The Importance of Visual Experience, Gender, and Emotion in the Assessment of an Assistive Tactile Mouse

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Abstract—Tactile maps are efficient tools to improve spatial understanding and mobility skills of visually impaired people. Their limited adaptability can be compensated with haptic devices which display graphical information, but their assessment is frequently limited to performance-based metrics only which can hide potential spatial abilities in O&M protocols. We assess a low-tech tactile mouse able to deliver three-dimensional content considering how performance, mental workload, behavior, and anxiety status vary with task difficulty and gender in congenitally blind, late blind, and sighted subjects. Results show that task difficulty coherently modulates the efficiency and difficulty to build mental maps, regardless of visual experience. Although exhibiting attitudes that were similar and gender-independent, the females had lower performance and higher cognitive load, especially when congenitally blind. All groups showed a significant decrease in anxiety after using the device. Tactile graphics with our device seems therefore to be applicable with different visual experiences, with no negative emotional consequences of mentally demanding spatial tasks. Going beyond performance-based assessment, our methodology can help with better targeting technological solutions in orientation and mobility protocols.

Index Terms—Assistive device, haptics, visually impaired, visual experience, gender, cognitive load, performance, behavior

1 Introduction

Assistive technologies refer to a wide range of devices, strategies, protocols and practices created to face and possibly reduce difficulties encountered by people with disabilities in every-day life. With regard to visual disabilities, assistive technology tends to compensate for the lack of independent mobility in unfamiliar routes and to facilitate the access to digital information, especially for blind subjects [1]. Furthermore, rehabilitation processes, namely Orientation and Mobility (O&M) protocols, have the role to train about noticing, memorizing and predicting regularities of explored environments. To do so, information is acquired through residual modalities, namely hearing and touch, which have different spatio-temporal acuity. The use of tactile maps has shown to enhance spatial knowledge [2]. The same rehabilitation methods created for learning maps cannot be used when blind people need to acquire digital content, normally organized in inaccessible graphical user interfaces designed for sighted users. Access to spatial (e.g. maps) or digital (e.g. websites) content by blind people is today strongly "serialized": keyboard-based or Braille bar-based navigation prevents building a mental picture easily. Web pages, for example, become incredibly long unidimensional vectors of information and remembering the exact location of content systematically becomes a highly demanding mental task. The development of a strong working memory by blind people can in part be a consequence of such drawback. However, there is evidence that manipulation of objects in the peripersonal space of blind people remains efficient [3] and that survey representations can be learnt by blind people [4], but to date there are no truly accessible and low-cost tools to convey dynamic graphical/geometrical content with touch to visually impaired subjects. A lot of research is attempting to make scientific content and graphics more accessible through touch-screens [5] using a variety of actuation modes [6], [7]. Using pin arrays seems a promising solution, but prototypes have a too much high price per pin [8]. We have proposed a minimalist tactile mouse and verified that the understanding of simple 2.5D solids is possible [9] in blindfolded individuals. We have also shown that it stimulates visuo-spatial pathways both in sighted and blind subjects [10].

Our research stems from the fact that rehabilitation methods are not standardized. A lack of technologies and methodologies aimed at improving spatial abilities of blind subjects is apparent [1]. Attempts to include subjective and objective aspects in training evaluations [11] are promising. However, this process remains incomplete if possibly important factors such as behavioral aspects are excluded [12] when proposing novel assistive aids. This happens even if it has been suggested that potential spatial abilities may be hidden in *how* subjects build environmental information [13].

