Interactive and effective representation of digital content through touch using local tactile feedback

By

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Author's declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: .... DATE: ....

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To my family
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LIST OF PUBLICATIONS

This thesis contains the following original publications:

1. M. MEMEO, C. CAMPUS, AND L. BRAYDA, *Do blind subjects differ from sighted subjects when exploring virtual tactile maps?*, in International Conference on Computers for Handicapped Persons, Springer, 2014, pp. 12–17

2. M. MEMEO, C. CAMPUS, L. LUCAGROSSI, AND L. BRAYDA, *Similarity of blind and sighted subjects when constructing maps with small-area tactile displays: performance, behavioral and subjective aspects*, in Haptics: Neuroscience, Devices, Modeling, and Applications, Springer, 2014, pp. 292–300

3. L. BRAYDA, C. CAMPUS, M. MEMEO, AND L. LUCAGROSSI, *The importance of visual experience, gender and emotion in the assessment of an assistive tactile mouse*, IEEE Transactions on Haptics, PP (2015), pp. 1–1

4. M. MEMEO AND L. BRAYDA, *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, Springer, 2016, pp. 75–85

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6. M. MEMEO, V. A. DE JESUS OLIVEIRA, L. NEDEL, A. MACIEL, AND L. BRAYDA, *Tactile treasure map: Integrating allocentric and egocentric information for tactile guidance*

The present author wrote the first draft of each publication. For what concerns the first three publications the present author was responsible for the analyses of data. For what concerns the last three papers she was responsible for designing the studies, implementing the software setups, conducting the user experiments and analysing data. The electronics and mechanical components of the tactile aids, used as part of experimental setups, have been designed and assembled in the Electronic and Design Laboratory at Fondazione Istituto Italiano di Tecnologia. The kinematic model of the most recent tactile aid was created by Marco Jacono, the chief technician at Robotics Brain and Cognitive Science Department of Fondazione Istituto Italiano di Tecnologia.

For the following publication:

1. E. MIGUEL, M. L. D'ANGELO, F. CANNELLA, M. BIANCHI, M. MEMEO, A. BICCHI, D. G. CALDWELL, AND M. A. OTADUY, *Characterization of nonlinear finger pad mechanics for tactile rendering*, in World Haptics Conference (WHC), 2015 IEEE, IEEE, 2015, pp. 63–68

the present author contributed with a small portion of data analyses conducted in the period immediately before the beginning of PhD.

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Chapter 1

Motivations of this research

1.1 Aim and contribution

The increasing availability of on-line resources and the widespread practice of storing data over the internet arise the problem of their accessibility for visually impaired people. The conveyed information is multifarious and uses different ways of representation, i.e. text, images, graphs. Text is generally rendered on refreshable Braille cells or text-to-speech engines, while limited solutions exist for graphical information [187]. Graphics are, in general, visually represented in a 2D topography in which the position in the 2D space refers to a meaning. In a typical vision-based environment, such as a PC screen or a website, the distinction among data is ensured by overlapping the content or by assigning content to a specific location in the 2D space. Colour labels, the use of shadows and the choice of a particular perspective help to compact multiple meanings: they are semantic features attached to a two-dimensional representation. Visually impaired people do not have access to such representations. Yet, they know how to interact with 3D spaces, such as a dressed table where the dishes, the fork, the knife and a glass have specific locations and precise functions to be remembered.

This is not possible with digital information.

A translation from the visual domain to the available modalities is therefore necessary to study if this access is somewhat possible. However, the translation of information from vision to another sensory modality, for example touch, is necessarily impaired due to the superiority of vision over touch during the acquisition process [6]. Yet, compromises exist as visual information can be simplified, sketched. A picture can become a map. An object can become a geometrical shape. Under some circumstances, and with a reasonable loss of generality, touch *can* substitute vision. In particular, when touch substitutes vision, data can be differentiated by modulating vibration attributes (e.g. frequency, amplitude and duration) [104], force feedback (e.g. changes in acceleration) [43] or adding a further dimension to the tactile feedback (e.g. from two to three dimensions) [57]. In this thesis the last mode has been chosen, because it mimics our natural way of following object profiles with fingers. Specifically, regardless if a hand lying on a object is moving or not, our tactile and proprioceptive systems are both stimulated and tell us something about which object we are manipulating, what can be its shape and size. We attempted to work with three dimensions because our goal is to display features of *geometrical* content, to which arbitrary semantics can be attached. Our motivation stems from the fact that much of everyday tasks performed by blind people make use, for example, of proprioceptive information represented by haptic and acoustic feedback in the peripersonal space [32], that is the space surrounding our bodies and where objects can be reached and manipulated. However, nowadays few effective methods exist which exploit this habit when accessing digital data; using touch to sense digital data in more than one dimension is something almost unknown to visually impaired persons. Some evidence reports that the brain of blind persons can process tactile digital information in similar ways to sighted persons [25]. The potential of blind persons in understanding digital three dimensional content seems largely underestimated.

The goal of this PhD thesis is to test how to exploit tactile stimulation to render digital information non visually, so that cognitive maps associated with this information can be efficiently elicited from visually impaired persons. In particular, the focus is to deliver geometrical information in a learning scenario. The contribution of this research is to demonstrate that it is possible to deliver a tactile three dimensional content with a simple stimulation mode which renders local geometrical features in three degrees of freedom, while global features are delegated to the person's active exploration.

In the physical world, sighted people perceive hundreds of visual objects at a glance, but automatically ignore items that are not important, not interesting or operationally irrelevant. With touch, this is very difficult to achieve. In fact, a person who is blind may need to establish selective perception filters to limit cognitive overload caused by over-detailed tactile environments. Some tactile maps installed in train stations, for example, are reputed useless by the blind community, as there is too much information only suitable for vision, certainly not for touch. There are essential operational features of objects, but there is also a frequent abundance of decorative properties that have no operational value and can be ignored [26]. When delivering digital content through touch, such content is not physical, but virtual. To build a percept of a real object, with appropriate stimulation means, is not obvious. What is 'appropriate' is a central topic addressed in this thesis. We consider the case of virtual geometrical content: **is it possible to find an appropriate stimulation mode that helps to effectively build mental models from virtual geometrical primitives?** Then, **how do visually impaired persons react to such stimulation mode, as compared to sighted persons?**

Moreover, a completely blind interaction with virtual environment in a learning scenario is something little investigated because visually impaired subjects are often passive agents of exercises with fixed environment constraints. For this reason, as ultimate research question of this thesis, **can visually impaired people manipulate dynamic virtual content through touch?** This process is much more challenging than only exploring and learning a virtual content, but at the same time it leads to a more conscious and dynamic creation of the spatial understanding of an environment during tactile exploration. As a result, visually impaired participants were able to actively handle the components of a virtual environment.

From the point of view of basic research in haptics this thesis demonstrates that both persons with and without visual impairment were able to understand spatial layouts of *global* tactile scalar fields by approximating them with *local elevation* and *local inclination* only, while missing information can be delegated to spontaneous proprioceptive strategies. This stimulation can be used in applications where vocal cues are insufficient to provide spatial information, such as web surfing. Vocal cues, in fact, are successful descriptive tools but they often appear to be annoying and lack spatial representation, which is crucial in the process of data recall [175], [86].

Moreover, this research can be used to improve the state of the art in rehabilitation engineering. More often the evaluations of rehabilitation protocols and aids, in the research context, are limited to the performances associated to the accomplishment of a task ([143], [29] and [150] offer a comprehensive review). However, the ability to fulfil a certain task remains incomplete and almost unpredictable if not associated to measures able to disclose the motivations and the modalities leading to a certain performance [63]. The subjective demand associated to a task can provide a complementary measure to further evaluate the impact of that tool on a visually impaired person [175]. Recent works suggest that performance can be predicted by a combination of behavioural and subjective variables [15]. The choice of a particular strategy and participants' perception of cognitive load, in fact, reflected the objective difficulty of the tasks. For this reason, in all the experiments described in this thesis, different classes of data were collected: together with performance evaluations, behavioral and subjective aspects were taken into account. Therefore behavior and subjective information helped to understand which are the underpinnings of a certain result [17] and consequently to plan targeted strategies that could possibly improve the performances.

1.2 Preview of chapters

Besides the present chapter in which the main motivations of this research are explained, the thesis comprises five more chapters.

In Chapter 2 the basic mechanisms to create a mental map, from the point of view of the population addressed and the provided technology, are described. It provides an overview of sensory substitution systems used as rehabilitation tools to create cognitive maps. The sense substituted is vision which is powerful and intuitive: it offers us spontaneous cues to develop mental representations of the surrounding environment. The touch is the residual sense targeted to substitute vision in order to develop spatial abilities in an alternative way. Together with the technological solutions, programmed methods to enable the growth of specific abilities should be provided: this issue is addressed in terms of perceptual sensitivity of touch.

Chapter 3 describes the solution provided to solve the problem of accessing digital information non-visually. The two prototypes proposed belong to the family of tactile devices and mostly the last one has been created with the intent to approach a real tactile exploration mechanism.

Chapter 4 presents the experimental studies, conducted and published, to test the assistive device described in Chapter 3 in terms of users' interaction, acceptance and learning process. To understand the role of visual disability in the development of a mental representation, two main populations were tested: blindfolded sighted and visually impaired individuals. Participants were tested in tasks of recognition and matching of virtual objects but also in perceptual tactile studies. Moreover, the methods to address data analyses are evaluated.

Chapter 5 contains the main novelty of this thesis: the possibility to actively handle virtual content in blind modality using touch. Visually impaired participants were asked to build 3D tactile objects in a virtual *Lego game*. Their performances were analysed together with usability of the system.

The last Chapter contains the main achievements of this thesis in terms of how they could be used and integrated in actual rehabilitation protocols. Moreover, future lines of research are provided in perspective of further hardware and software developments and alternative approaches to learning methodologies.

Additionally, there are two appendices. The first appendix presents media content relative to the description of the tactile assistive devices proposed and their integration with a head-mounted display in order to create a system for tactile guidance in a non-visual environment. The second appendix provides details about the validation of wireless handshaking protocols during the phase of tactile aids testing.

Chapter 2

Cognitive mapping through haptics

Vision offers us spontaneous cues to develop mental representations of surrounding environments. Its absence, as in the case of visually impaired people, entails a series of alternative mechanisms to functionally reorganise brain areas in order to develop spatial abilities.

For learning spatial skills that facilitates the development of mental maps, touch could be a valid substitute to vision [151]. To achieve successfully this substitution, understanding visual and tactile processes and their interpretation is crucial. Several sensory substitution devices made it possible to partially replace one sensory modality with a vicarious one. However, their adoption should encompass multiple aspects: the social effects, their acceptance, usability and learning. A consistent limitation to their adoption comes from psychological and social factors, such as the reluctance to try new devices. Moreover, if devices are unaffordable, bulky, hard to set up and to be manipulated by the blind users, they are not efficient enough for real world use. On the other hand, having a device which is comfortable, moderately inexpensive and easy to operate does not ensure its prolonged efficacy and use since it is crucial to set targeted procedures for training the final users. It often happens that potential users have to self-train on these devices without a clear set of lessons to follow. Programmed methods to enable the growth of specific abilities are absent too. However, there are studies showing that subjects who have received serious longitudinal training not only learn to use the devices far better, but are able to better process the information and learn how to code space [106]. This extended guidance is also important on emotional and motivational bases, especially if the stimuli are confusing and hard to explore or understand.

Standard rehabilitation tools render images in two dimensions using swell papers or handmade solutions. Those low-tech solutions are usually necessary in Orientation and Mobility

(O&M) rehabilitation programs, i.e. protocols targeted to teach visually impaired people how to safely and effectively navigate in unknown environments. Those solutions can be used as pre-planning aids that provide the user with information before arriving in an environment (e.g. tactile maps, physical models) but additionally, if modular, they can be verification setups, i.e. tools to verify the comprehension of the structure of the explored space. Current tools, however, present severe limits: they are handmade, they cannot be easily reconfigured while changing the environments or adapted depending on the ability of different users [20]. Therefore, in this thesis we propose to overcome this pitfall shifting the spatial content from real to virtual environment, transforming the physical models in digital models.

2.1 Cognitive mapping in absence of vision

Cognitive mapping is the mental process enabling a person to acquire, code, store, recall, decode and manipulate data about a spatial layout [42]. This process is subjective, since it deals with the ability of inferring spatial meaning from personal behavior and personal point of view. Mapping is achieved by manipulating information which come from specific tools or the available senses. The output of cognitive mapping process is crystallized in a time-dependent mental representation called cognitive map, defined as an internal model based on functional relationships among meaningful and self-explanatory elements distributed in the space [175].

The ability of building spatial configurations is traditionally thought to be inherently anchored to vision. The loss of vision is therefore expected to have a high impact on spatial cognition. Research on spatial cognition in congenitally totally blind individuals has a long-standing tradition. Many behavioural studies indicate that vision is necessary for the acquisition of spatial knowledge. However, there is also evidence suggesting that in absence of vision the acquisition of spatial knowledge is not completely absent (a review of those studies can be found in [151]). The presence of cortical reorganisation after visual deprivation ensures the growth of structural mechanisms which ground imagery skills. Cortical areas in the brain regions, usually involved in the process of visual information, are progressively (5 days are sufficient) recruited for tactile processing [36]. Moreover there is evidence that mechanisms devoted to spatial imagination in sighted and congenitally blind persons are not too dissimilar [182] and that similar level of performances are achieved in tasks involving visual imagery [198].

2.1.1 Spatial knowledge

The availability of information modulates the acquisition of spatial knowledge. Due to the complexity of real environments, it is convenient for researchers to specify which piece of information is essential to be delivered in order to let users build an appropriate cognitive map in absence of vision. A first method to discriminate attributes of the environment is to divide them spatially and label them with a location mark. To localize these attributes, they should be defined in terms of distance and direction features. Distance and direction are spatial references which can be explicitly rendered in an absolute or a relative frame of coordinates [42].

2.1.2 How to measure spatial knowledge

As for methods researchers used to estimate distances, in [126], five techniques are identified: ratio scaling, interval and ordinal scaling, mapping, reproduction and route choice. Since all of them involve the measurement of psychological quantity (cognitive distance) which corresponds to a directly measurable physical quantity (physical distance), these five classes represent psychophysical methods to estimate distances. *Ratio scaling* transfers basic psychophysical scaling techniques in the distance frame of reference: the subjects estimate locations comparing their percept with known and codified distances such as the length of a ruler or a scale. Paired comparisons of one pair of distances and its relative ranking is the method adopted by the *interval* and *ordinal scaling* distance estimation technique. Then, *mapping* is defined as the simultaneous representation of multiple places in a scale smaller than the environment. Consequently the distances set on the map are compared to the actual locations of the real environment. The *reproduction* technique consists in assigning/reproducing distances which match the actual scale. Finally, the *route choice* requires the inference of perceived distances from the choice of a route the subject makes when asked to take the shortest between two ways. In [79] the author evaluates three additional categories of generating verification data from estimation tests: graphics, completion and recognition tasks. *Graphics* verification task consists in producing a map sketch, by drawing a portion or a complete map of a certain location. *Completion* instead requires participants to fill incomplete map or questionnaires with missing locations, while *recognition* measures the ability of participants to correctly recognize spatial relationships.

Distances perceived by users were evaluated by researchers using several analysis techniques. Ratio scaling, mapping and reproduction distances have been evaluated with linear and non-linear regressions, shifting the subjective domain of perceived distances in the objective one of physical distances [42].

Additionally, ratio and ordinal scaling along with reproduction have been analysed using multi-dimensional scaling methods which classify each basic element of distance data positioning them in a specific coordinate of the space [42].

Although graph validation tasks offer a higher variety of data, they have been investigated with subjective classifications which depend on the expertise of participants in drawing and on the personal evaluation of researchers, thus the concept of repeatability was hard to achieve. Analysis of completion and recognition tasks consist of half-quantitative measures such as self-made questionnaires and accuracy scores [79].

Their acceptance as adequate evaluation tasks was a long process, started in the 1990s, but led to the expansion of a base of empirical evidences for the development of a methodological framework as scientists started seeking innovative ways to evaluate how much a cognitive map is understood and to enhance the homogeneity and efficacy of methods to investigate data. Currently, designs consist of battery of tests to cross-validate findings. The strategy of multiple testing ensures a structural validity (whether tests are measuring what they are supposed to) with examinations of a convergent validity (tests created to measure if the same phenomenon produces the same result) [42].

2.1.3 Spatial information acquisition

The haptic search to acquire information of a spatial layout is influenced by the number of input sources involved in the task.

