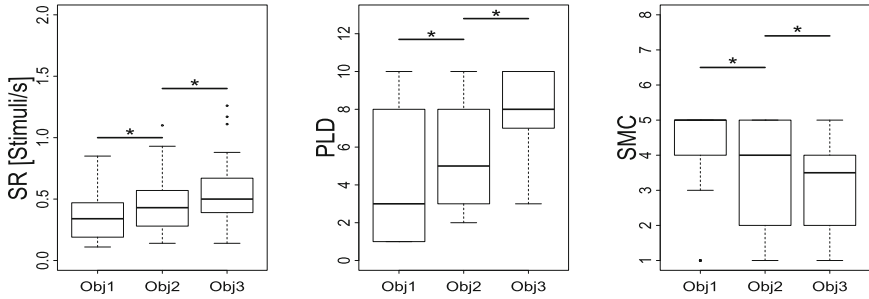


Fig. 3. Stimuli Rates (SR), Perceived Levels of Difficulty (PLD) and Score of Maps Construction (SMC) in function of object complexity. Both blind and sighted subjects are considered together. Box plots show medians (continuous lines), 25% and 75% quartiles (box limits) and whiskers embracing all the data set. Population with not a Gaussian distribution may lack one or both whiskers. Starred links join significantly different conditions ($p < 5 * 10^{-2}$).

resulting from the first question; the Stimuli Rate (SR), a *behavioural objective measure* of acquired information (stimuli per second): for each object and subject, we counted the upward movements of the lever during the exploration, then divided by the whole exploration time; the Score of Map Construction (SMC), a *performance measure* reflecting the number of correct answers in the questionnaire. From SMC we obtained the Correctness of the Map Construction (CMC), an *a posteriori* binary classification of performance thought to be used by Orientation and Mobility operators: mapping was correct (COR) when SMC was greater or equal to 1 point (i.e. $\geq 25\%$ of right answers), otherwise it was incorrect (INC). This threshold was chosen to distinguish subjects who acquired an at least partial amount of spatial information from those who didn't understand any aspect of the explored object, to clarify possible spurious effects. The effect of object complexity, taken as independent variable, on the dependent variables was evaluated by repeated measures ANOVA post-hoc (Tukey HSD) analyses. When distributions were not Gaussian (according to Shapiro-Wilks test), non-parametric Friedman and Wilcoxon tests were respectively used for analysis of variance and for post-hoc comparisons. Statistical analyses were accomplished with R software [11]. All P values were corrected for multiple comparisons using the False Discovery Rate (FDR) method.

3 Results

3.1 Map Complexity Modulates Information Acquisition, Cognitive Load and Performance Independently of Visual Capability

In a first step, we investigated possible effects of object complexity on dependent variables, without distinguishing between blind and sighted subjects. We found (Fig. 3) a significant effect of object complexity on SR ($F(2, 58) = 20.27$,