Emotional impact. Research in cybertherapy and education [14] indicates that assistive aids have a lot in common with serious games: widely used in health care, they can reduce stress in preparatory sessions [15], in long term treatments [16] and can improve skills in

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Manuscript received 1 Sept. 2014; revised 16 Mar. 2015; accepted 21 Apr. 2015. Date of publication 26 Apr. 2015; date of current version 14 Sept. 2015. Recommended for acceptance by N.G. Bourbakis, J.A. Gardner, N. Giudice, V. Hayward, M.A. Heller, and D. Pawluk.
For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org, and reference the Digital Object Identifier below.
Digital Object Identifier no. 10.1109/TOH.2015.2426692

learning/recollecting abilities and spatial understanding [17]. The mood of visually impaired subjects and its relation with other measures are not, however, systematically evaluated when assessing assistive technology. Emotional status, especially anxiety, is a factor negatively influencing performances in rehabilitative [18], as well as in educational settings [19]. A feeling of anxiety has shown to affect also working memory resources [20]. High levels of challenges mixed with poor or limited abilities could possibly lead to strong anxiety feelings before tests. Since haptic technology often relies on interaction metaphors to be understood and learnt, it could be interesting to know whether or not a mentally demanding task with an assistive technological aid also entails a variation in anxiety states. Crucial impacts on usability derive from this aspect.

Visual experience. The spatial ability of blind subjects compared with sighted subjects showed a strong dependence on the kind of task [21]. Even if the classification of blindness is rather fragmentary and gives opposing results making comparisons difficult [22], [23], visual deprivation/experience seems to modulate spatial abilities [24]. If we do not consider groups of people with diverse prior visual experience separately, it becomes difficult to conclude if an assistive aid can be more beneficial for the congenitally blind than for the late blind individuals. Analyzing if and how much prior visual experience modulates the capability of using a certain technology seems a necessary step.

Gender differences. Several studies regarding visuo-tactile tasks reported gender differences in terms of performances but just a few investigated this issue associating it with the use of assistive devices [1]. It has been shown that while increasing their working memory load during active tasks, males outperform females in the manipulation of mental images [25] and in the interpretation or recall of visual characteristic of images [26]. There exists a gender-dependent perception of cognitive load, on the other hand, that is more marked as the elements to be kept in working memory increase (see [24] for a review).

Summarizing, very few studies addressed the problem of designing and assessing an assistive device able to train visually impaired subjects with a joint analysis of data going beyond the sole performance (the most widely used parameter), but also considering behavioral, subjective and emotional aspects and how these may vary according to prior visual experience or to gender-related aspects.

In the context of a more robust assessment of our haptic assistive aid, in this work we answer the following research questions:

Research questions. 1) is our device increasing the anxiety state? 2) is the mental mapping affected by visual experience? 3) is the mental mapping affected by gender?

2 METHODS

2.1 Participants

The participants were 40, classified according to visual deprivation and visual experience: 6 congenitally blind (3 M and 3 F) aging 39.5 ± 16.1 years (mean±SD), 16 late blind (8 M and 8 F, 39 ± 14.4 Y) and 18 sighted subjects (9 M and 9 F, 31.5 ± 10.65 Y). We considered congenitally blind people who lost their sight before age of 3 years and late-blind subjects who had seen till 12 years.

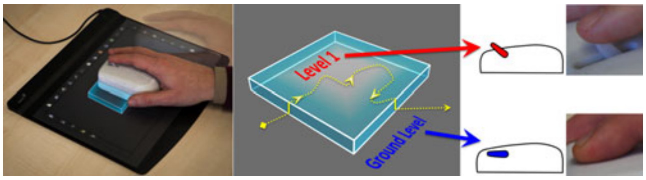

Fig. 1. The TActile MOuse (left) allows perception with a single *taxel* of a virtual object (in blue). The shadow represents the hand motion. Exploration path (center) on the first of the three objects, e.g. a one-level ziggurat, by free motion of the TAMO across the (X,Y) plane. The lever of TAMO displays H values continuously indicating the object height (Level 1) and the surrounding space (Ground Level) for each pixel on the tablet. Finger-lever contact (right) depending on up/down lever position.