Psychophysical studies demonstrate that the use of only one hand is preferred to reach better precision in stimuli discrimination. In particular, when both hands are used to estimate lengths, they are less precise than the unimanual condition [133]. In the experiment conducted in [133], the bimanual exploration was done with the two index fingers, being free in the air, discriminating the length of a wooden parallelepiped. The unimanual exploration, instead, was carried out with the index and thumb of the dominant hand. Results demonstrate that the presence of an internal frame of reference, as it happens using one hand, produces lower discrimination thresholds. In addiction, both the left and the right hand share similar performances in the perception of curved surfaces [76]. In this study of Kappers and collegues [76], participants judged the curvature of hand-sized objects with the right, the left or both hands. While results with bimanual exploration present higher thresholds, the accuracy achieved with the left and the right hand is comparable and higher than the condition with both hands. Similarly, the comparison of sinusoidal stimuli is more efficient with the same hand than with two hands [128]: on average, in the intermanual condition (two hands involved) participants were less precise than in the intramanual condition (two fingers of the same hand involved). This is the reason why the experiment of curvature discrimination described in section 4.3 was performed with one hand.

The main exploratory procedure for perceiving shapes, i.e. contour following, is performed with only one finger [92]. Moreover, one-finger exploration is a spontaneous strategy in a scenario in which haptic modality is used to explore raised line drawings and guessing the shape depicted on them [168]. The use of two fingers, compared to the use of one, leads to no improvement in perceiving outlines of 2D shapes and pictures [102]. When touching a 2D tactile map with the thumb and the index along opposite sides of a map, the information gathered is richer because it comes from two different positions of the contour and it includes distance information. However, no significant enhancement in recognition accuracy is found by choosing two-finger instead of one-finger exploration [68]. In addiction, by increasing the number of contact areas does not improve the performances in identifying real objects; while by increasing the spatially distributed information on the contact area is more important and lead to better recognition rate [69]. The assistive tools proposed in this thesis stimulate only one finger and the main improvement from the first to the second prototype is the enlargement of the contact area under the fingertip.

One key aspect to investigate during the completion of tasks is the behavior of people and how this affects the process of presenting data and learning spatial skills. A particular class of assistive technologies, described in section 2.2, provides the possibility for the user to interact with the tactile graphics. Manipulation of spatial content needs the presence of a virtual environment in order to be responsive to users' actions.

One way of manipulating the tactile environments is to voluntary adjust the portion of the visual scene to touch by zooming in the original picture to understand better its details. However the zooming technique is not easy to operate because it should be tuned to the information density while preserving the same context meaning. Several groups studied how to render the magnification process of virtual tactile pictures. Methods used can be grouped in two: vision and object oriented. The vision-oriented technique consists in applying visual techniques to increase pictures, such as linear zooming [204] or using logarithmic steps [105]. During the phase of training, the participants have the possibility to build a mental map of the objects included in the dataset. Once the image is zoomed, the mental representations previously stored can be used as a reference. However the exploratory movements will be adapted to the current image depending on the information availability and the size of the elements in the scene [203]. Another approach focuses on object-oriented magnification. It consists in generating a specific zoomed scene showing only the particular element/object selected by user [148]. Mental representation, in this case, is multi-layered: moving across multiple magnification levels generates different mental images in the working memory to allow manipulating the information back and forth. Since the object-oriented was more usable than vision-oriented magnification and led to a higher number of correct answers [148], we can conclude that the evaluation of those techniques in terms of interaction behavior highlights the importance of adapting methodology configurations to the main sense involved in the task. However, the object-oriented technique required a long training which should be considered if the magnification process is employed in the rehabilitative protocols. In this thesis the zooming effect has been evaluated depending on the kind of geometrical descriptors delivered through touch and visual impairment (see section 4.4). Misjudgements about size of virtual objects strongly affect the accuracy of visually impaired participants (who tend to underestimate object sizes) and of blindfolded sighted subjects (who overestimate size only when inclination cue is present).

Besides the issue of the limitations related to personal aspects such as visual prerequisites and potentiality of expanding skills, the modality of acquired information should be taken into account. Fortunately, much of the relevant content conveyed by graphical material is spatial (e.g., points, lines, contours, and regions) and most of this spatial information can be conveyed by both tangible and visual displays. Indeed, a growing body of literature supports the notion that spatial information encoded from vision, touch and other spatial modalities leads to the development of common and amodal representations in the brain: they function equivalently in supporting spatial behaviors [101]. A strategy based on haptic imagery (i.e., mental representations generated on the basis of previous haptic experience) can be almost as accurate as strategies based on visual imagery in many different cognitive tasks [151]. Therefore touch seems to be an adequate substitute of vision for tasks concerning learning graphical content that is spatially distributed. A good aid display for graphical content should provide accurate perception, taking care of physiological aspects of the vicarious sense; it should also support accurate learning and representation of information facilitating subsequent mental transformations and computations [131].

Section 2.2 describes the issues of presenting spatial content in absence of vision from the point of view of the sense involved in the perception (here touch) and the devices built to help in the construction of mental maps in visually impaired people.

2.1.4 The role of touch in discovering spatial features of the environment

2.1.4.1 Physiological basis of touch

Being the largest organ of the human body, the skin has the essential role to protect internal organs from any harm coming from the external world. Thus touch mediates the physical interactions with the environment and with other human beings. However only the hands and (unconsciously) the feet [62] are continuously used in the interactions with the external world. The term *haptics* refers to any kind of perception, sensation and manipulation actively achieved via the tactual sense.

The sense of touch is composed by two systems: the *cutaneous* and the *proprioception* senses which differ for the kind of sensory inputs.

The *cutaneous* (or *tactile*) system collects tactile information, mostly from the hairless skin, by means of mechanical stimulation of the skin and in particular through its deformation and/or by the motion across surfaces. The deformations are sensed by receptors present in the dermis and the epidermis [72]. The receptors sense these changes in the skin contour and react according to their physiological function, their morphological and functional properties (sensitive to static or dynamic cues), their size and structure of their receptive fields. Furthermore those receptors have diverse density along the skin area. To simplify their characterization, they are classified on the basis of two pairs of features: their adaptation to prolonged indentation and the structure of receptive field. Two of them, characterized by a Fast Adaptation to indentation are called FA units and are respectively Meissner corpuscles having small receptive field size (around 12.6 mm^2 in the hand) and Pacinian corpuscles with large receptive field (around 101 mm^2 in the hand) [71]. Meissner corpuscles are responsible for the detection of low-frequency vibrations (from 5 to 40 Hz) and for stable precision grasps and manipulations. Pacinian corpuscles detect high-frequency vibrations (from 40 to 400 Hz) and are responsible for the perception of fine textures. The two receptors characterized by a Slow Adaptation rate are denoted as SA: the Merkel cells with small receptive field (around 11.0 mm^2 in the hand) and Ruffini endings with large receptive field (around 59 mm^2 in the hand) [178]. Merkel cells detect very-low-frequency vibrations (less than

5 Hz) and are responsible for the perception of coarse textures. Finally, Ruffini endings have the ability to detect finger positions and the direction of object motion and force due to skin stretches.

The *proprioceptive* system includes the vestibular and the kinesthetic senses and refers to the awareness of static and dynamic (i.e. that changes over time) body location, limb positions and muscular tensions. Both static and dynamic postures are based on signals from sensors placed in the skin and muscles and partially from joints receptors [47]. Since it is rare to stimulate the sense of touch without proprioceptive stimulations (and viceversa), a combination of tactile and kinesthetic cues are always sensed together. Proprioception judgements of distances and orientations are anisotropic in the kinesthetic space [103]. When a subject judges distances in the kinesthetic space by moving the finger or the hand between the endpoints defining a distance, radial distances are phenomenally greater than physically equal tangential distances. Thus, a subject feeling an L-shaped Figure lying flat on a table directly in front would experience the line segment lying in the median plane longer than the physically equal segment in the fronto-parallel plane. This kinesthetic misjudgement has been confirmed in the experiment described in section 4.4 of this thesis where participants had to matched real with virtual objects.

Additionally, for lines within a fronto-parallel plane, kinesthetic discrimination of orientation is noticeably worse for oblique lines than for vertical or horizontal lines [90]. According to Gentaz and collegues [48] this phenomenon, called *oblique effect*, is due to the frame of reference adopted in humans which is categorized by a vertical and a horizontal axis. Moreover, the configuration of hands and jointly their movement biases the discernment of kinesthetic distance [103]. This effect is present also when oblique lines have to be reproduced [9] in both 2D and 3D space, with no effect from visual deprivation. When tracing curved raised paths (changing in distance) with one finger, the judgement of the euclidean distances between the two endpoints of the path is overestimated [95]. The overestimation of euclidean distances has been found also in the experiment described in section 4.4 since the size of objects in virtual environment was systematically thought to be doubled. However, this effect is true for only blindfolded sighted people and in presence of a specific geometrical descriptor: the elevation.

2.1.4.2 Spatial features

When it comes to manual exploration, there are many features that can be tactilely perceived, along with the perception of temperature and textures, such as geometrical features that generally include the perception of size, shape, curvature and orientation in space.

Size and shape. Size and shape perception depends on the scale of objects; either the object fits under the fingertip revealing its features mostly by skin indentation or larger than the fingertip, reflecting its shape with the essential contribution of kinesthetic inputs [94]. How to recognize objects with touch is an extensively studied topic [93]: the preferred technique to perceive shape feature is to slide a finger across an object surface. People who use touch to identify object features, i.e. the visually impaired, develop strategies and gain experience. This is profoundly different compared to those mainly exploiting vision to achieve the same goal, i.e. sighted subjects.

Object recognition is modulated by the amount of familiarity: regularly explored shapes present mentally stored patterns in terms of exploration strategies, perception and proprioception. Blind individuals in [61] were quite quick and accurate in mentally rotating a series of familiar stimuli (e.g., Braille characters), this result is confirmed also in [81].

The number of fingers used and consequently the possibility to handle the object to recognize has also an effect on the level of accuracy: in a bi-manual task in which 3D objects could be haptically manipulated, blind participants showed to outperform their sighted peers [38]. Instead similar rates are achieved when participants are asked to discriminate differences between 3D unusual shapes with random orientation presentation [129]. This result has been confirmed in our study of object recognition (see section 4.2 for further details) with the difference that objects were explored in a virtual environment. Moreover, if object matching is done with hand-sized unfamiliar objects, the accuracy is still similar between sighted and visually impaired subjects [198]. In fact, it was reported that the cognitive load of blind people in the perception of unfamiliar virtual tactile objects, was similar to that of sighted persons. This was measured both from the subjective and from the neurophysiological standpoint with EEG [25]. When, on the contrary, basic geometrical shapes have to be recognized, blind are more accurate than blindfolded sighted participants. This trend is confirmed also if shapes are presented in an unusual orientation or with distorted contours, thus with no prototypical objects [171]. However, in our test, blindfolded sighted outperformed visually impaired participants: the reason is twofold. First of all, the objects could not be manipulated but where fixed in one position. Secondly the exploration involved the use of a tactile stimulation which was approximating a real stimulation (which is what visually impaired people experience in their everyday life). Results are extensively discussed in 4.4.

Curvature. Curvature, one of the main geometrical properties, has been largely studied in the literature. Edges, contours and profiles of objects can all be defined in terms of curvature. A small curved surface pressed on a passive fingertip generates a response from the mechanoreceptors in the skin, which is directly converted in a pressure gradient. Slowly adapting receptors modify their responses depending on the cue: increasing the indentation force and curvature, they increase response intensity and firing rate [53]. Furthermore, on an anaesthetized finger, slow (SA) and fast (FA) adapting receptors respond differently to a static or a ramp skin indentation with objects changing in curvature [87]. While SAs adapt their firing rate to both ramp and static stimuli presentations, FAs respond only during ramp phase. SAs therefore govern the recognition of spatial parameters of the overall object shape as distribution of curvatures. Both SAs and FAs are important to discriminate small differences in curvature of object having the same shape. Local slope of large curves is the main source of discrimination of curvature [196] in both static and dynamic exploration [145]. Considering dynamic exploration, this result has been confirmed in the experiment described in section 4.3 using a low-cost tool. Systematic results are difficult to be achieved when object size is beyond fingertip dimension, because curvature perception depends on multiple and interacting factors. The direction of hand movements on the surface and the adoption of specific exploratory scanning techniques differently affects curvature discrimination [37]. Finally, curves are also judged depending on the portion of the hand exploring them [144] or whether they are concave or convex [179].

Haptic exploration of objects. Given the curvature and the orientation in space, the haptic perception of an object, then, is mainly achieved with both uni-manual and bi-manual exploration. The way a object is explored, in absence of vision, depends on the property we want to find: in [92], Lederman and Klatzky observed a set of exploratory procedures, voluntary generated, which were systematically related to the object feature to be discovered. Those procedures are mainly bi-manual but some require only a uni-manual exploration. For instance, a static contact allows people to feel temperature, while perceiving the shape of an object is achieved by following the contours, or by grasping the object. Moreover the property of hardness is revealed by pressing one finger one the object and judging the force exerted on it. Finally, texture is revealed by rubbing laterally the fingers on the surface; while weight relies on the proprioceptive feedback by holding the object in the hand.

2.1.5 Spatial information elaboration

Our brain has the intrinsic ability to adapt to environmental pressures, physiologic changes and experiences [138]. The malleability of sensory representation in the brain must be considered one of the striking developments in perception [94]. As an example, in [139] authors reported a study in which normal, sighted subjects were blindfolded for a period of five days. As the interval progressed, the striate and peristriate cortex was activated progressively more during tactile stimulation. When the blindfold was removed and subjects were permitted to see, all changes produced during the blindfolding interval were eliminated.

The adaptation induces to spontaneously elaborate information, thus enhancing the feasibility of creating a training program to facilitate the development of a specific ability [192]. As a rough estimate, at least 100 hours of training are required to reach some proficiency in a complex cognitive skill [181]. However targeted training can ameliorate the completion of a spatial task, as described in [152]. Three kind of training strategies have been tried in order to discuss the most effective to be used with an assistive aid transforming visual images in vibrotactile signals. Trainings were categorized as passive, active and interactive as the level of responsiveness of environment increased. The study suggested that when environmental conditions are responsive to one' s behavioral activity, the activity itself is enhanced. In other words, our minds integrate with the environment in a way that when the environment responds to our actions we are able to synchronize with it, activating more channels of mental activity.

Therefore, to study the spatial ability of visually impaired people, a responsive virtual environment was created and tested (see Chapter 5 for more information).

2.2 Sensory Substitution

Sensory substitution is a process of rerouteing one lacking or defective sensory modality into another modality.

The first sensory substitution device was the Electrophtalm which transformed electronically visual pictures in auditory and tactile cues [167]. However, historically the term *sensory substitution* was first introduced by Paul Bach-y-Rita and colleagues in [7] as a mean of replacing the visual modality with the sense of touch. In that research, the purpose was to collect environmental information: the Tactile-to-Vision Substitution System (TVSS) was both a practical aid for blind people and a way of studying brain plasticity. Sensory substitution, since then, has been exploited to investigate human perception and cognition [112], brain function [127], human-machine interaction [3] and rehabilitation [149].

The two senses involved in the substitution present peculiar perception and interpretation processes. The differences between the two senses concern the anatomy, physiology, neurophysiology and consequently the kind and amount of available information in both cases. The replacement of sensory channel leads, therefore, to unavoidable modifications of the information structure to be transferred. To succeed in the transduction process between the substituted sense and the vicarious one, one requires a system able to perceive the desired information (sensor), interpret and transduce the informative data (coupling apparatus), and transmit it to a device which stimulates the vicarious sense (stimulator). A *metaphor* is defined as the mental passage that leads one object in the first modality to be expressed in the second modality. For example, a wooden cylinder might be the tactile metaphor for a visual scene of a round cake.

The design of a sensory substitution systems requires knowledge and experience in multiple fields linked to human perception, cognition and engineering. Applications of sensory substitution systems are not limited to disabled persons, but include also artistic context [98], serious games [111], augmented and virtual reality [107]. When the application is meant specifically to replace one impaired sensory modality, the technologies developed are classified as *assistive*.

In the following sections of this chapter, visuo-tactile sensory substitution systems will be investigated to understand *how* and to which *extent* it is possible to substitute vision with touch. First there will be a brief explanation of the differences between touch and vision and then, the assistive solutions developed to substitute vision with touch will be addressed.

2.2.1 Vision compared with touch

The main difference between vision and touch is the way they can collect information about the environment.

Vision has the ability to provide an immediate overview of a scene giving both the central and peripheral information. While touch needs to directly contact the elements of a scene and thus it does not offer a peripheral experience.