$P = 2 * 10^{-7}$) which increased from *obj1* to *obj2* ($t(29) = 3.88$, $P = 5 * 10^{-4}$) and from *obj2* to *obj3* ($t(29) = 3.69$, $P = 9 * 10^{-4}$). Similarly, object complexity affected PLD ($\chi^2(2) = 28.10$, $P = 8 * 10^{-7}$ according to Friedman test) which increased from *obj1* to *obj2* ($V = 49.5$, $P = 3 * 10^{-3}$, according to Wilcoxon test) and from *obj2* to *obj3* ($V = 36$, $P = 1 * 10^{-3}$). Conversely, as expected, we found a decreasing trend for SMC ($\chi^2(2) = 18.45$, $P = 9 * 10^{-5}$) from *obj1* to *obj2* ($V = 64$, $P = 6 * 10^{-3}$) and to *obj3* ($V = 161$, $P = 9 * 10^{-4}$). Therefore, when task difficulty increased, acquired information and cognitive load increased while performance decreased. When considering blind subjects only, we found an effect of object complexity on SR ($F(2, 42) = 3.44$, $P = 4 * 10^{-2}$): it increased from *obj1* to *obj2* ($t(14) = 3.21$, $P = 6 * 10^{-3}$) and from *obj2* to *obj3* ($t(14) = 4.6$, $P = 4 * 10^{-4}$). A similar trend was observed for PLD ($\chi^2(2) = 14.31$, $P = 8 * 10^{-4}$), increasing from *obj1* to *obj3* ($V = 54$, $P = 8 * 10^{-3}$) as well from *obj2* to *obj3* ($V = 55$, $P = 5 * 10^{-3}$). SMC showed a significant decreasing trend ($\chi^2(2) = 10.18$, $P = 6 * 10^{-3}$) from *obj1* to *obj2* ($V = 0$, $P = 5 * 10^{-2}$) and to *obj3* ($V = 0$, $P = 2 * 10^{-2}$). When considering sighted subjects only, they qualitatively showed similar increasing trends for both SR and PLD. The trend was almost significant for SR ($F(2, 42) = 1.85$, $P = 8 * 10^{-2}$), while it was fully significant for PLD ($\chi^2(2) = 10.79$, $P = 5 * 10^{-3}$) which increased from *obj1* to *obj3* ($V = 102.5$, $P = 10^{-2}$) and from *obj2* to *obj3* ($V = 88.5$, $P = 2 * 10^{-2}$). SMC showed a decreasing trend, despite it didn't reach significance ($\chi^2(2) = 5.72$, $P = 5 * 10^{-2}$). Therefore, the trends observed in the whole sample are genuinely present and similar in blind as well as in sighted subjects. In a second step, we checked possible effects of visual deprivation on performance, information acquisition and cognitive load. We compared blind and sighted subjects without distinguishing between explored objects: we found (Fig. 4) similar SR ($V = 621.5$, $P = 14 * 10^{-2}$), similar PLD ($V = 504.5$, $P = 51 * 10^{-2}$) and SMC ($V = 270.5$, $P = 32 * 10^{-2}$). Then, we compared groups within each single explored object. For the first object, blind and sighted subjects showed a similar SR ($V = 53.5$, $P = 97 * 10^{-2}$), PLD ($V = 65.5$, $P = 43 * 10^{-2}$) and SMC ($V = 12.5$, $P = 47 * 10^{-2}$). We found similar results for *obj2* (SR: $V = 72.5$, $P = 5 * 10^{-1}$; PLD: $V = 57.5$, $P = 78 * 10^{-2}$; SMC: $V = 46$, $P = 7 * 10^{-1}$) and for *obj3* (SR: $V = 91$, $P = 8 * 10^{-2}$; PLD: $V = 55$, $P = 9 * 10^{-1}$; SMC: $V = 44$, $P = 61 * 10^{-2}$). Therefore, stimuli rates, perceived levels of difficulty and score of map construction during the mapping task were independent of visual experience.

3.2 Introducing Correctness: Even Excluding Possible Spurious Effects, Similarities are Confirmed

We studied if the observed effect of complexity and the absent effect of visual deprivation depended on map correctness (CMC). Therefore, we attempted to perform previously described analyses separately on correct and incorrect mappers (see Table 1). Importantly, we found no difference between blind and sighted subjects, comparing the number of correct mappers. This was true considering all objects together ($\chi^2(1) = 1.66$, $P = 2 * 10^{-1}$), as well separately considering *obj1* ($\chi^2(1) = 0$, $P = 1$), *obj2* ($\chi^2(1) = 0.29$, $P = 6 * 10^{-1}$) and *obj3* ($\chi^2(1) = 0.29$, $P = 6 * 10^{-1}$). This suggests that the success in constructing a tactile map with