Analysis of variance (ANOVA) did not reveal any age difference, based on GENDER $F(1,116) = 0.06$, $P > 0.05$, or GROUP $F(1,116) = 0.06$, $P > 0.05$, or their interaction $F(2,117) = 0.95$, $P > 0.05$. All subjects were right-handed and their visual impairment was assessed by the Istituto David Chiossone in Genova. Informed consent was obtained from all participants and protocols complied with the Declaration of Helsinki.

2.2 Experimental Setup and Protocol

The device used in this study is called TActile MOuse (TAMO): it is a portable mouse-shaped electronic device able to deliver haptic information representing 2.5D top-view maps.

Task-wise, it is similar to previous prototypes such as the Haptic Tabletop Puck [27] and the VT-Player [28], designed to acquire graphical content. However it adopts a single tactile stimulator, acting as the tactile equivalent of the pixel (*taxel*), to encode virtual heights as angles. Subjects can freely move the device on a 210 × 297-mm sensing tablet connected to a PC, in order to feel virtual heights at absolute positions. Bas-relief representations can therefore be displayed, as shown in Fig. 1, as TAMO generates a taxel for each pixel of the tablet. More details on the device are available in [9].

In the protocol, the sighted subjects were blindfolded prior to using the device. Subjects subsequently explored with TAMO the top-view tactile maps of three gradually more complex virtual scenarios (see Fig. 2), i.e., a one-level, a two-level and a four-level ziggurat. No training was provided for the subjects. The subjects were asked to build a cognitive map in a constrained time: each object was explored ten times, each time with 10 s of exploration and 10 s of rest, with 2 min pauses in-between objects. Pauses were inserted to satisfy two opposite needs: on one side to break the information acquisition, therefore decreasing the probability of possible “ceiling” effects; on the other side, to improve the process of map construction: this procedure has shown positive effects in a rehabilitation context [29]. After the pauses, subjects answered to a questionnaire to evaluate the quality of mental construction and expressed a subjective measure of cognitive load. The protocol was the same as that applied in [30]. In addition for this study and this sample, anxiety was evaluated pre- and post-experiment with the State-Trait Anxiety Inventory (STAI), a psychological inventory based on a four-point Likert scale

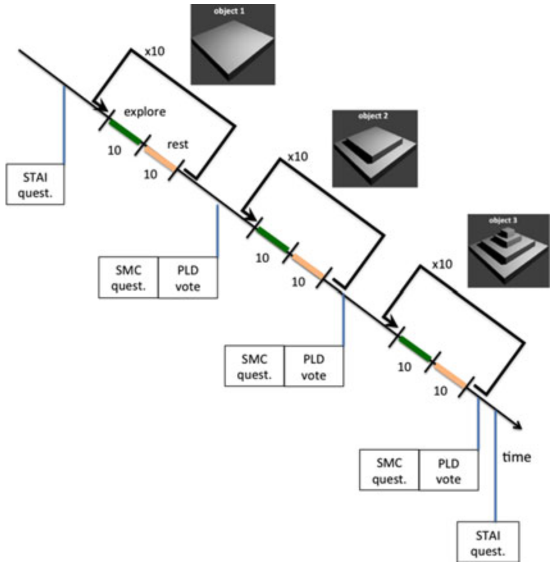

Fig. 2. Experimental protocol: three virtual objects of increasing complexity were displayed with TAMO, for constrained amounts of time, with interleaving rest periods. Questionnaires about anxiety (STAI) were given at the beginning and at the end of the whole experiment, while those about performance (SMC) and mental workload (PLD) were given at the end of each object exploration.

consisting of 40 questions on a self-report basis [18]. The STAI measures two types of anxiety—state anxiety, or anxiety about an event, and trait anxiety, or anxiety level as a personal characteristic. In this study we were interested in state anxiety in order to detect the emotional condition of subjects pre- and post- the use of the tactile mouse.