There are several issues related to get an overview of a scene haptically. Touch is inherently limited to the space immediately surrounding our bodies, i.e. the *peripersonal* space [154]. Objects within the peripersonal space can be grasped and manipulated while objects placed beyond this space, i.e. in the *extrapersonal* space, cannot normally be reached without moving toward them.

That said, tools can potentially extend the space reached via haptics and their frequent use can lead to expand users' perception of their peripersonal space. This insight has been proved by Serino et al. [163] studying the use of the white cane by visually impaired people: blind persons integrate in their body schema the tools that they use to perceive the world.

Although peripersonal space can be enlarged with long-term experience with the cane, tactile perception of the environment remains limited. Tactile perception mediated by a tool, in fact, is influenced by the properties of the parts in contact with the skin and the mechanical features of the specific tool. In the example of the white cane, users feel the features of the terrain through the handle of the cane slithering on the ground by means of a spherical tip, see Figure 2.1 for more details. Forces exchanged between the terrain and the sphere are transmitted to the user's hand (which grips the handle) by means of a long tube: it gives a tactile sensation which is different from directly touching the terrain with bare hands. Moreover, tactile information delivered to the hand is oversimplified since the contact point with the ground is only one. Therefore, even extending the peripersonal space with a tool, touch has poorer performances than vision. However, the brain integrates such information very well: mediated interaction with touch is functionally meaningful. This metaphor suggests that blind persons can interact with objects that they cannot directly touch, something very interesting when the goal is to access digital information.

On the other hand, there are tasks in which touch is much more efficient than vision. Vision can judge the weight of objects only in contexts in which they are handled by other people and not only looking at the object alone [158] . Touch gives a direct experience of weight since it relies on the use of the muscle as a sensory organ and thus is more precise than vision [174], having a threshold of around 4 grams [21] (half of the threshold of vision). Additionally, touch is 25% more precise than vision in the perception of textures: sight was not adequate for the detection of roughness although touch yielded high accuracy (92% of correct answers) [60]. Finally, vision may not be necessary for perceiving the shape of objects located in the peripersonal space since touch appears to be sufficient [130]: it happens when the circumstances resemble those of ordinary life (e.g., participants able to actively manipulate objects and see/touch them from a variety of perspectives). In fact, it is possible to identify objects with a quick exploration of few milliseconds, called a *haptic glance*, especially when the observer has a previous knowledge of what is going to be touched and when the identification is based on local properties such as texture [80].

2.3 Assistive devices for tactile cognitive mapping

Haptic perception has a crucial role in the construction of cognitive maps [175], with non visual cues [134]. The geometrical primitives delivered through touch such as points, lines, up to shapes in 2D and 3D, can then virtually represent abstractions of real objects or spatial cues of unknown environments [86]. However the 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 becomes a highly demanding mental task. Thus 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.

Graphics contain components spatially arranged in a 2D topology. The location of an object can be coded either by reference to participant's own body and/or movements, i.e. using an egocentric frame of reference, or relating it to some external framework, i.e. using an allocentric frame of reference [175]. For instance, I can determine the position of the computer on my desk either by its distance and direction from where I am sitting (by extending my arm in a particular direction relative to my body) or by its position relative to the layout on my desktop (e.g. between the mouse and the lamp). Both methods should allow me to have a representation of it in my mind and reach for it accurately.

Graphical representations in the form of tactile maps, for visually impaired people, provide the spatial structure of the environment at a scale accessible to touch and without the disorienting effects associated with travel in the real world. Maps provide elements arranged in a top-view perspective facilitating the voluntary use of the allocentric frame of reference. The exercise of relating a map to the environment that is represented by the map, can potentially enhance abstract level of spatial imagery in the long term [122]: encouraging the use of externally based coding frameworks for structuring spatial representations of the environment makes the spatial relations between locations more accessible. On the other hand, the aids for the navigation in a real environment encourage the use of an egocentric frame of reference and help to reach contingent decisions.

There are specific procedures encompassing the learning of spatial content from a map, the learning of maps with direct experience of a real environment and the verification that the acquired spatial relations are correct: such is the goal of Orientation and Mobility protocols (O&M). They consist in instructing individuals who are blind or visually impaired with safe and effective travel through various environments. Protocols of O&M simultaneously involve egocentric and allocentric perspectives. The prevalence of one over the other affects the decoding of spatial information [162], but there is no definitive understanding about the adoption of those systems in absence of vision using only haptic modality as it happens for the visually impaired population. This is the reason why, we propose a setup to improve spatial processing in O&M training by providing more information and autonomy to the subject while exploring dynamic tactile maps (see Appendix A). In addition, since the setup provides both allocentric and egocentric information, it can be used as a platform to study how each reference frame is applied to understand space during the exploration of tactile maps.

O&M protocols make use of multiple solutions to display graphical content and to help in the navigation in physical environments: those solutions can be divided in low-tech and high-tech and they are described in the following sections. The main help given by low-tech solutions is that they provide simple, cheap and lightweight aids, with an extra cost in terms of mental effort (see Figure 2.1). High-tech solutions, on the other hand, offer a richer feedback (see Figure 2.2) and a greater easyness to use, at the expenses of bulkiness and price.

2.3.1 Low-tech assistive tools: Embossed pictures

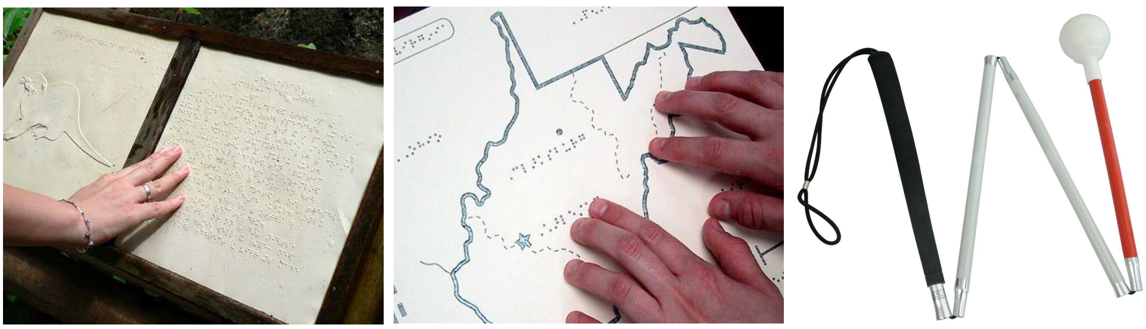
Low-tech solutions described in this section represent the principal methods to assist visually impaired people in the construction of mental maps of real (aids for navigation) and real-but-scaled (embossed pictures and tactile maps) environments. Graphical information can be presented with embossed methods, transforming edges and lines in relief patterns. Embossed pictures are easily understood by non-sighted people. Moreover, blind people are able to draw using strategies similar to their sighted peers when they need to represent perspectives, profiles and spatial arrangements [77]. They adopt lines to symbolize edges of surfaces, portray scenes from a single point of view, associate motion to depictions of irregular lines and use symbolic shapes (heart or star) to convey abstract messages [77]. Tactile pictures can even be drawn on boards: a thin layer of plastic fastened to a rigid backing is carved by means of picks or special ballpoint pens. At the beginning embossed pictures were composed by different layers, adding materials as cloths or strings to a carton base. The following development of this technique has been the introduction of thermoforming process. It consists in forming 3D models by heating plastic materials and modelling them with molds having the desired shape. Another method is to use the swellpaper or microcapsule paper, a special paper covered with a microscopic capsules sensitive to changes in temperature: when heated these capsules expand in correspondence of the black parts of the drawing (see Figure 2.1). Recognition rate of raised-line images on microcapsule is high for both blindfolded sighted and visually impaired subjects and additionally they are better understood than images produced with a plastic sheet on a drawing board [142]. In the case of line graphics representation, it has been shown that embossed modelling techniques were less effective than engraved methods for haptic exploration [201].

2.3.2 Low-tech assistive tools: Tactile maps

Maps are translated to touch modality using the embossing techniques previously described. The relevant information is presented clearly (irrelevant 'noise' which may be experienced in the actual environment, is excluded); with relative simultaneity (a map can be explored rapidly with two hands and with less demand on memory) [28]; and without the issues associated with travel in the real environment (e.g. veering or anxiety). Furthermore, if maps can encourage blind people to represent the environment by externally based codes [177], they may form a crucial component of mobility training [194]. Perception, understanding and manipulation of simple geometrical solids are paramount to use tactile maps, especially at the developmental age, and failure to do so can result in problems later in orientation and mobility [66].

In a study conducted to assess the effect of different instructions (direct experience vs. tactile map exploration vs. verbal description) on acquiring knowledge about a real unfamiliar space in a group of blind participants, it was found that even a brief exploration of a tactile map facilitated blind orientation and mobility of individuals in that environment [44].

However tactile maps can represent only a limited amount of information. Also, specific information such as distances is difficult to be represented on raised-line maps. An enhancement of interactivity of raised-line paper maps, therefore, is desirable. A first attempt to design audio-tactile maps based on swellpaper has been done by Parkes with the device NOMAD [137]. From this idea derived a tool developed in [19] where authors added users' input interaction and speech output to a standard tactile map placed on an apparatus to collect multiple fingers input. This improvement showed that interactive maps are good solutions for improving map exploration and cognitive mapping elaboration in visually impaired people.



(a) (b) (c)

Figure 2.1: (a) Embossed papers containing text and images. (b) A particular example of embossing technique, the tactile map. (c) The white cane in the configuration in which it is closed to be easy to transport.

2.3.3 Highly technological assistive tools: aids for graphical information

The following sections will describe tools employed to help visually impaired people in accessing graphical information and orient themselves in a real context.

Small-area graphical aids. Small-area displays are devices relying less on touch and more on proprioception and motion [110]: here the resemblance of tactile maps to their real counterparts is lower, however with reasonable device dimensions and costs.

The OPtical to TActile CONverter, called Optacon, initially created with the purpose of helping visually impaired people to read texts, could also be employed to read images. The Optacon is a device that consists of a camera, an elaboration unit and a tactile device based on pin-array technology. The camera, manipulated by one hand, is the input device capturing the text or one part of the printed image and sending it to the elaboration unit which converts it in tactile data, see Figure 2.2. In the last version of Optacon, these data are sent to a matrix of 20x5 vibrators [50] which are activated according to the pattern sent by the camera and return its correspondent tactile feedback to a stationary fingertip. At the beginning, in 1978, the Optacon was a successful system since it gave the possibility to access to several sources of information, the printed ones, which were unreadable by the blind population. The major limit of Optacon is that it separates, between the two hands, the act of exploration : one hand acquires the printed image while the other receives the tactile stimulation. This pitfall decreased its usability and restrained its diffusion and use. The advent of speech synthesisers definitively caused its exit from the market. Nowadays it is mostly used for basic haptic research on tactile perception [114] or the accuracy performances for maps accessibility [51].

An advanced tentative to automatically produce haptic diagrams from printed and static representations was also tested [200]. The authors presented a complete system for the generation of haptic graphics, their display and interaction. The system was formed by a scanner to acquire the printed image, a PC as an elaboration unit and a force feedback device (Phantom described also in this section) to allow the interaction of users.

Minimal information or, better, information delivered only on one finger, causes the continuous motion of users' arms in order to integrate the perception on the fingertip to proprioception for recognizing tactile pictures. The following devices, i.e. tactile mice, laterotactile device and the class of surface haptic displays, exploit this process of picture reconstruction through touch.

Laterotactile display, previously known as the STReSS2, [100] is a substitution device generating lateral skin deformation to convey the illusion of exploring 2D shape on a flat surface. It consists in an array of pins moving laterally which are actuated by piezoelectric bending motors. The display was tested in tasks to discriminate tactile icons with both vibrating contours and varying textures. It is interesting because it attempts to provide an alternative way for blind persons to perceive raised line drawing: it approximates height information (the raised line) with tangential information, using a haptic illusion. However, it lacks the possibility to deliver three dimensional spatial content, which is a crucial information in rehabilitation scenarios [193].

Some devices trade off the resolution to reduce the costs and therefore use one or two Braille cells. One example of this simplification is a mouse-shaped device called VT-Player [147] intended to be a tool for one finger exploration, see Figure 2.2. It provides tactual information about shapes and edges of a map inciting the user to move the device to explore in debt picture features using temporally integrating cues from the Braille-cells and the consecutive action. VT-Player has a tactile display consisting of 32 pins separated, in two panel, which rise and fall as the user moves the device. It utilizes optical tracking technology to know the position of the user hand in space and it has a USB connection to the computer. In the same line, Virtouch Mouse [184] is a tactile mouse and navigation screen which enables users to recognize shapes, diagrams and pictures but also to draw symbols, icons and graphics layout. It contains three tactile displays, each with 32 rounded pins arranged in a 4x8 matrix. Even if those devices do not offer tangential forces due to the friction deriving on the action of rubbing surfaces with the fingertip, several works emphasized the usefulness of tactile mice, mostly in education: when graphics were explored with both audio and touch [189] or for teaching science [195].

Phantom (see Figure 2.2) and Falcon devices, created to enhance virtual environment interactions, have been used in rehabilitative context to render 3D surfaces [40]. Those haptic tools measure users' hand position and exert a force vector based on the objects present in the virtual environment. They offer a considerable range of forces to provide access to haptic only math and science applications [195]: forces are both static and dynamic. The only pitfall is that accessibility to a virtual environment is not direct but mediated by a stylus or a sphere. It is a limit because sensing the force-feedback on a single point through a stylus (forcing the hand to be in a 'grasp' position) is not a natural way of interacting and of perceiving the shape of objects. In [85] visually impaired participants used a Phantom to develop a cognitive map of an unknown environment. Participants created new exploration strategies, such as the one simulating walking with a long cane enabling them to walk the perimeter of the room and at the same time to explore its corresponding inner areas: a strategy only possible within the virtual environment. Furthermore, Lahav and colleague found evidences that the more the constructed map is robust, the more subjects' performance is successful.

Large-area graphical aids. Large-area displays are technological solutions mostly relying on tactile feedback and less on proprioception. Those displays have to be used with both hands [84]: here the spatial information is exhaustive at the price of bulky and costly devices.

The class of *surface haptic displays* is characterized by devices exploiting differences in friction, on a glass or plastic layers, to deliver graphical content [131]. An example belonging to this class is TeslaTouch [199] which makes use of modulations in electrovibration to deliver tactile content, see Figure 2.2. They are portable devices and are able to create a tactile percept on a completely flat surface. However, they present the drawback of delivering information only in dynamic conditions, since when the finger is steady, no cue is conveyed. Those displays are the dual of haptic mice. Mice give height information on a steady finger, exploiting proprioception. On the contrary, surface haptic displays do not give height, only texture, and information is only provided when the finger moves. Another consistent drawback is that friction involves the whole screen, therefore natural multi-finger touch cannot be used.

The following haptic displays are classified as *refreshable displays* with pin arrays. They have the advantage that density of dots, activated individually, is able to reproduce complex tactile pictures. However the high resolution leads to higher manufacturing and consequently sales costs. The Hyperbraille is one graphics-enable display from METEC Engineering Ltd. [187], see Figure 2.2. The first product they released was the Dot Matrix Display, DMD 120060, where 7200 tactile dots could be presented in a matrix of 60x120 pins: it has been the first display that could present tactile graphical structures on-line from the computer. METEC technology uses vertical piezo reeds spaced 2.5mm and enables user to interact with tangible media since it is touch-sensitive: users can use their finger as input cursor. Handy Tech produced the Graphic Window Professional (GWP), a matrix of 24x16 refreshable pins, to display tangible images from a computer [31]. The inter-dot distance is 3mm and also here the user can interact with the display zooming in or out the image, thus changing its resolution. Among the refreshable displays, it is interesting to speak about inFORM: a system built at Massachussets Institute of Technology formed by 900 motorized pins, shaped as parallelepiped [96]. Users can interact with it thanks to an overhead camera recoding gestures and transferring those data to inFORM which acts consequently. It enables guided interaction with dynamic constraints, object passive motion and physical rendering of content and UI (user interfaces). However, this technology is not yet commercialized and has not yet been tested in the context of rehabilitation.

To reduce dimensions of refreshable displays, the actuation system can be modified to have less motors and control an adequate number of pins: it is the idea behind BlindPAD project whose aim is to create an affordable tactile tablet to deliver abstract mathematical concepts to visually impaired people. Intentionally violating Braille specifications, the pins of BlindPAD device have higher dimensions than refreshable displays, since its purpose is to deliver graphics and not texts. It has been recently shown that pin arrays improve spatial abilities of blind and visually impaired children as much as traditional paper, however with the great advantage of presenting stimuli automatically [97]. The children therefore require minimal assistance from rehabilitation practitioner.