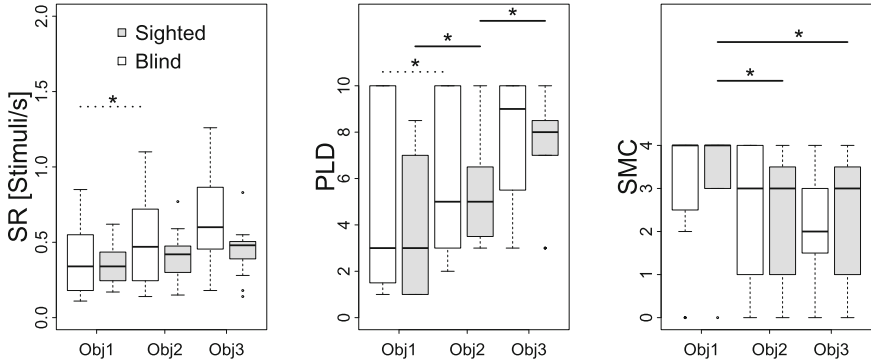


Fig. 4. Stimuli Rates (SR), Perceived Levels of Difficulty (PLD) and Score of Maps Construction (SMC) in function of object complexity and visual ability. Starred links join significantly different conditions ($p < 5 * 10^{-2}$) with continuous lines for sighted and dotted lines for blind subjects.

the TAMO is independent of visual experience. As shown in Table 1 sample size of incorrect mappers was not sufficient to perform further analyses on single objects separately, therefore in the following we considered only correct mappers. For correct mappers, SR increased from *obj1* to *obj3* ($t(59.9) = 3.16$, $P = 3 * 10^{-3}$), while PLD increased from *obj1* ($W = 1120.5$, $P = 9 * 10^{-5}$) and from *obj2* ($W = 1020.5$, $P = 4 * 10^{-3}$) to *obj3*. Conversely, SMC decreased from *obj1* to *obj2* ($W = 243$, $P = 4 * 10^{-2}$) and to *obj3* ($W = 191$, $P = 3 * 10^{-3}$). Then, we distinguished blind from sighted correct mappers. In blind subjects SR increased from *obj1* to *obj3* ($t(18.43) = 2.45$, $P = 2 * 10^{-2}$); PLD increased from *obj2* to *obj3* although it slightly failed the significance ($W = 105$, $P = 6 * 10^{-2}$); SMC decreased from *obj1* to *obj3* ($W = 42.5$, $P = 4 * 10^{-2}$). Sighted subjects showed similar patterns: SR increased from *obj1* to *obj3* ($W = 53.5$, $P = 4 * 10^{-3}$); PLD increased from *obj1* ($W = 164.5$, $P = 2 * 10^{-3}$) and *obj2* ($W = 159.5$, $P = 4 * 10^{-3}$) to *obj3*. Finally, SMC decreased from *obj1* to *obj2* ($W = 58$, $P = 5 * 10^{-2}$) and to *obj3* ($W = 55$, $P = 4 * 10^{-2}$) As a last step, we compared blind with sighted correct mappers, without distinguishing between explored objects: blind and sighted correct mappers had similar SR, PLD and SMC, respectively with $W = 903.5$, $P = 21 * 10^{-2}$, $W = 767.5$, $P = 93 * 10^{-2}$ and $t(76.2) = 0.21$, $P = 83 * 10^{-2}$. Also for incorrect mappers, SR, PLD and SMC were vision independent, (respectively $W = 903.5$, $P = 21 * 10^{-2}$; $t(2) = 2$, $P = 18 * 10^{-2}$ and $t(8.48) = 1.73$, $P = 12 * 10^{-2}$). Importantly we found no difference between blind and sighted correct mappers also separately considering the three explored objects, for SR (*obj1*: $W = 79.5$, $P = 6 * 10^{-1}$; *obj2*: $W = 99.5$, $P = 4 * 10^{-1}$; *obj3*: $W = 120$, $P = 7 * 10^{-2}$), for PLD (*obj1*: $W = 81$, $P = 6 * 10^{-1}$; *obj2*: $W = 75.5$, $P = 7 * 10^{-1}$; *obj3*: $W = 96$, $P = 5 * 10^{-1}$) and for SMC (*obj1*: $W = 101.5$, $P = 6 * 10^{-1}$; *obj2*: $W = 83$, $P = 1$; *obj3*: $W = 86$, $P = 9 * 10^{-1}$).

Table 1. Results of post hoc distinction between correct and incorrect mappers.