2.3 Variables

The dependent variables, related to spatial abilities, reflected the rate at which spatial information was acquired, the cognitive load in constructing the map, the anxiety of the subject and a measure of subjects' performance. More specifically:

SR. The Stimuli Rate (SR) is a behavioral objective measure of acquired information (tactile stimuli per second). SR values were calculated counting the upward movements of the lever during the exploration, then divided by the whole exploration time. It corresponds to how many tactile contacts with the virtual object the subjects is actively experiencing.

PLD. The Perceived Level of Difficulty is a subjective measure of cognitive load due to the map construction. For each object PLD values were collected asking subjects to rate, in a scale from 0 to 10 (0 means very easy and 10 very difficult), the difficulty in constructing the mental map.

Δ*STAI*. The variation of the points obtained by answering the STAI questionnaire before and after the experiment. Positive/negative ΔSTAI score indicate increasing/decreasing levels of anxiety.

SMC. The Score of Map Construction is a performance measure of the evaluation of map understanding for each object. SMC was based on the number of correct answers in the following questionnaire: (1) how many objects did you identify on the tablet? (correct answer was "one"); (2) apart from the ground level, how many different levels did you detect? (correct answer was "one" for the first object, "two" for the second and "four" for the third); (3) what was the contour of each level? (correct answer was "square"); (4) how were the levels located with respect to each other and with respect to the center of the tablet? (correct answer was "concentric and in the center"). These questions evaluated the subjects' ability position, the shape and touch perception and the capability to correctly integrate spatial stimuli. For each exploration, the sum of points was considered as a measure of performance.

The independent variables taken into account were the complexity of the virtual object to be mapped, gender and visual experience.

2.4 Statistical Analyses

All the statistical analyses were performed using R software [31]. Given that the dependent variables resulted non normally distributed according to the Shapiro-Wilk Normality Test (always $SW > 0.41$, $P<0.05$), statistical comparisons were performed using general linear models (GLMs), while post hoc comparisons were performed with Wilcoxon tests [32] and P values were retained as significant after false discovery rate (FDR) correction for multiple comparisons.

2.4.1 Comparing Anxiety Before and After the Use of TAMO

In a first step, we evaluated the possible variations of anxiety due to the use of TAMO. To this aim, we fitted a GLM considering ΔSTAI as a dependent variable, and GROUP (visual experience) and GENDER as factors.

2.4.2 Evaluating the Effects of Gender, Visual Experience and Object Complexity on Mapping Process

In a second step, we evaluated the possible effects of visual experience, of gender and of object complexity on acquired information, cognitive load and performance in exploring objects with TAMO. Therefore we separately considered SR, PLD, and SMC as dependent variables and for each dependent variable we fitted a GLM considering GROUP, GENDER and OBJECT as factors.

3 Results

3.1 Training with the TAMO Decreases Anxiety

The initial STAI median was 28.5 within the range [20-50], meaning that the level of anxiety before the experiment was very far from full scale value of 80. We performed an ANOVA on the GLM evaluating the effects of GROUP, GENDER, and their interaction on ΔSTAI. Significant effects emerged for GROUP, $F(2,102) = 4.64$, $P < 0.05$, as well as for the interaction between GROUP and GENDER, $F(2,99) = 3.51$, $P < 0.05$. Post hoc Wilcoxon tests showed that the decrease in the STAI scores were stronger for late blind subjects compared to the other groups. The difference was fully significant with respect to the early blind subjects, $W = 293$, $P < 0.05$, while it was almost significant with respect to the sighted subjects, $W = 621$, $P = 0.08$.

However, distinguishing genders within each group revealed that the significant effects were actually due to the female participants who showed a stronger STAI decrease for the late blind group compared to the congenitally blind