Since maps are abstract representations of a generic environment they can also be represented using graphical user interfaces (GUIs) through which sighted people manipulate graphical objects on computer screens is actually a map. Computer users can interact by clicking on menu items or buttons or moving graphical objects on the screen. However, in absence of vision it is difficult to handle a standard mouse since it has a relative position system and gives no feedback about the position of the pointer on the screen. A first effort in the development of software aids to let visually impaired people interact with the computers was the GUIB project [34]. The GUIB design is based on translating the screen contents into a tactile presentation which emulates the spatial organization of graphical user interfaces. Tactile feedback is given by means of Braille displays, as those previously described.

Clearly the technological aids described so far deliberately choose either to concentrate on information derived from height (pin arrays, tactile mice, the Optacon) or on information derived from tangential forces (surface haptic displays, STRESS). Interestingly, there is a lack of devices that integrate curvature as one of the main rendering primitives.

An overview of all the classes of devices described in this section can be found in Figure 2.2.

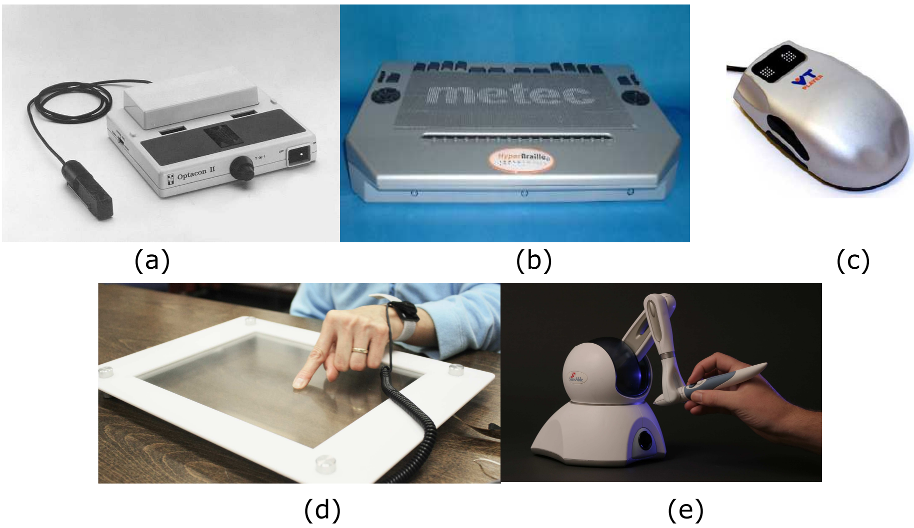


Figure 2.2: (a)The Optacon, a tactile device based on pin-array technology. (b) The HyperBraille, a refreshable display from METEC. (c) VT-Player a mouse-shaped device to deliver graphical content from touch, using two fingers. (d) TeslaTouch, a tool belonging to the class of surface haptic displays. (e) A force feedback device, the Phantom.

Aids for guidance and mobility Navigation skills involve the ability of localizing oneself and travelling in a space. In addition, it requires updating spatial information related to the environment and efficiently employing such information in emergency cases, such as getting lost or accessing interrupted roads. The previous knowledge of the navigation path facilitates the reaching of the desired destination [85]. To store data about the itinerary, our brain has to collect and elaborate information on spatial landmarks, on position and orientation of geographical reference points. This process facilitates the creation of a mental schema representing a simplified version of the real itinerary.

Moreover, while navigating in absence of vision, a guidance can facilitate and accelerate the destination reaching. The user can be updated with the assistive device about the local directions to follow to improve locomotion and increment independence of visually impaired people.

A seminal study demonstrating that tactile information can guide subjects' movements was conducted in [67]. A 20x20 tactile display positioned on the back of subjects was used to deliver patterns of moving stimuli. Test was conceived as a game, called "batting a ball": players had 3 seconds to guess the direction of a ball moving towards them (see Figure 2.3). They were seated and had to organize an appropriate response to stop the ball.

Then, the Tactile Vision Substitution System (TVSS) is one of the first attempt to compensate vision with touch and allow blind users to navigate safely. The more recent version of the TVSS

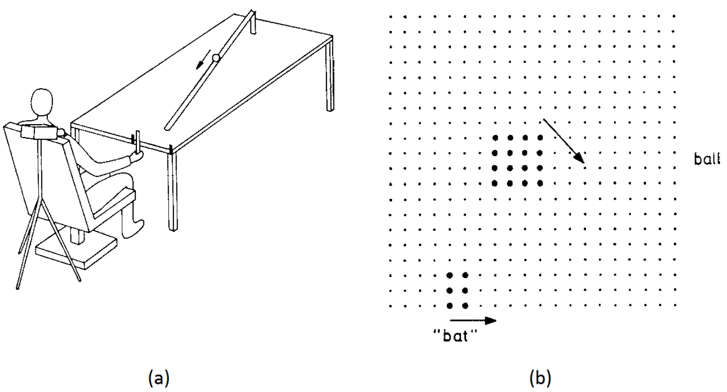


Figure 2.3: (a) Experimental situation in the "batting a ball" study [67]. (b) Example of a momentary tactile stimulation in the "batting a ball" study. The ball does an oblique path and the participant (bat) has to catch it.

has a camera on the head which picks up environmental information and transform them in tactile patterns delivered to the chest *via* electrodes [5], see Figure 2.4. Exploiting the same concept, Elecktrophtaml reproduced visual information on the forehead [167], see Figure 2.4. Chest, head or back present the same perspective of vision since they represent information on the same plane and are more intuitive to process. In this case tactile feedback is given in the form of egocentric frame of reference. The egocentric frame of reference may lead to some limitations in spatial updating, but it is appropriate when a guidance is needed [151].

However, when cues are on the tongue, they are presented on a reference system which is transversal to the visual plane. Thus, it may be important to know the perspective adopted by people in discriminating the stimuli. In [2], Arnold and collegues found that the majority of participants (80%) spontaneously chose a self-centred perspective insted of a decentred one. This choice affects the recognition of symmetrical patterns such as the misdjudgement of the letters 'b' and 'd'. Given that, the design of stimmuli should be limited to unambiguous ones. Many tools exist which deliver tactile feedback to the tongue, one of them is the Tongue Display Unit (TDU) [73], see Figure 2.4: a programmable electronic device developed in 1999 which evokes tactile sensations passing a local electric current through the skin. Those substitution devices are useful because they provide tactile feedback letting the hands to be free but at the same time using vibrotactile displays limits the range of stimuli variability.

2.3.4 Highly technological assistive tools: Improving the white cane

The white cane is the most widespread tactile assistive tool for blind people to interact with the surrounding environment. There is a specific class of assistive technologies built to integrate the white cane in order to improve its effectiveness. Such a device is known as a *virtual cane*, or an *Electronic Travel Aid* (ETA). Virtual canes solve several of the main problems of white canes: they are less obtrusive because there are no collisions between the ETA and people or fragile objects in the vicinity, their reach is longer (several meters vs. 1 m), and their weight and shape enable them to be easily pointed at different heights, thus providing protection from higher obstacles. Therefore, any device that attempts to either augment or replace the white cane should enable better independent mobility in natural environments, including reduction of the number of collisions [108] and being at the same time both simple and intuitive to use [155]. The ETA reported here have already been tested with sighted and blind people. A complete list can be found in [35].

One example is the GuideCane [12], a sensor attached at the distal end of the handle of the white cane. The sensor head is mounted on a steerable but unpowered two-wheeled steering axle. Ultrasonic sensors mounted on the sensor head detect obstacles and steer the device around it. The user feels the steering command as a very noticeable physical force through the handle and is able to follow the path given by GuideCane.

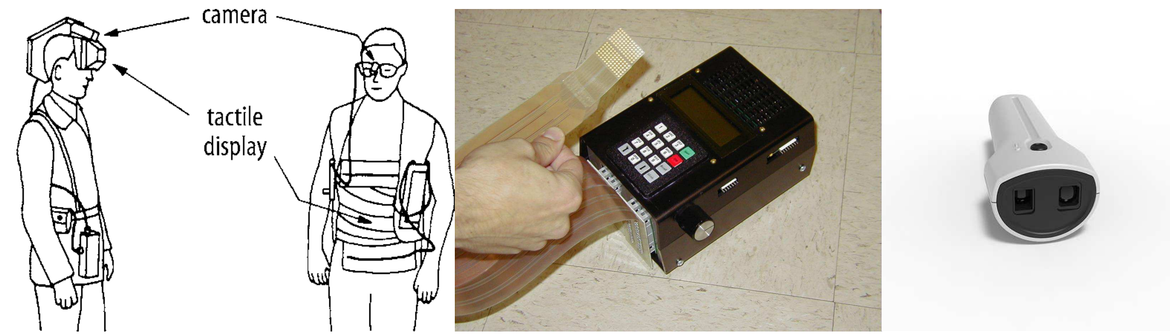
Tom Pouce and Teletact are other examples of additional technology to the canes [45]. The first, Tom Pouce, is intended to detect obstacles in front of the users' hands using an infrared proximeter: a light emitting diode panel scatters light on the obstacles, detectors read those signals and in case of threshold proximity, it alerts the user. Its resolution is 20 degrees horizontally and 50 vertically. Teletact is a laser Telemeter with a higher accuracy than infrared: 1% in the range of 10cm up to 10m. If an obstacle is detected the device signals it by means of tactile cues (stimulating with vibrations intervals proportional to obstacle distance) or audio (using 28 musical tones codifying obstacle distances).

In [13] is described an assistive tool, called Navigation Aid for Blind People, able to give information to the blind about urban walking routes and to provide real-time information on the distance of over-hanging obstacles within 6 m along the travel path. It detects possible obstacles using one ultrasonic sensor integrated into the cane and two on users' shoulders. The type of tactile feedback delivered is vibrations.

A step toward unobtrusive aids has been explored in [24] with the EyeCane: a low-cost finger-sized device. The EyeCane can detect obstacles in the range from 0 to 1m using narrow infrared beam in the direction in which the device is pointed with a resolution of 5 degrees. Vibration produced to alert users is modulated in frequency and amplitude. An overview of all the classes of devices described in this section can be found in Figure 2.4.

2.4 On the efficacy of sensory substitution aids: what are they for today?

In this chapter, sensory substitution devices for delivering graphical content through touch have been described. Graphics, as images or maps, are formed by basic components placed in meaningful positions in a 2D topology.



(a) (b) (c)

Figure 2.4: Examples of sensory substitution devices used to give direction cues to visually impaired people. (a) Two devices with a matrix of point stimuli fed from a camera, the Electrophthalm (left) and a version of the Tactile Visual Substitution System (right) [63]. (b) The Tongue Display Unit (TDU), a technology that translates visual patterns from a video camera to electro-stimulation patterns on the tongue. (c) The EyeCane transforming point-distance information into tactile cues delivered on the hand.

Low-tech solutions to elicit the creation of mental maps from graphics exist and are effective. However, they present limits since they cannot be easily reconfigured while changing the environments or adapted depending on the ability of different users [20].

Presenting virtual shapes instead of real solid models has the potential of spanning over a much larger taxonomy of objects, however using a single device. To build a virtual percept of a real object with appropriate stimulation means, however, is not obvious. To better target the technology to users' needs, physiological features of touch should be taken into account when designing the device. The tool we propose in Chapter 3 includes changes in skin deformation and pressure on the whole fingertip, since the end-effector in contact with the finger is a flat disk of 20mm. Depending on the participant's actions, the fingertip indentation can elicit the Merkel receptors (when a steady pressure is present), the Ruffini endings (the skin on the fingertip is stretched) and the Pacinian corpuscles (because of changes in pressure are created). Meissner corpuscles are not involved because their role is mainly related to fine texture detection which is not relevant for the topic of this thesis.

To find a suitable solution for delivering graphical content, tools proposed in literature range from small-area to large-area tactile display. Those solutions exploit different kind of technologies.

By presenting tactile stimuli with mechanical moving parts (such as pins) helps to create bas relief-like tactile representations. Whether these pins reside on a fixed screen, or whether they reside on top of a mouse can have a large impact on the way the end user processes such information. In this thesis we will rely more on the second approach, where information is tactile on one finger only and proprioception is more elicited, compared to multi-finger touch. While pin arrays are ideal because they mimic raised-line drawings, they may not render three-dimensional shapes. Putting pins on top of mice does not solve this problem either. Therefore, for the purpose of this thesis, one solution is to go beyond pin-based technologies and render bas-reliefs differently, by exploiting the third dimension with an extended actuation mode. Moreover, since several studies emphasized the usefulness of tactile mice, mostly in education [189], [195], in this thesis the tool we propose is a mouse-shaped tactile device, called TAMO (see Chapter 3 for further details). Although it does not offer tangential forces deriving on the action of rubbing surfaces with the fingertip, it is able to mimic a real exploration merging tactile stimulation to the proprioception of the arm.

Tools as the Optacon, split the actions of exploring and sensing the content between two hands, causing possible confusions during the process of information acquisition. To overcome this limit, TAMO provides the input (acquisition system) and output (tactile stimulation) feedbacks on the same hand.

Surface haptic displays are effective in modulating friction to create a tactile percept on a completely flat surface but they present the drawback of delivering information only in dynamic conditions: when the finger is steady, no cue is conveyed. TAMO, instead, offers a tactile stimulation which is informative in both static and dynamic touch because it approximates a tactile scalar field providing, as geometrical primitives, inclination and elevation.

Finally, there exist powerful devices, such as Phantom and Falcon, which render 3D surfaces exerting both static and dynamic forces. They enhance virtual tactile interaction when vision is present, but in a haptic-only scenario, their feedback seems less natural. This is caused by the nature of the interaction which is mediated by a stylus and which forces the hand to an unnatural position during the exploration of objects. With TAMO, we propose to solve this issue designing the end-effector in order to not annoy the users while the exploration occurs. The end-effector is a flat disk and gives the illusion of touching objects as if a coin was put between the object and the fingertip. The motion of the end-effector is sustained by the actuation system of TAMO itself therefore allowing users to perform an unconstrained exploration.

CHAPTER 3

EXPERIMENTAL SETUP: ACCESSING DIGITAL INFORMATION WITH A TACTILE SENSORY SUBSTITUTION SYSTEM

In the field of assistive tools for visually impaired people, there are few suitable solutions delivering graphical contents through the residual senses. Additionally, the number is even smaller if considering the solutions adopted in blind rehabilitation centres. Standard rehabilitation tools render images in two dimensions using swell papers or hand-made solutions, which cannot be reconfigured, adapted or possibly shared. Some interesting results in terms of representation of two-dimensional graphics were obtained [166],[165] (see chapter 2 for a wider list), but three dimensional concepts still rely on solid models of objects, which are expensive to produce, not easily editable and often bulky.

Presenting virtual shapes instead of real solid models has the potential of spanning over a much larger taxonomy of objects, however using a single device. To solve the problem of accessing digital information non-visually, therefore, we propose two devices meant to deliver not only planar graphics but also the third dimension in a virtual environment. The effort is to create a new generation of tactile user interfaces, where tactile icons of simple shape and size can be manipulated in a desktop setup and to which semantic information can be attached (e.g. text or spoken text, music). The two devices, shaped as standard PC mice, were designed to produce a system which progressively imitates real haptic exploration, merging tactile cues with arm movements and providing, step by step, an enhanced touch sensation. A mouse-shaped device can be handled with one hand and can deliver the tactile sensation on one finger of the same hand. These features allow to integrate tactile feedback received locally on the fingertip to the proprioceptive feedback determined by the active motion of the arm.

How to render the third dimension is a current matter of research: we study how the point of contact that stimulates the finger, can represent different features of objects, such as elevation, inclination or both. In this way, the role of each descriptor can be separately evaluated.

3.1 General description of the system

This section describes the elements of the assistive tool proposed to enhance spatial abilities of visually impaired people through touch. The tool created is composed by multiple components: their features and roles are illustrated in the following sections. The system can be divided in two subunits: a tactile user interface (TUI) and a portable computer (PC), see Figure 3.1.