Object	Blind		Sighted	
	COR	INC	COR	INC
object 1	13	2	14	1
object 2	12	3	14	1
object 3	12	3	14	1

4 Discussion

This study supports the hypothesis that tactile mapping of virtual objects is a high-level process which can be considered at least partially independent of visual experience. Here we compared blind and sighted subjects during the tactile exploration of different virtual objects, evaluating the mapping process *while* subjects are learning to use a device (no training preceded the experiments). To clarify how mapping is affected by visual deprivation, we compared measures related to different and complementary aspects: stimuli rates (SR), perceived difficulties in constructing a map (PLD) and scores of map construction (SMC) as measures respectively reflecting the amount of acquired information, cognitive load and mapping performance. We found that map complexity influences all measures coherently and, importantly, similarly in blind and sighted people. Furthermore, this result was confirmed also when only considering subjects - the majority of our sample (87.7%) - to whom the TAMO conveyed, at least in small part, the spatial information of the explored map. Considering the construction of virtual maps with touch, we can provide answers to our research questions (see Fig. 2):

- Are blind and sighted subjects comparable when considering measures of performance, cognitive load and information acquisition? Yes. No difference emerged between groups, considering explored objects both globally and separately. Importantly, this was true - *at the same time* - for all our dependent variables. Therefore, blind and blindfolded sighted people seemed to share a *similar* abstract level of mapping process. This is important, given that providing maps of unknown environment is likely to improve Orientation and Mobility abilities. This is also true for *newly* blind people who are still missing long term strategies usually developed by blind people.
- How much task difficulty, as compared to visual deprivation, modulates these variables? *Only* task difficulty (red continuous arrows in Fig. 2) and *not* visual deprivation seemed to modulate our measures. Moreover, task difficulty seemed to modulate *coherently* the considered measures: increasing the number of levels in the explored object increased both the amount of information (SR) and the related cognitive load (PLD), but, as expected, decreased performances (SMC).
- Are these possible modulations linked to an at least partially successful mental map construction? Tentatively yes. The relationships between our measures

were found to be mostly due to correct mappers and to equally affect both blind and sighted subjects. This suggests that the link between different and complementary aspects *can* be considered as a marker of correct mapping - which is in agreement with our previous studies based only on blindfolded sighted subjects [10]- despite an insufficient number of incorrect mappers does not allow, here, a direct comparison between INC and COR.

Admittedly, our setup has elements of arbitrariness. First, objects were not randomized: the experiment was designed as a whole training with an increasing complexity. However, to minimize spurious learning effects, we set short amounts of exploration time. The low contribution of learning and the prominent contribution of complexity in our results is confirmed by the negative significant trends of SMC, which should be either positive or at least non-significant, had learning had an effect. Second, performance could be evaluated by physically reproducing explored objects. However, the items in our questionnaire accurately quantify all aspects of mapping performance. Third, the low threshold to define a map as correct is arbitrary, but could help to detect *potential* abilities: it separates subjects with even an embryonic map understanding from the others. The discovery of potential skills would be however more apparent with longitudinal studies. Fourth, concerning Stimuli Rate, although a priori one cannot be sure that every single rising pin delivers information which is systematically acquired, rather than discarded as noise, the fact that tactile stimuli in our setup derives from active, rather than passive, exploration reinforces the hypothesis that stimuli are actually acquired. In addition we have also shown in past works [9] that this same setup elicits, on average across series of stimuli, brain regions linked to spatial imagination, which would not be the case if tactile stimuli were mainly noise. Last, acquired information could be evaluated with other kinematics data, while other indicators for cognitive load exist, such as NASA-TLX tests [12]. The absence of significant effects of this study would benefit from further confirmation derived by an increased sample size. Although another possible misleading cause of absence of significance may reside in lack of sensitivity of measures, our dependent variables were significantly modulated by object complexity while not by group, therefore showing a sufficient degree of reliability. This study adopts a minimalistic device possibly useful for O&M programs of blind subjects, since in most cases TAMO delivered at least one piece of spatial information. Considering behavioral and subjective aspects as a methodology, and how they relate to performance, may better help to interpret spatial abilities and plan more targeted rehabilitation steps.

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