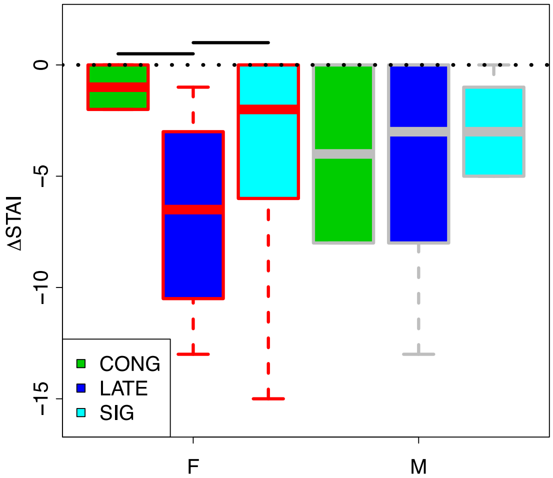

Fig. 3. Variation of subjective anxiety level before and after training with TAMO for CONGenitally blind, LATE blind and SIGhted subjects and by gender. Dotted red line is the reference level in which no change in anxiety occurs. Horizontal black lines indicate significant differences ($P < 0.05$). Red and gray contours of boxplots highlight the gender. Both females and males were less anxious after test, independently from visual experience.

group ($W = 18$, $P < 0.05$) and compared to the sighted group ($W = 144$, $P < 0.05$).

It is important to note that the differential anxiety was systematically lower at the end of the experiment: Wilcoxon tests showed that all groups and genders had—also when they were considered singularly—ΔSTAI < 0 (in all the cases $P < 0.05$). The ΔSTAI was particularly pronounced for the late blind females, as shown in Fig. 3. No subject reported an increase in anxiety.

This results suggest that the TAMO can be a comfortable and unstressful tool when used to test mental mapping abilities.

3.2 Mapping with the TAMO Does Not Depend on Visual Experience

We performed three separate ANOVAs on the GLMs, evaluating the effects of GROUP, GENDER, OBJECT and their interaction, respectively on information acquisition, cognitive load and performance. Results are reported in Table 1. We found that the process of tactile mapping with the TAMO coherently modulated SR, PLD and SMC: from the first to the last object we found increasing trends for PLD and SR, while a decreasing trend for SMC, as shown in Fig. 4 and Table 1.

This suggests that, when we increase the complexity of the explored object, the amount of acquired information and the cognitive load needed to process this information increase, while the quality of performance decreases. Importantly, the complexity of the explored objects did not modulate differently the variables of the considered groups, as showed by the non-significant interaction between GROUP and OBJECT. This suggests that the complexity of the explored virtual objects similarly affects subjects with non-similar visual experience.

Both PLD and SMC showed a significant main effect of GENDER, which was instead absent for SR, as shown in Fig. 5 and Table 1. This result suggests that males and females shared the same behavior, coded as the amount of acquired information during tactile exploration, but they strongly differed in the cognitive processing of the acquired information. In particular female subjects showed lower performances than male and exhibited a stronger mental effort in conceiving mental maps.

We found an effect of GROUP on SMC which was, instead, not present in PLD and SR. However, a trend of the interaction between GENDER and GROUP was observed for PLD (Table 1 in *italic*). Moreover, the same interaction was fully significant for the ΔSTAI variable (see Fig. 3) as stated in 3.1. Therefore the GROUP effect observed in SMC

TABLE 1
Results of the General Linear Models for Perceived Levels of Difficulty, Stimuli Rates, and Scores of Map Construction