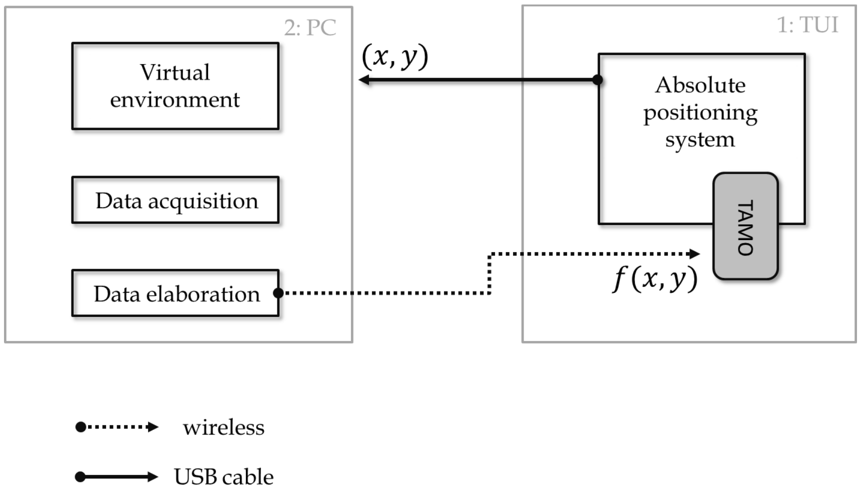


Figure 3.1: System Overview.

The TUI comprises a tactile device commanded from the user, the TAMO (abbreviation of TActile MOuse), and a system to track its movements. In particular, TAMO stands for two assistive tools which were sequentially built: one is a minimalistic tactile mouse, TAMO1, and the other is its evolution, TAMO3. The positioning system is a commercial graphic tablet and offers an absolute position tracking, overcoming one of the issues of using mice as rehabilitative tools. The graphic tablet was connected to the pc Precision M64000 from Dell, via USB. With TAMO users explored a virtual environment created with Matlab™software. Moreover, mouse position and specific information concerning the tests were acquired and recorded in Matlab™environment. The commands to activate the end effector of TAMO were calculated given the position of the mouse in the x-y plane and the features of the virtual environment. Finally, the commands were sent via XBee, a wireless module, to the tactile mouse.

The choice of using mice as assistive tools comes from the success they have with untrained users, such as congenitally blind who never used an electronic mouse, in the construction of mental maps [132]. However, there are issues related to the adoption of haptic mice in rehabilitation of visually impaired individuals [147]. In particular, they have poor accuracy of haptic position information, since commercially available mice are relative positioning devices. Moreover, they can present a mismatch between the position sensor of the mouse and tactile end effector as it happens with the VT-Player device in [147]: it has two Braille-cells, both stimulating the finger, which receive the position input from one-point sensor placed under the mouse. This shift, from one-point input to two-point stimulation, generates confusion during the acquisition of tactile information. To solve those issues, as previously explained, the setup proposed uses an absolute positioning system and a single end effector centred on the mouse position transmitter.

3.2 Minimalistic device for graphical information delivering: TActile MOuse 1

The device called TActile MOuse 1 (TAMO1), is the end-effector of a larger sensory substitution system described in [30] for the first time.

3.2.1 Concept

TAMO1 is a minimalistic device aimed at getting 3D virtual maps through the sense of touch, see Figure 3.2. The punctual haptic feedback provided, the simplest which can be imagined, is meant to understand how much graphical information can be delivered stripping down the tactile stimulation.

3.2.2 Description of the TAMO1

The mouse is 108 mm long, 67 mm wide and 37 mm high (maximum height). It is formed by multiple components as shown in Figure 3.3: the servomotor with its lever (tactile end effector), the positioning board to detect the absolute position of TAMO1 in the x-y plane, the power board to transfer the power from battery, the motor driver, the Li-ion battery, XBee receiver to collect data for controlling the position of the lever and the power switch.

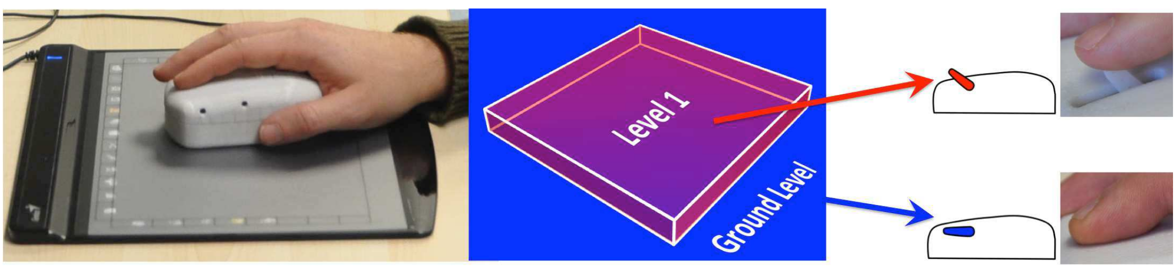


Figure 3.2: TActile MOuse 1 operating principle. Left: TAMO1 moved on the positioning tablet; Center: when the finger is on top of the virtual object, the lever rises at Level 1, otherwise it lowers to Ground Level. Right: finger-lever contact.[119].

Servomotors TAMO1 displays the profile of virtual objects by means of a lever, i.e. the shaft of the servomotor inserted in the device. Servomotors are small devices usually used in radio controlled models which incorporate a DC motor, a gear train, a potentiometer, an integrated circuit and an output lever. Wires sticking out from the case are three: one is for the power, one for the ground and one for the control input line. The lever is controlled in position through the changes in the resistance of the potentiometer. It can be positioned to a specific angular position by sending a coded signal: an electrical pulse of variable width (pulse width modulation) where angular position is proportional to pulse width. Until the coded signal persist on the input line, the servo will maintain the angular position of the lever exploiting the physical limits offered by threads of gears and thus without wasting power. When the signal in input changes, the angular position of the lever is adapted to the new signal. The servo used was HS-5055MG from HighTec and its main features are summed in the table 3.1.

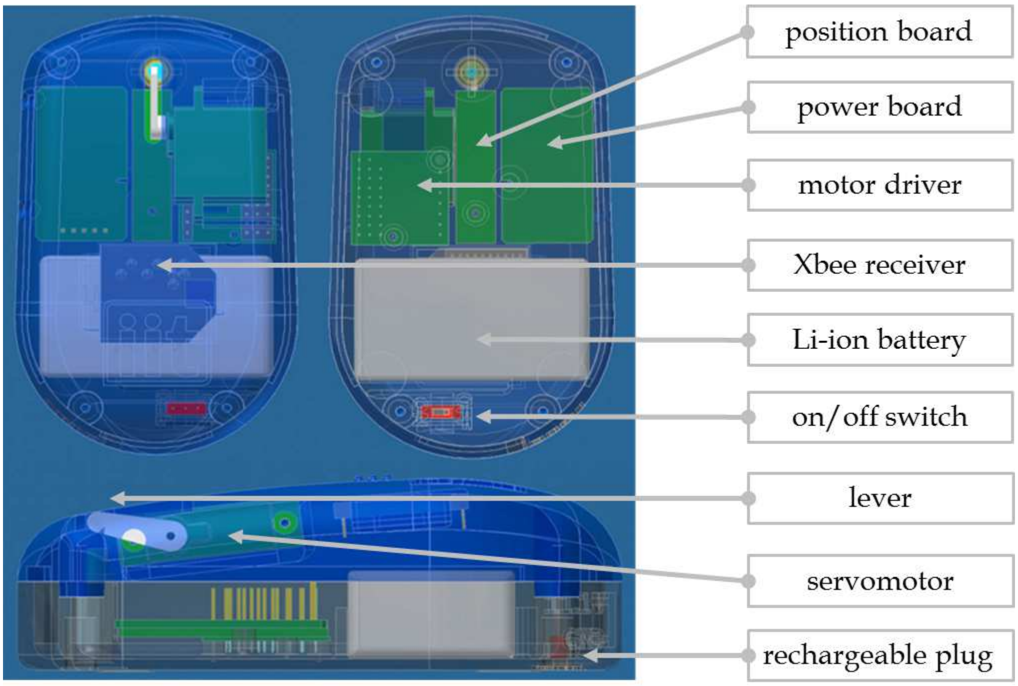


Figure 3.3: (Left) Components disposition in the TAMO1 from top-view, bottom-view and side-view. (Right) Name of components of TAMO1. Picture was selected from [16].

Positioning board The position of the TAMO1 is tracked thanks to the tablet Genius G-Pen F610. This tablet is sold jointly with a pen having a control circuit which has been transferred in the TAMO1 and which is the *positioning board* depicted in Figure 3.3.

Motor driver As driver for the servo, the Pololu micro serial servo controller was used. It can control up to 8 servomotors with a resolution of 0.5 μs and consuming on average 5 mA of current.

Table 3.1: Main features of the servomotor used for TAMO1 device.

Servo HS-5055 MG	
No-load speed	0.20 s/60°
Stall torque	1.3 kg*cm
Max PWM signal range	750-2250 μs
Motor type	carbon brush
Current drain - idle	3 mA
Current drain - no-load	3 mA
Potentiometer Drive	6 slider indirect drive
Gear type	straight cut spur

Table 3.2: Main features of the XBee radio module used for TAMO1 device.

XBee radio module 802.15.4	
Frequency	2.4 GHz
Data rate	250 kbit/s
Communication protocol	802.15.4
Supply voltage	2.8 to 3.4 VDC
Max. current consumption (trasmitting)	45mA
Max. current consumption (receiving)	50 mA

Wireless communication The XBee ensures the reception of coded signals coming from the computer which have to be sent to the servo. XBee is a family of compatible radio modules from Digi International. The radio module used for the board of TAMO1 was XBee 802.15.4 and its main features are summed in table 3.2.

3.3 Approaching real touch with TActile MOuse 3

TActile MOuse 3 (TAMO3) is the following version of TAMO1 and is targeted to construct mental maps via dynamic touch: it is called TAMO3 since it has three degrees of freedom.

3.3.1 Concept

TAMO3 is a new tactile mouse able to deliver graphical content by approximating a surface with elementary geometrical descriptors: elevation, inclination and their combination. TAMO3 imitates real touch reproducing phalanx movements and fingertip deformations respectively with elevation and inclination cues, see Figure 3.4 for more details. The introduction of a richer feedback, as compared to TAMO1, implies to investigate the role of each geometrical descriptor that make it possible to render virtual objects. For this reason, the experimental tests described in Chapter 4 analyse the contribution of each descriptor separately. The new tactile device involves the whole fingertip area in contact with the virtual surface: indentation on the fingertip during an active exploration induces dynamic changes in contact forces and area [121] which can lead to modifications in object reconstruction strategies. We hypothesize that the larger contact area of the end effector (tactor) together with the presence of more degrees of freedom, that TAMO3 has respect to TAMO1, let people infer object features even without moving the device: it is informative in both static and dynamic touch. Admittedly, this device lacks the tangential feedback, mainly used to produce directional cues or create the illusion of touching a bump [136]. However, the metaphor of rendering a curved shape presenting just the lateral forces associated with sliding over that bump is a tactile illusion. Furthermore it lacks the contribution of finger proprioception in the process of constructing a tactile map.

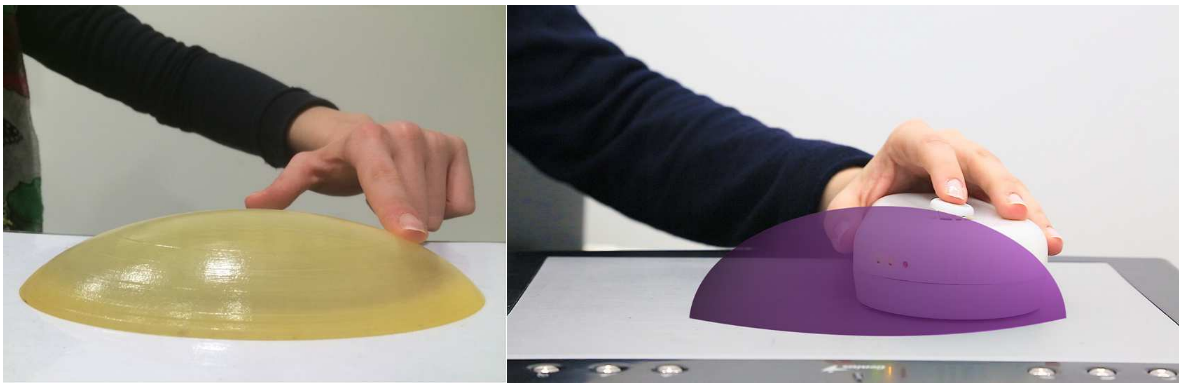


Figure 3.4: Exploration of a real object with the bare finger sliding on the surface (left). The correspondent virtual object tactually rendered with TAMO3 (right).

During the exploration of real surfaces, the stimulation of different regions of the fingertip implies a different configuration of the hand and consequently an in-built movement of the wrist, see Figure 3.6. Free explorations in a real environment are characterized by the unpredictability of hand configurations contacting the surfaces. The position of the fingers determines a specific tactile sensation. In particular, when each fingertip is exploring one point of a non-planar surface rotating the wrist, the indentation of the skin changes according to the orientation of the finger. Tactile devices dealing with virtual reality lack this feature and this decreases the truthfulness of their stimulation. The main difficulty of updating the tactile feedback according to the orientation of the wrist consists in the time required to measure the angular position of the wrist and to generate an adequate tactile feedback. In order to be considered reliable and veridical, the refresh of tactile feedback should occur in the range of 30 - 40 ms [89]. To the best of our knowledge this device is the first attempt to face this issue. It offers the possibility to update the stimulus of the end effector every 33 ms according to the orientation of the wrist. The description of the analytical methods used to render inclination cues in an absolute positioning frame of reference, independently on how the mouse is handled, are explained in section 3.3.4.

3.3.2 Description of the TAMO3

The mouse is 140 mm long, 90 mm wide (largest width) and 25 mm high. It allows motion of a tactor across the Z-axis (therefore eliciting an elevation cue) as well as around the two axes

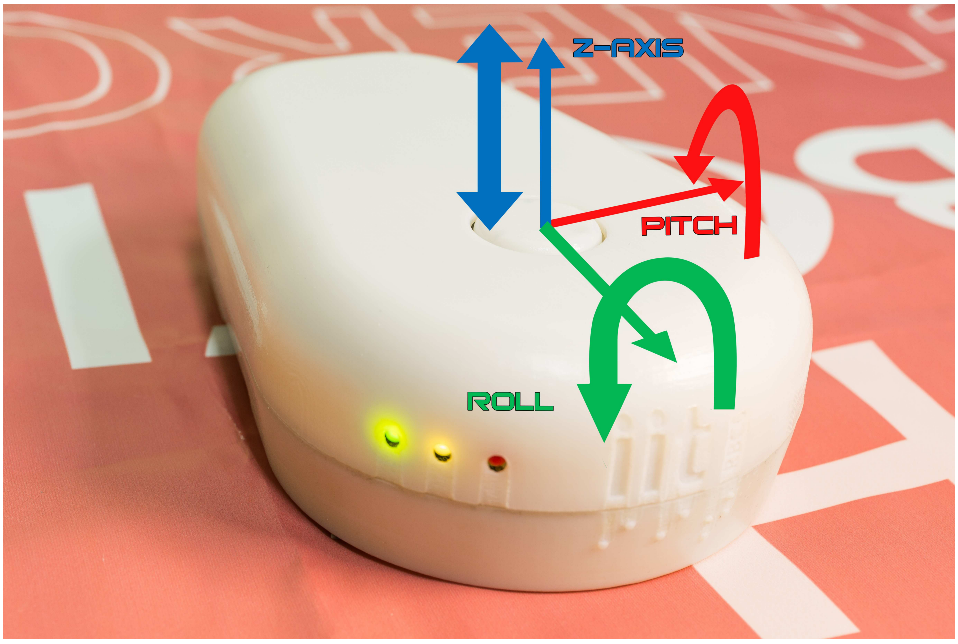


Figure 3.5: TActile MOuse 3 (TAMO3) is a portable mouse able to produce tactile feedback on one finger by means of a flat end effector (tactor). The tactile feedback imitates real touch and provides three degrees of freedom: elevation, roll and pitch.

forming the plane perpendicular to the Z-axis (roll and pitch cue). The tactor and the axes are shown in Figure 3.5. The tactor is composed by a moving disk, with a diameter of 20mm; its motion is controlled by three independent servomotors which are connected to three pushing rods nestled in the lower surface of the tactor in three points 120 degrees far apart from each other; the tactor motion can be assimilated to the stationary swashplate (in fact the yaw cue is absent) of a helicopter with cyclic/collective pitch mixing control [65]. Both the tactor and the mouse external cover are built out of a 3D-printed 'verowhite' resin.

The main components of TAMO3 are described in detail in the following paragraphs.

Microcontroller The board of TAMO3 has the microcontroller STM32L151CBU6 produced by STMicroelectronics. This controller is ultra-low-power and based on a ARM Cortex-M3 core operating at 32 MHz frequency and having a high-speed embedded memories (Flash memory up to 128 Kbytes and RAM up to 16 Kbytes). It includes a real-time clock and a set of backup registers which remain powered in Standby mode.

Wireless communication The initial radio module connected to TAMO3 board was the Bluetooth RN42XVP-I/RM from Roving Networks. It was then exchanged with the XBee module used for TAMO1 (described in section 3.2) because of delays in transmission explained in Appendix A.

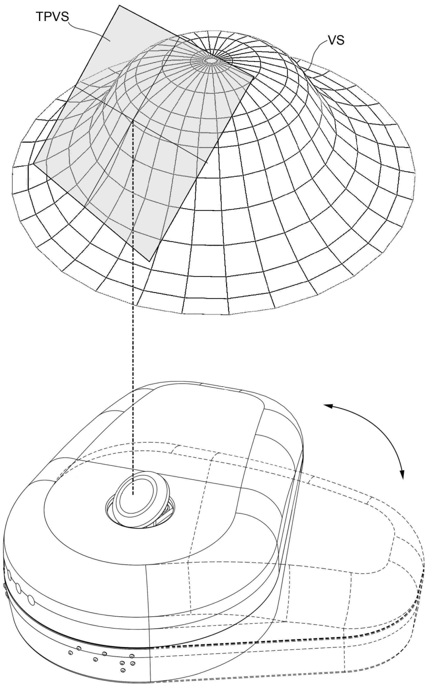


Figure 3.6: TAMO 3 haptic rendering: it gives local tactile feedback according to device or, equally, hand orientation. VS is the Virtual Surface and TPVS is the Tangential Plane to the Virtual Surface. TPVS represents position and inclination of tactor, TAMO3 end effector.

Positioning coil One open core coil allows TAMO3 to be tracked from the absolute positioning system, i.e. a graphic tablet. Coil is controlled by a square wave generated by the microcontroller and having 168 kHz as maximum frequency. The magnetic signal is detected by the graphic tablet and then transmitted to the computer.

Servomotors TAMO3 uses three servomotors to control the tactile end effector, i.e. the tactor. Servos are positioned on the board 120 degrees far apart from each other and controlled with three signals with pulse width modulation at a frequency of 200 Hz having a width which varied from 1 to 3 ms (PWM signal). The model used in TAMO3 is Hitec HS-5056MG and its main features are summed in the table 3.3.

MEMS components The peripheral device of the microcontroller manages the following MEMS components of TAMO3:

Table 3.3: Main features of the servomotor used for TAMO3 device.

Servo HS-5056 MG	
No-load speed	0.12s/60°
Stall torque	0.99 kg*cm
Max PWM signal range	900-2100 μs
Motor type	3-pole
Current drain - idle	3 mA
Current drain - no-load	3 mA
Potentiometer Drive	6 slider indirect drive
Gear Type	metal

- the accelerometer and magnetometer LSM303DLHC featuring a 3D linear acceleration sensor with a full scales of $\pm 2g/\pm 4g/\pm 8g \pm 16g$ and a 3D digital magnetic sensor with full scale of $\pm 1.3g/\pm 1.9g/\pm 2.5g \pm 4.0g$;

- the digital gyroscope L3G4200D, a low-power three-axis angular rate sensor with a full scale of $\pm 250/\pm 500/\pm 2000$ dps.

Supply TAMO3 electric supply is constituted by four rechargeable Nickel-metal hydride batteries. Each battery has a nominal tension of 1.2 V so the total tension is 4.8 V.

3.3.3 Kinematic model of TAMO3

The motion of the tactor is guaranteed by the presence of three servomotors. The movements of the servomotors are transmitted to the tactor thanks to three rods fastened to their levers through a linchpin and to the tactor base through a spheric joint. This section describes how the model of the system tactor-rod-lever-servomotor, i.e. the kinematic chain of TAMO3, calculates the angles to command servos (see Figure 3.7 for further details).

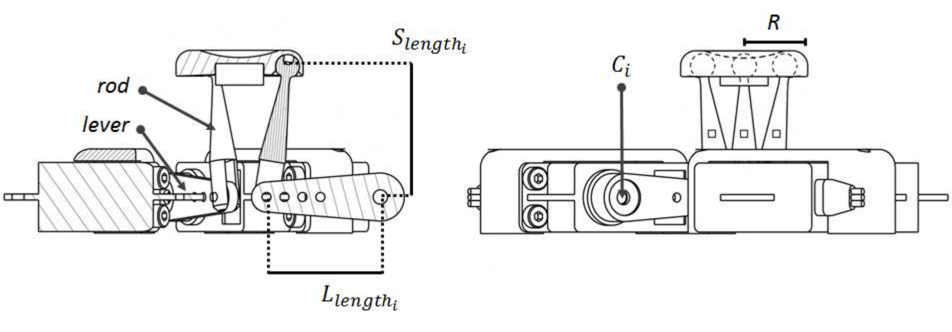


Figure 3.7: Sections of TAMO3 mechanical components with particular attention to its kinematic chain. There are the levers of each servo, having length L_{length_i}, which transmit the motion to metallic rods (having length S_{length_i}). C$_i$ is the coordinate array of lever centres of rotation and R is the tactor radius.

The kinematic model returns the values of angles of servomotors having in input tactor elevation (z-axis variable shown in Figure 3.5) and the three components of the tactor normal vector. Starting from the geometric disposition and physical dimension of components of TAMO3 it is possible to calculate the coordinates of center of rotation, C_i, for the lever of each servo

$$C_i = \begin{bmatrix} x_{0i} \\ y_{0i} \\ z_{0i} \end{bmatrix}$$

where i=1,2,3 indicates the three servos.

The parameters of tactor, retrieved depending on the created virtual environment, can be expressed as

$$h = \begin{bmatrix} 0 \\ 0 \\ H \end{bmatrix} \qquad n = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix}$$

where h is the array containing the height of tactor and n the array with the components of the vector which is normal to the tactor. The final position of the rod in three dimensions, $S_{i|j}$, is found with the following equations:

$$\begin{aligned} r_{1i} &= -C_i \\ r_{2i} &= h - r_{1i} \\ u_{i|j} &= \|(r_{1i} \times r_{2i}) \times n\| \\ t_i &= \sqrt{\frac{R^2}{\sum_j u_{i|j}}} \\ S_{i|j} &= h + l_{i|j} * t_i \end{aligned}$$

where R is the radius of the tactor and $j = i$ = 1,2,3 indicate respectively each Cartesian axis and the three servos.

In order to calculate the angles of lever, a new set of coordinate system is created, R_i:

$$\begin{aligned} vx &= \|r_{1i}\| \\ vz &= \|vx \times r_{2i}\| \\ vy &= \|vz \times vx\| \\ R_i &= \begin{bmatrix} vx^{\intercal} & vy^{\intercal} & vz^{\intercal} \end{bmatrix} \end{aligned}$$

The coordinates of the rod, s_i, are transformed from 3D in 2D with the rototranslation:

$$s_i = (S_{i|j} - C_i) * R_i$$

zero value is assigned to the third component. Then it is possible to obtain the values of the angles of lever, δ_{lever_i}, expressed in radiants:

$$
\begin{aligned}
px_i &= S_{i1} \qquad \text{(1 means the first component)} \\
py_i &= S_{i2} \qquad \text{(2 means the second component)} \\
L_{i1} &= L_{length_i} \\
L_{i2} &= S_{length_i} \\
a_i &= \frac{px_i^2 + py_i^2 - L_{i1}^2 - L_{i2}^2}{2 * L_{i1} * L_{i2}} \\
b_i &= \sqrt{1 - a_i^2} \\
\delta_{lever_i} &= \left(\left(\frac{sin(py)}{cos(px)} \right)^{-1} - \left(\frac{sin(L_{i2} * b_i)}{cos(L_{i1} + L_{i2} * a_i)} \right)^{-1} \right)
\end{aligned}
$$

where a, b are parameters depending on physical dimensions of the components of TAMO3 and on the actual status of TAMO3 while L_{length_i}, S_{length_i} are respectively the length of the lever and of the rod.

3.3.4 Invariance of the tactor inclination to wrist motion

This section describes the method used to update TAMO3 end effector depending on the orientation of the wrist. The final frequency of update achieved is 30 Hz: the tactor refreshes its status every 33 ms. This frequency seems reasonable since the perception of simultaneity of two stimuli occurs in the range of 30 - 40 ms [89]: it is referred to the condition in which finger is static thus when the haptic system is more sensitive, i.e. it presents the lowest perception thresholds.

The method used to update the status of the tactor consists in picking up the data of angles of servos from a lookup table stored in the board of the TAMO3. The choice to store the angles of servos on-board was caused by the need to achieve fast data recall. If those angles were stored in the PC, the time required to access them would be constrained by wireless communication features.

The lookup table has been generated for each servo from a simulation performed in Matlab® environment. To decrease the dimensions of the lookup tables and thus the delay to access to its data, the simulation was done for a representative set of the heights of the tactor. For simplicity of visualization and calculation, the spherical coordinate system was chosen, see Figure 3.8 for further details. The angle of tactor is represented as a function of *azimut* and *elevation* angles as in the following equation:

$$\delta_{lever_{i|n}} = f(azimut, elevation)$$

where n indicates the set of chosen heights of the tactor, n = 15.2,19.4,23.6,27.8,32 mm. In the simulations *azimut* angle was varied within the range [-180°,180°] and *elevation* within the range [55°,90°], results are shown in Figure 3.9.

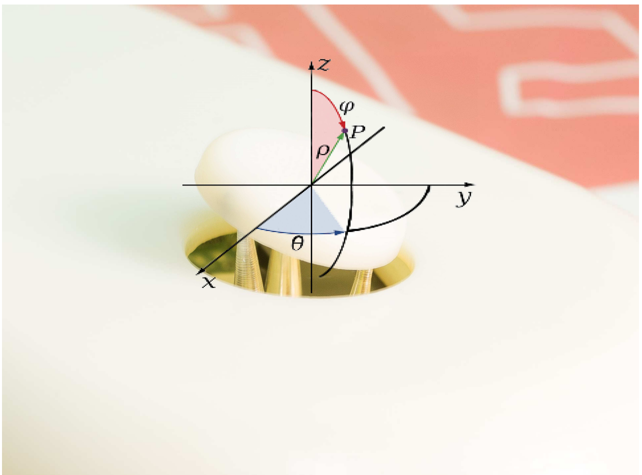


Figure 3.8: Values stored in the lookup tables are expressed in terms of spherical coordinates. θ represents the *azimut* angle, φ the *elevation* angle and ρ the distance between a generic point P and the axis origin. The spherical reference system is showed on the tactor, here $\rho = 1$ since it represents the normal to the surface of the tactor.

Looking at the plot with the δ_{lever_i} for all the three servos (last plot on the right in Figure 3.9) it is evident that, for fixed values of *elevation*, curves have a sinusoidal trend dephased of a certain Θ analysed in the following paragraph. For fixed values of *azimut*, the *elevation* shows a quadratic dependence. Moreover the initial $\delta_{lever_{i|n}}$ status depends on the specific height value. Those considerations led to the formulation of the following model:

$$\delta_{lever_{i|n}} = k_{offset} + (a * Elevation^2 + b * Elevation + c) * sin(f * Azimut + \Theta)$$

The model is necessary to predict values of $\delta_{lever_{i|n}}$ and successively fill the lookup tables. In Matlab environment, the model was tested with the functions of the 'Curve Fitting Toolbox'. The chosen algorithm for the fit was the Levenberg-Marquardt method [109],[99], usually implied for least-square estimation in case of non-linear parameters. Figure 3.10 represents the sum of squares due to errors (SSE), i.e. a statistic which measures the total deviation of the response values from the fit to the actual response values. It is also called the summed square of residuals and is usually labelled as SSE. A low value of SSE indicates that the model has a smaller random error component, and that the fit will be more useful for prediction. As depicted in Figure 3.10, SSE values decrease while increasing the heights of the tactor: at 32 mm the SSE are five times less than at 15.2 mm. The major source of error is due to the inability of fitting portion of curves with high slope, thus mostly those next to maximum and minimum peaks. The SSE in fact has its smallest values when the heights of the tactor are next to the boundaries of the working area of tactor, i.e. the working area of servos, where the available positions to be performed are characterized by small inclinations. All experimental tests described in this thesis (see chapter 4) did not use the orientation sensitivity feature, since it has been recently added. However, the

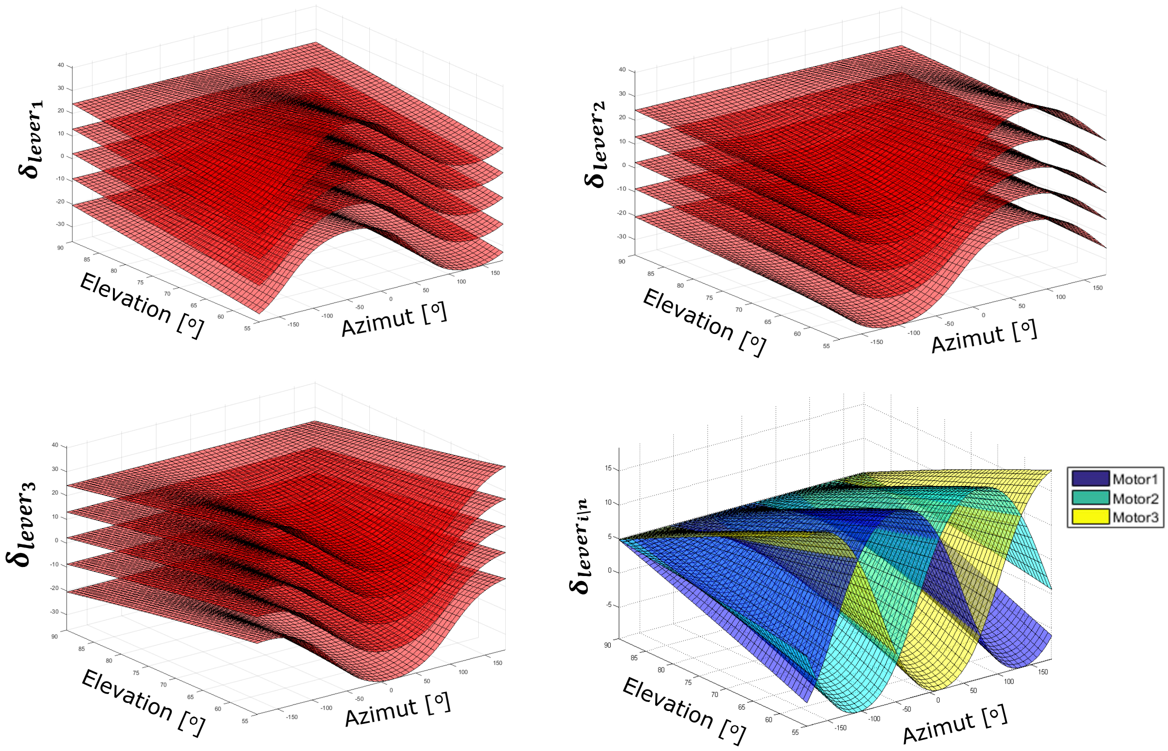


Figure 3.9: For each value of the heights of the tactor, graphs show simulated values of angles of servo labelled as the first, δ_{lever_1} (top-left graph), of the angles of the second servo, δ_{lever_2} (top-right) and of the angles of the third servo, δ_{lever_3} (down-left), respect to *azimut* and *elevation* variations. The last graph shows the simulated values of the angles for all the three servos at a specific height: 23.6 mm.

discrepancy of SSE should be taken into account while performing perceptual tests and it will be matter of further evaluations.

3.4 Absolute positioning system

The position of both tactile mice is detected by means of a commercial graphic tablet connected via USB to a computer hosting Windows 7. Discarding its physical dimensions, the tablet adopts the resolution of the used computer. In every experiment the computer was the Precision M64000 from Dell and the chosen resolution was the maximum: 1920x1200 pixels. The dimensions of the computer display and the tablet were normalized in order to make an exact correspondence between the movement of the mouse done by the user and the relative movement of the pointer on the screen.