Measure	Effect	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
SR	GENDER	1	0.10	118	5.21	2.41	0.12
	GROUP	2	0.12	116	5.09	1.44	0.24
	OBJECT	2	0.72	114	4.37	8.82	**0.0003**
	GENDER:GROUP	2	0.00	112	4.36	0.01	0.99
	GENDER:OBJECT	2	0.02	110	4.35	0.24	0.79
	GROUP:OBJECT	4	0.14	106	4.20	0.87	0.49
	GENDER:GROUP:OBJECT	4	0.02	102	4.18	0.14	0.97
PLD	GENDER	1	139.75	118	1,110.48	17.64	**0.0001**
	GROUP	2	29.50	116	1,080.98	1.86	0.16
	OBJECT	2	200.26	114	880.72	12.64	**<0.0001**
	GENDER:GROUP	2	41.25	112	839.47	2.60	*0.07*
	GENDER:OBJECT	2	13.93	110	825.54	0.88	0.42
	GROUP:OBJECT	4	13.10	106	812.44	0.41	0.80
	GENDER:GROUP:OBJECT	4	4.23	102	808.22	0.13	0.97
SMC	GENDER	1	15.41	118	254.58	7.41	**0.008**
	GROUP	2	17.07	116	237.52	4.11	**0.02**
	OBJECT	2	12.92	114	224.60	3.11	**0.04**
	GENDER:GROUP	2	7.33	112	217.26	1.76	*0.18*
	GENDER:OBJECT	2	2.72	110	214.55	0.65	0.52
	GROUP:OBJECT	4	1.93	106	212.62	0.23	0.92
	GENDER:GROUP:OBJECT	4	0.63	102	211.99	0.08	0.99

Significant effects ($P < 0.05$) in ***bold****, interesting trends in italic. A colon divides interacting factors.*

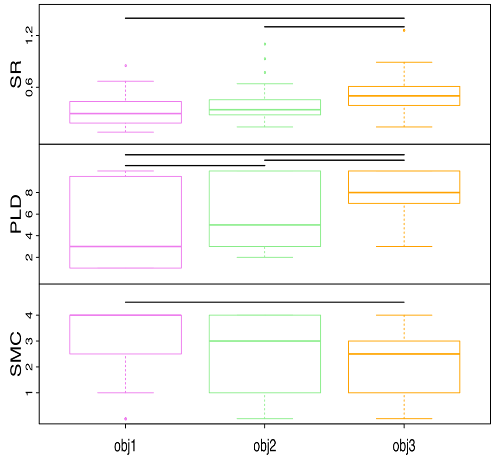

Fig. 4. Stimuli rate, perceived level of difficulty and score of map construction as a function of the object. Black lines show significant differences ($P < 0.05$). Pink, green, and orange boxplot contours highlight virtual objects. All variables appear to be modulated by object complexity.

seems to be a spurious epiphenomenon which is actually ascribed to a mix of cognitive load and anxiety. Fig. 6 provides an overview of the mentioned results.

4 Discussion

In this work we assess a tactile device aimed at the construction of cognitive maps with virtual objects. The evaluation is based on variables linked to: performance, mental workload when constructing a map, the amount of acquired tactile information and the variation of emotional status. We show the modulations of the above-mentioned variables due to the complexity of virtual objects, the gender and the amount of visual experience. The relation between all these quantities can tell a lot about what is behind the quality of cognitive mapping, especially in the quest for obtaining metrics able to measure spatial abilities of visually impaired subjects. Our goal is contributing to solve the problem of accessing digital information non-visually, by demonstrating that bidimensional user interfaces can be used by blind people. Here we show that our device can be used to learn simple geometrical objects to which in principle it is possible to associate any semantic content. Applications span from access of graphics and scientific content on the web to the learning of 2.5D maps of real environments. Moreover methodologies applied in this study can complement and potentially improve O&M rehabilitation protocols.

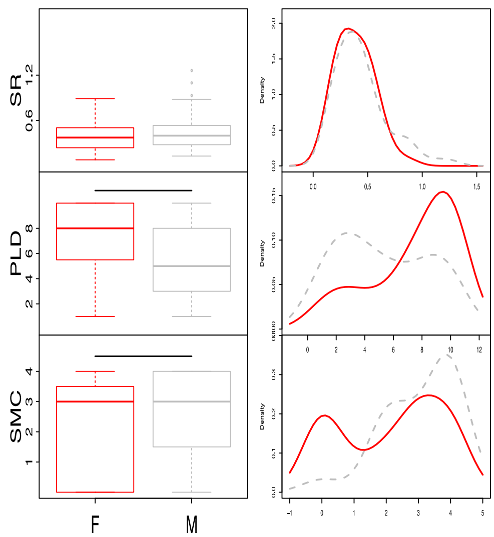

Fig. 5. Left: boxplots of SR, PLD and SMC distributions, red and gray contours highlight gender. Black lines show significant differences ($P < 0.05$). Right: density of probability of the distributions, no difference appears between females and males in terms of behavior. Marked differences emerge in subjective cognitive load and performance.

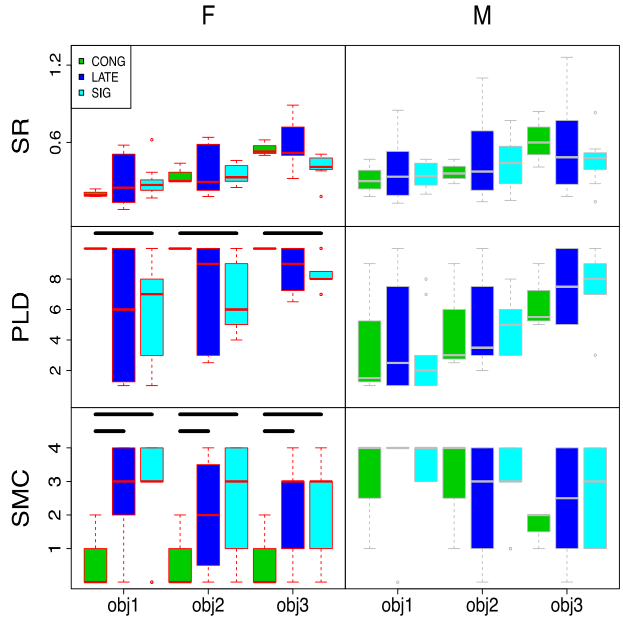

Fig. 6. Stimuli rate, perceived level of difficulty and score of map construction grouped by gender (boxplot contours) and visual experience (boxplot colors). Black lines show significant differences ($P < 0.05$). Cognitive load is globally not affected by visual experience. Modulation of SMC is highly due to the low performance of the congenitally blind females. Behavior is not affected by visual experience.

Our first step was to look for possible anxiety variations associated to the use of the TActile MOuse measured with a differential State-Trait Anxiety Inventory. Having found negative variations in all the subjects, we can reliably argue that our device does not negatively affect the emotional state of the congenitally blind, late blind and sighted subjects, regardless of the mental fatigue spent to build our three virtual objects (which sometimes is very high). This is important as mental and emotional aspects, when assessing assistive technologies, can appear decoupled.

However, effects of gender and visual experience emerged: while males were similar, irrespective of the presence and kind of disability, females and, in particular, the late blind females showed a stronger ΔSTAI reduction. Although we cannot ascribe the specific cause of such decrease to any other variable that we considered, the peculiarity of disabled females is not only a property of the anxiety metric but extends to both perceived difficulty and performance. This means that, interestingly, a set of three independent measures of different domains coherently expresses the same phenomenon. We found higher cognitive load for women, which is in agreement with the literature [26].

Our second step was to evaluate how subjects interacted with the assistive technology as a function of the task difficulty, expressed as geometrical complexity of virtual objects, and as a function of gender and different visual experiences.

We confirmed that task difficulty is a coherent factor for the interaction, whereas visual impairment is not [30], [33].