Since the dimensions of the two devices are different, i.e. TAMO3 is bigger than TAMO1, the size of tablets has been chosen accordingly. For experiments with TAMO1 the tablet was the

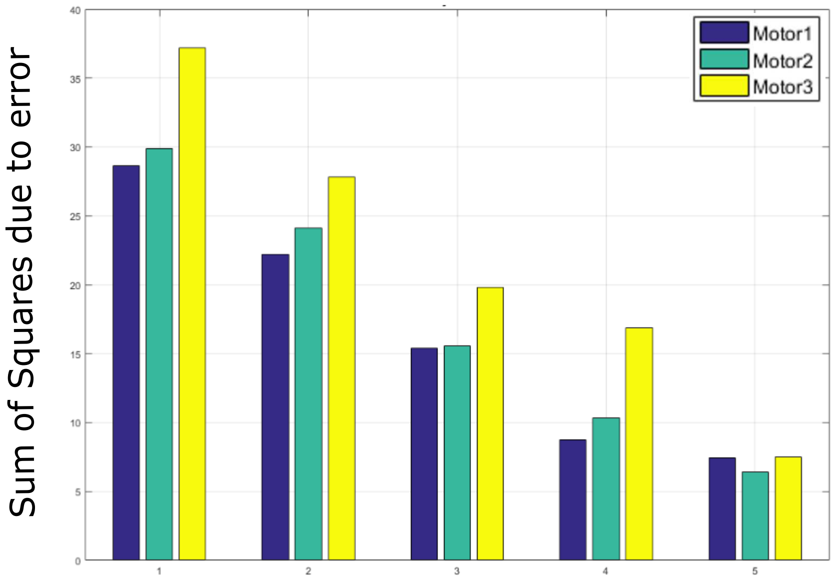


Figure 3.10: Sum of squares due to errors for each of the 5 heights of the tactor previously chosen: 15.2,19.4,23.6,27.8,32 mm

Genius G-Pen F610, see Figure 3.11 on the left. It has a 152x254 mm working area, a resolution of 2000 LPI (lines per inch) and wireless pen. The control circuit of the pen has been integrated in the board of the TAMO1. For tests conducted with TAMO3 the tablet used was Genius PenSketch M912 having a working area of 228x305 mm and resolution of 5120 LPI (Figure 3.11 on the right).

Figure 3.11: The two graphic tablets used as absolute positioning systems for the experiment with TAMO1 (a) and TAMO3 (b).

Chapter 4

Investigation of tactile descriptors and multiple-domain parameters to effectively deliver digital content

The development of assistive tools for visual disabilities refers to the creation and testing of devices, procedures and protocols to integrate and tentatively overcome problems visually impaired people face in their everyday life. Processing spatial information is important for many tasks such as to navigate or orient ourselves in a real or virtual environment, to locate objects in near or far-spaces and to infer spatial relations among different objects. When acquiring spatial content, haptic feedback has shown to be useful to compensate the lack of visual information [18]. However, the assessment of tactile aids can be difficult due to possible mismatches between subjects' perceived and real stimuli [159]. This is because most studies have simply focused on current spatial abilities (competence) rather than on potential, for instance by looking at gross performance on spatial tasks without considering the specific representations or strategies underlying performance [175]. There exist studies which address the relationship between the strategies to solve spatial tasks and the consequent spatial performance [122], [172], [176]: this approach offer the possibility to understand if the lack of vision imposes or not a limitation on the range of strategies to code spatial relationships. Moreover, performance is influenced by the emotional status in rehabilitative [202], as well as in educational settings [125]. Additionally, the gender has an effect in the perception of cognitive load associated to a spatial task and in the manipulation of mental images (see [33] for a review). Jointly analysed, these parameters (strategy, emotion and gender) facilitate the evaluation of the underpinning of a certain performance. Since the analysis of multiple-domain parameters offers a new approach to evaluate the spatial abilities, it let to develop a targeted methodology to exploit people potential.

In this Chapter, the devices and the methodology we proposed are used as tools to investigate the ability to build cognitive maps [175], from tactile graphics.

The following four sections provide an overview of the chapter.

4.0.1 Study 1 with TAMO1. Common factors between blind and sighted subjects

To understand the role of visual disability in the development of a mental representation from virtual objects, in the first place, blindfolded sighted and visually impaired participants were tested on a task of tactile mapping. It turned out that sighted and blind share similar exploratory strategies, perception of task difficulty and understanding of the virtual map. Thus, visual deprivation seems not to affect the skill of abstracting spatial content from tactile cues. However, the understanding of abstraction ability remains incomplete and almost unpredictable if not associated to measures able to disclose the motivations and the modalities leading to a certain performance [63]. This is why we introduced beside performance measure, behavioral and subjective variables [148].

4.0.2 Study 2 with TAMO1. Gender and visual experience effects

One important aspect of rehabilitation is also the diversity of individuals to deal with. In considering the understanding of space by blind people it is important to make a clear distinction between people who have been blind since birth or early in life, and those who have lost their sight later and have therefore had some visual experience [175]. In addiction, it has been shown that gender affects the information acquisition process [164] and the interpretation of tactile images [115]. Therefore, in a further study, we wondered whether or not factors such as blindness onset and gender modulated performance. It appeared that visual experience was not to be a primary effect in conditioning performance but only an epiphenomenon. Furthermore, both males and females share similar acquisition processes to learn tactile maps, but are different in mental effort perceived and in the way of integrating tactile cues to create mental maps. The insights described offer suggestions to integrate rehabilitation protocols with a new set of variables, taking into account behavioral and subjective aspects, and evaluating population characteristics as multifarious parameters which differently modulate the mapping process.

4.0.3 Study 3 with TAMO3. Perception of basic geometrical 3DOF descriptors

The understanding of three dimensional shapes implies the possibility to deliver geometrical contents useful in various scenarios. Geometrical descriptors conveyed with haptic sense can represent abstractions of real objects or direction guides in unknown places [86]. Additionally, a tactile map could stand for whatever 2D or 3D structured topology carrying a meaning for each spatial coordinate such as web content layout. Objects composing the tactile maps are explored and, if possible, manipulated in order to be classified and to extract their main features. Among their characteristics, i.e. shape, height, base, curvature and dimension, the curvature information seems to be the one facilitating a better object classification and consequently recognition [75]. Since curvature feature contains multiple elementary descriptors and given the need to simplify information delivered through assistive devices [141], curvature discrimination was tested separating the influence of each geometrical descriptor. Results show that inclination is an efficient cue to discriminate curvature, as previously affirmed in [196]. Adding elevation cue to inclination does not significantly increase the ability to evaluate curvature changes. On the other side, processing inclination information leads to higher levels of mental effort perceived. Therefore, performance and task load provide different and complementary trends suggesting the importance of both measures for the assessment of an assistive technology.

4.0.4 Study 4 with TAMO3. Understanding of solid geometry

Consequently the same descriptors were tested in an experiment of matching real and virtual objects. Results show that the use of all elementary descriptors causes a better understanding of a virtual object explored by touch, regardless the presence of visual impairment. Interestingly, blind population showed to properly rate their performance: it is an important aspect to consider in perspective to independently tune exercise difficulty in rehabilitation contexts.

4.1 Study 1. Similarity of blind and sighted people in constructing virtual maps

Haptic feedback has shown to be useful to compensate the lack of visual information when acquiring spatial content [18]. Although many behavioural studies indicate that vision is necessary for the acquisition [176] and the elaboration of [157] of spatial knowledge, it is indeed possible to teach blind subjects tactile maps of unknown environments [70]. In fact, there is evidence suggesting that in absence of vision the acquisition of spatial knowledge is not completely absent [151].

However, the mechanisms that could elicit a visuo-spatial representation from a tactile stimulation are necessarily complex, because discovering an object with touch implies the stimulation of several types of mechanoreceptors, continuous motor programming and proprioception and hypothesis generation and testing in the working memory [83].

For this reason, in this study, we simplified the touch perception using a minimalistic tactile device and then we investigated if visual impairment influenced or not the ability to create a mental map. Therefore, we quantitatively compared 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:

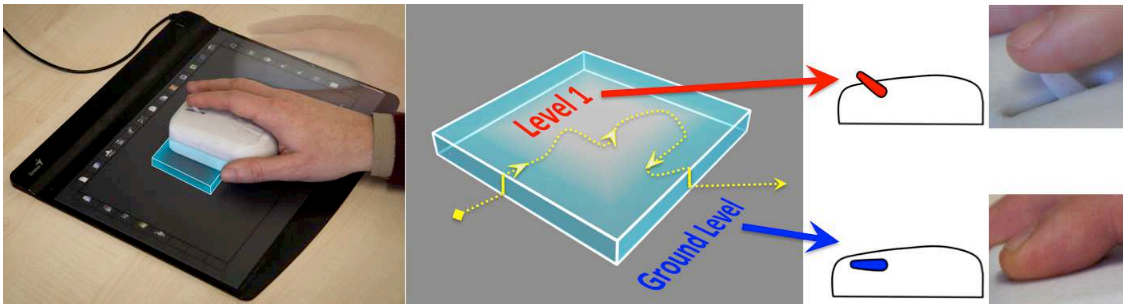


Figure 4.1: The TActile MOuse 1 (left) allows perception with a single *taxel* of a virtual object (in blue). The shadow represents the hand motion. Exploration path (center) on the first of the three objects, e.g. a one-level ziggurat, by free motion of the TAMO1 across the (X,Y) plane. The lever of TAMO1 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.

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?

4.1.1 Materials and methods

Participants. From no15 blind subjects with age 34 ± 12 (mean $\pm$ standard deviation) and 15 blindfolded sighted subjects, with age 33 ± 8 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.

Procedure. Device used for the test was The TActile MOuse 1 (TAMO1). It is a minimalistic device aimed at getting 3D virtual maps through the sense of touch (see Fig. 4.1), see section 3.2 of Chapter 3 for a detailed description. Subjects subsequently explored with TAMO1 the top-view tactile maps of three, gradually more complex, virtual objects (Fig. 4.2), 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

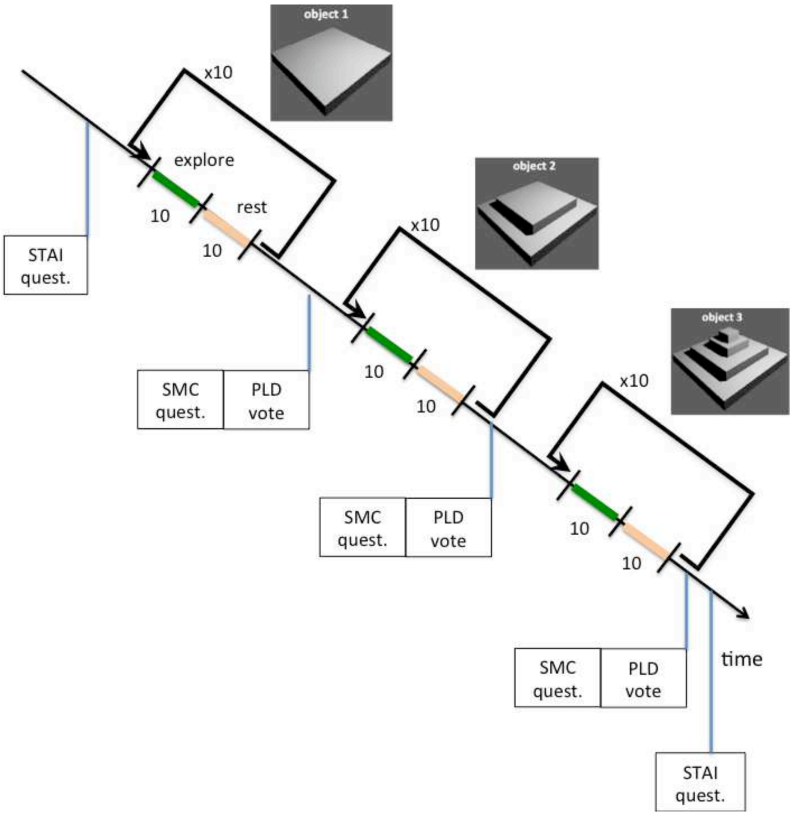


Figure 4.2: Experimental protocol: three virtual objects of increasing complexity were displayed with TAMO1, for constrained amounts of time, with interleaving rest periods. Questionnaires about anxiety (STAI) were given at the beginning and at the end of the whole experiment, while those about performance (SMC) and mental workload (PLD) were given at the end of each object exploration. Answers to STAI questionnaire will be analysed in section 4.2.

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.

A detailed explanation of the whole experiment procedure can be found in Figure 4.2.

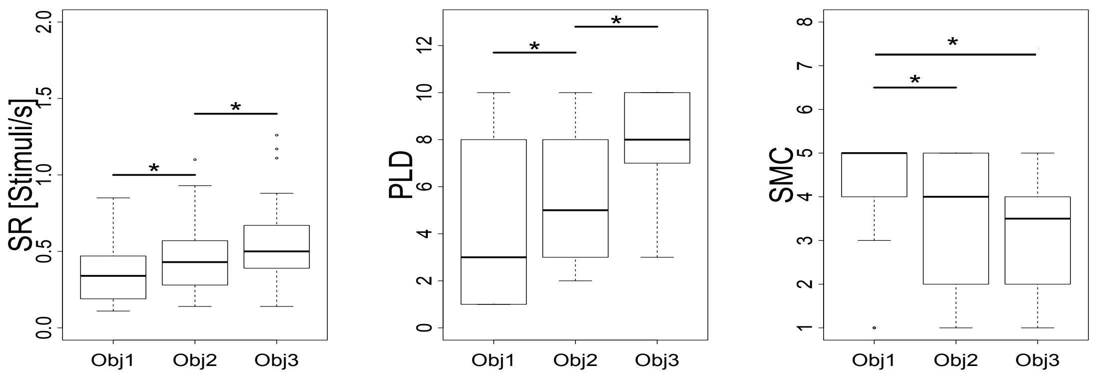


Figure 4.3: Stimuli Rates (SR), Perceived Levels of Difficulty (PLD) and Score of Maps Construction (SMC) in function of object complexity. Both blind and sighted subjects are considered together. Box plots show medians (continuous lines), 25% and 75% quartiles (box limits) and whiskers embracing all the data set. Population with not a Gaussian distribution may lack one or both whiskers. Starred links join significantly different conditions ($p < 5 * 10^{-2}$).

Analysis. The following dependent variables were considered: the Perceived Levels of Difficulty (PLD), a *subjective measure* of cognitive load due to map construction, 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 in rehabilitation scenario: 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 post-hoc comparisons. Statistical analyses were accomplished with R software [170]. All p values were corrected for multiple comparisons using the False Discovery Rate (FDR) method.

4.1.2 Results

4.1.2.1 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. As depicted in Figure 4.3, we found 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 (χ^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 (χ^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 (χ^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 (χ^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 not significant for SR, while it was fully significant for PLD (χ^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 (χ^2(2)=5.72, p=$5 * 10^{-2}$). Therefore, the trends observed in the whole sample are genuinely present

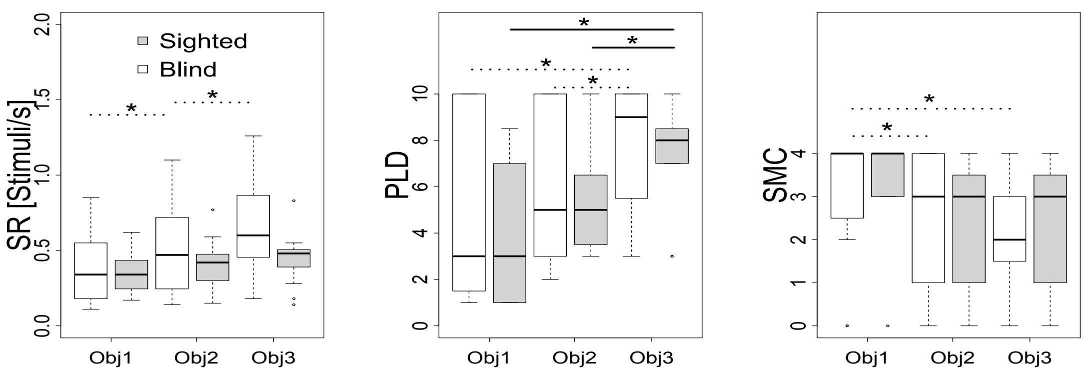


Figure 4.4: Stimuli Rates (SR), Perceived Levels of Difficulty (PLD) and Score of Maps Construction (SMC) in function of object complexity and visual ability. Starred links join significantly different conditions ($p < 5 * 10^{-2}$) with continuous lines for sighted and dotted lines for blind subjects.