The coherence is testified by an increase in information acquisition rate going along with an increase in cognitive load but a decrease in performance. The increase in the behavioral measure can be ascribed mainly to an increasing tactile spatial density, since multi-level ziggurat have more virtual ridges. The increase in workload suggests to be coupled with the decrease in performance. In addition, the weaker significance of the decreasing trend of performance could be due to a partial learning effect (we did not randomize objects). We speculate that complexity effects are still dominant, otherwise we should have observed better performance and lower workloads for later objects, which is not the case. Mapping scores for the most difficult object were between 1 and 3 for 50 percent of the variance, indicating that on average subjects were able to understand, at least partially, the geometry of complex objects. Congenitally blind females exhibited very low scores, even if the same happened with easier objects. Congenitally blind males, instead, performed better and similarly to late blind and sighted subjects. Our tactile mouse was tested in this work with 2.5D flat objects only. Feeling full 3D objects—where the facets opposite to the hand can be touched—would require other more expensive instruments such as the Phantom. However, objects having a curved height profile can be displayed (we discuss vertical resolution of the lever in [9]) and might be easy to perceive. Here we focused on objects for which perception of edges was crucial and almost entirely dependent on subject's strategy and capability of integrating subsequent up-down stimuli. Curved height profiles, where sharp edges in principle may not exist, would also require a more refined definition of the Stimuli Rate. In this work it was indeed our intention to check if blind subjects can integrate tactile and proprioceptive cues into a meaningful mental image. Although it has been shown that this task is less easy than others [34] we show that it is possible, indicating that the potential of the tactile mouse with other objects seems very high.

Interestingly, the presence and onset of blindness did not significantly affect the rate at which tactile information was acquired by subjects. The TActile MOuse does not seem to be group-specific from the motor point of view, therefore the strategies to explore unknown virtual objects do not seem to be due to past visual experience. One might have argued that sighted subjects currently using PC mice could have been facilitated with our device, but our interpretation is that blind and sighted subjects appear in this task on the same footing because the kind of tactile stimulus is new for both and because objects are abstract, therefore minimally influenced by past experience. There are very few attempts to assess tactile devices with a set of variables as the one proposed in this work. Moreover these parameters comply with an ecological way of collecting data, which is peculiar to rehabilitation protocols. Our measure of the amount of acquired information can be collected in an unsupervised way, is quantifiable and has been shown [9] to correlate with performance. Using more extensive methods of information pick-up [35], [36], related to contour following, may strengthen our findings.

Admittedly, in this study we considered small groups of congenitally blind subjects: this reflects the small percentage of such individuals in the global population. Previous studies considered a small sample size [37] together with an imbalance within samples [38]. Moreover, to partially overcome this limitation, we used nonparametric methods because they are more robust in cases of small samples and are less statistically powerful than their parametric counterparts: the fact of reaching significance suggests strong effects in our data [39].

In the context of designing an assistive device we can provide answer to the aforementioned research questions:

1) Is our device increasing the anxiety state? No. A measure of anxiety revealed a systematic decrease after the use of TAMO device. The female blind subjects showed peculiar patterns not only with the anxiety state but also with the cognitive load and performance metrics, suggesting that assessments of this kind of assistive devices may consider a set of diverse variables, including mood.
2) Is the mental mapping affected by visual experience? Tentatively no. The effect of visual experience was significant only for performance, while interaction emerged with gender in the anxiety and cognitive load measures. Therefore visual experience seemed not to be a primary effect in conditioning performance but only an epiphenomenon. However, a larger sample of congenitally blind subjects can convince more about the peculiarity of females; apart from this, an early or temporary loss of sight looks to be irrelevant, with our device, in an efficient development of maps.
3) Is the mental mapping affected by gender? Yes. Both males and females share a similar acquisition processes to learn tactile maps, but we found differences in mental effort and in efficiently integrating tactile cues into geometrical concepts.

This is important when modeling user behavior: O&M practitioners may apply corrected metrics, or adapt them, or present a different set of tasks, when testing different genders.

This study is a further contribution more to the view [11] that performance alone is an insufficient measure of a rehabilitative step, if not coupled with metrics linked to behavioral, mental and emotional status. Although such considerations are valid in this study with our device only, these relations may be verified with other haptic devices and methodologies linked to the rehabilitation of visually impaired subjects.

Acknowledgments

The authors would like to thank Cristina Becchio for scientific advice, Laura Taverna for graphic art, and Marcello Goccia for text revision. Thanks to the rehabilitation operators of the Istituto David Chiossone. Special thanks to all our volunteers. This research is partly supported by the EU FP7 grant BLINDPAD (611621).

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