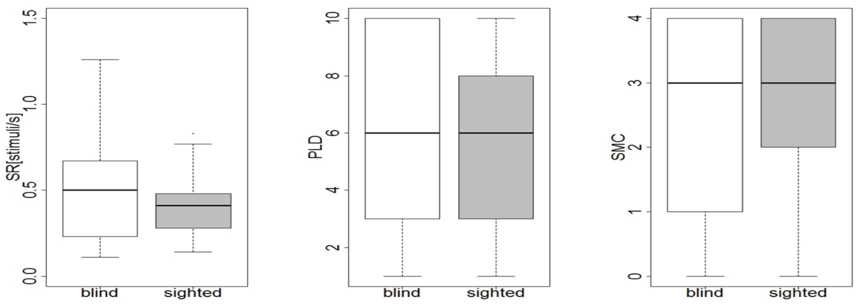


Figure 4.5: Stimuli Rates (SR), Perceived Levels of Difficulty (PLD) and Score of Maps Construction (SMC) in function of visual ability. Starred links join significantly different conditions ($p < 5 * 10^{-2}$) with continuous lines for sighted and dotted lines for blind subjects.

and similar in blind as well as in sighted subjects. See Figure 4.4 for further details.

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, as shown in Figure 4.5 we found 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. An overview of the schema followed during the analyses is shown in Figure 4.6.

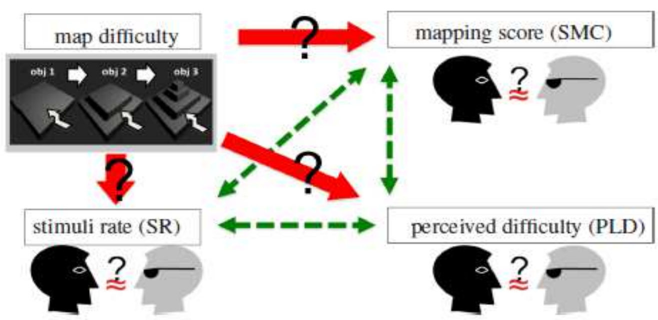


Figure 4.6: Methodology: blind and sighted subjects freely explore three virtual environments, of which we measure the effect (red continuous arrows) on performance, cognitive load and information acquisition. We investigate relations between these variables (green dashed arrows).

4.1.2.2 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 Tab. 4.1). 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 TAMO1 is independent of visual experience. As shown in Table 4.1 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 4.1: 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

4.1.3 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 TAMO1 conveyed, at least in small part, the spatial information of the explored map. 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, if 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 exploration reinforces the hypothesis that stimuli are actually acquired. In addition we have also shown in past works [14] 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 [58]. 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.

4.1.4 Contribution to rehabilitation protocols

Considering the construction of virtual maps with minimal touch information, we can provide answers to our research questions (see Fig. 4.6):

- 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.4.6) 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 [15]- despite an insufficient number of incorrect mappers does not allow, here, a direct comparison between INC and COR.

This study adopts a minimalistic device possibly useful for O&M programs of blind subjects, since in most cases TAMO1 delivered at least one piece of spatial information. Considering behavioral and subjective aspects as a methodology, and how they relate to performance, may help to better interpret spatial abilities and plan more targeted rehabilitation steps.

4.2 Study 2: The importance of visual experience, gender and emotion in the assessment of an assistive tactile mouse

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 [62]. Attempts to include subjective and objective aspects in training evaluations [63] are promising. However, this process remains incomplete if possibly important factors such as behavioral aspects are excluded [49] when proposing novel assistive tools. This happens even if it has been suggested that potential spatial abilities may be hidden in *how* subjects build environmental information [175].

Emotional impact. Research in cybertherapy and education [46] indicates that assistive tools have a lot in common with serious games: widely used in health care, they can reduce stress in preparatory sessions [140], in long term treatments [191] and can improve skills in learning/recollecting abilities and spatial understanding [124]. 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 [202], as well as in educational settings [125]. A feeling of anxiety has shown to affect also working memory resources [188]. 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 [171]. Even if the classification of blindness is rather fragmentary and gives opposing results making comparisons difficult [82] [129], visual deprivation/experience seems to modulate spatial abilities [33].

If we do not consider groups of people with diverse prior visual experience separately, it becomes difficult to conclude if an assistive tool can be more beneficial for the congenitally blind than for the late blind individuals. Analysing 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 [62].

It has been shown that while increasing their working memory load during active tasks, males outperform females in the manipulation of mental images [164] and in the interpretation or recall of visual characteristic of images [115]. 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 [33] 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.

Research questions. In the context of a more robust assessment of our haptic assistive tool, in this section we answer the following 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?

4.2.1 Materials and methods

Participants. The participants were 40, classified according to visual deprivation and visual experience: 6 congenitally blind (3 M and 3 F) ageing 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.

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.

Procedure. The device used is the TActile MOuse 1 (TAMO1), the same for experiment described in section 4.1. More details on the setup are available in Chapter 3. The protocol was the same as that applied in section 4.1 and depicted in Figure 4.2. In addition for this study and this sample, anxiety was evaluated pre- and post-experiment with the State-Trait Anxiety Inventory, the STAI, a psychological inventory based on a 4-point Likert scale consisting of 40 questions on a self-report basis [10]. 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.

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 Δ STAI score indicates 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.

Analysis. All the statistical analyses were performed using R software [170]. 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 [156] and p values were retained as significant after false discovery rate (FDR) correction for multiple comparisons [11].

4.2.1.1 Comparing anxiety before and after the use of TAMO1

In a first step, we evaluated the possible variations of anxiety due to the use of TAMO1. To this aim, we fitted a GLM considering ΔSTAI as a dependent variable, and GROUP (visual experience) and GENDER as factors.

4.2.1.2 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 TAMO1. 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.

4.2.2 Results

4.2.2.1 Training with the TAMO1 decreases anxiety

The initial STAI median, 28.5, was 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 not significant with respect to the sighted subjects, $W = 621$, $p > 0.05$.

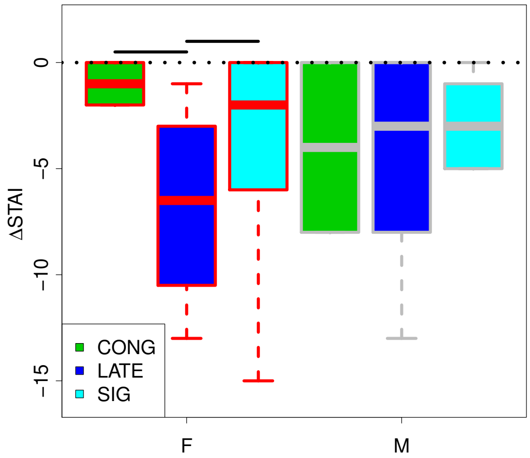


Figure 4.7: Variation of subjective anxiety level before and after training with TAMO1 for CONGenitally blind, LATE blind and SIGhted subjects and by gender. Dotted black line is the reference level in which no change in anxiety occurs. Horizontal black lines indicate significant differences ($p < 0.05$). Red and gray contours of boxplots highlight the gender, respectively women and men. Both females and males were less anxious after test, independently from visual experience.

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 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 - $\Delta STAI < 0$ (in all the cases $p < 0.05$). The ΔSTAI was particularly pronounced for the late blind females, as shown in Figure 4.7. No subject reported an increase in anxiety.

This results suggest that the TAMO1 can be a comfortable and unstressful tool when used to test mental mapping abilities.

4.2.2.2 Mapping with the TAMO1 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 4.2. We found that the process of tactile mapping with the TAMO1 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 Figure 4.8 and Table 4.2.

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

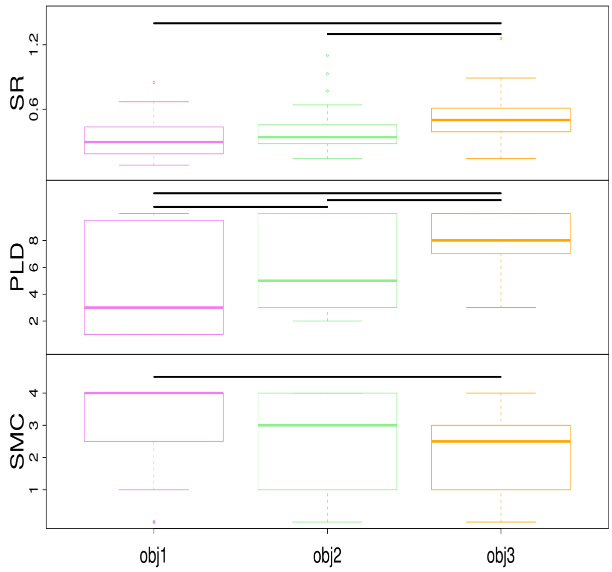


Figure 4.8: Stimuli Rate, Perceived Level of Difficulty and Score of Map Construction as a function of the object. Black lines show significant differences ($p < 0.05$). Pink, green and orange boxplot contours highlight virtual objects. All variables appear to be modulated by object complexity.

the quality of performance decreases. Importantly, the complexity of the explored objects did not modulate differently the variables of the considered groups, as shown 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 Figure 4.9 and Table 4.2. 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 4.2 in *italic*). Moreover, the same interaction was fully significant for the ΔSTAI variable (see Figure 4.7) as stated in section 4.2.2.1. Therefore the GROUP effect observed in SMC seems to be a spurious epiphenomenon which is actually ascribed to a mix of cognitive load and anxiety. Figure 4.10 provides an overview of the mentioned results.

4.2.3 Discussion

In this study we assessed 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

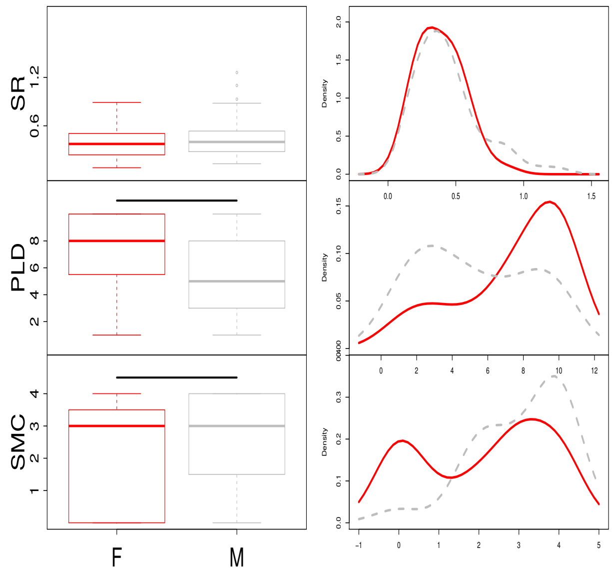


Figure 4.9: Left: boxplots of SR, PLD and SMC distributions, red and gray contours highlight gender. Black lines show significant differences ($p < 0.05$). Right: density of probability of the distributions, no difference appears between females and males in terms of behavior. Marked differences emerge in subjective cognitive load and performance.

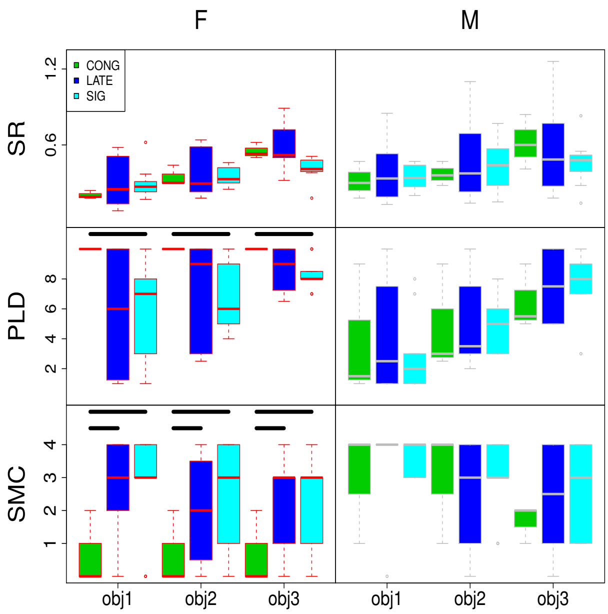


Figure 4.10: Stimuli Rate, Perceived Level of Difficulty and Score of Map Construction grouped by gender (boxplot contours) and visual experience (boxplot colors). Black lines show significant differences ($p < 0.05$). Cognitive load is globally not affected by visual experience. Modulation of SMC is highly due to the low performance of the congenitally blind females. Behavior is not affected by visual experience.

Table 4.2: Results of the General Linear Models for Perceived Levels of Difficulty, Stimuli Rates and Scores of Map Construction. Significant effects ($p < 0.05$) in **bold**, interesting trends in *italic*. A colon divides interacting factors.

Measure	Effect	Df	Dev	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	1110.48	17.64	**0.0001**
	GROUP	2	29.50	116	1080.98	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

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.

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 female 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 [115].

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 ([118], [119]).

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% 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 study 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 [15]) 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 study it was indeed our intention to check if blind subjects can integrate up-down movements of the lever and proprioceptive cues into a meaningful mental image: 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. TAMO1 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 in using our device, but that was not the case: our interpretation is that blind and sighted subjects appear in this task on an even footing because the kind of tactile stimulus is new for both groups 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 study. 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 [15] to correlate with performance. Using more extensive methods of information pick-up [14],[92], 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 [55] together with an unbalance within samples [23]. 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 [169].

4.2.4 Contribution to rehabilitation protocols

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 TAMO1 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 for maps to be efficiently developed with our device.

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 modelling 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 [63] 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.

4.3 Study 3: Mind the bump: effect of geometrical descriptors on the perception of curved surfaces with a novel tactile mouse

We have shown that sequences of virtual height profiles, arranged to form regular polygons, can be effectively understood by both blind and sighted participants [15]. However, coding virtual objects only in terms of height profiles can restrict the taxonomy of shapes to be displayed and consequently the possibility to apply the most effective procedure to classify objects: the contour following [92]. In particular, among all the geometrical features associated with the objects (i.e. base, height, curvature, size and resolution) the process of shapes discrimination is highly influenced by curvature [75]. Curvature can be haptically rendered according to three different geometrical descriptors [145]: with elevation alone (0^{th} order), with slope alone (1^{st} order) or summing the contribution of both ($0^{th} + 1^{st}$ order). Previous studies [145, 196], demonstrated that local orientation is both sufficient to elicit perception of curvature and essential for curve discrimination with dynamic touch [41]. Elevation instead can not provide sufficient information to process curvatures in a better way than inclination: thresholds related to surfaces profiles delivered only by height information are significantly higher [180, 196]. Those outcomes, jointly to the need of simplifying information given via touch, [141] suggest to make sure about the role of each curve descriptor, especially when designing assistive devices. Here, we propose to render haptic curved objects with a new portable device, the TActile MOuse 3 (see Figure 4.11), using a curvature discrimination task to assess the function of each tactile descriptor and the mental effort required to process it. The stimulation is provided by a tactor (i.e. an end effector stimulating only one finger) moving in three degrees of freedom, so that geometrical descriptors of 0^{th} or 1^{st} order, or a combination of both, can be displayed in each point of a two-dimensional space. We seek whether or not discrimination of curved surfaces with our device depends on the kind and amount of geometrical descriptors. Our hypothesis is that local surface orientation should be the dominant cue, as previously found in [196], i.e. that haptic inclination is crucial for curvature discrimination, while height information is marginal. Since the design of assistive devices cannot discard the mental demand associated with information display [185], to further evaluate the process of interaction, we coupled psychophysical evaluation with a measure of

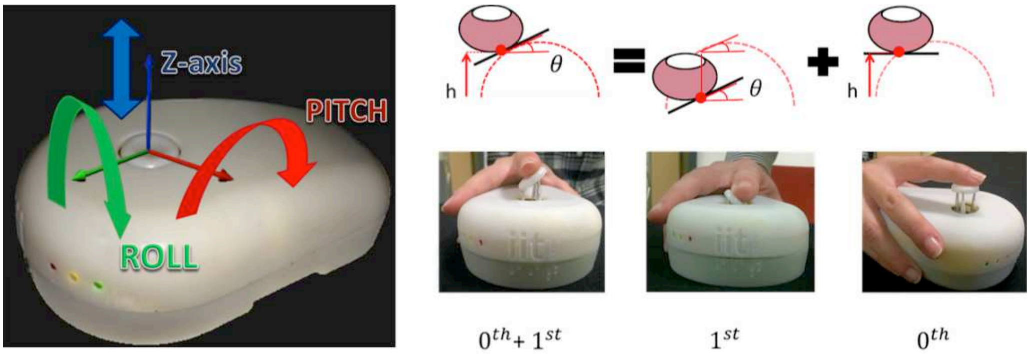


Figure 4.11: Left: The TActile MOuse 3, the haptic device we proposed for this study. The tactor moves in three degrees of freedom: elevation, roll and pitch. Right: The three geometrical descriptors (top part) tested:$0^{th}+1^{st}$, which is a combination of 1^{st} and 0^{th} order. The bottom part shows how the tactor of the TAMO3 renders the descriptors.

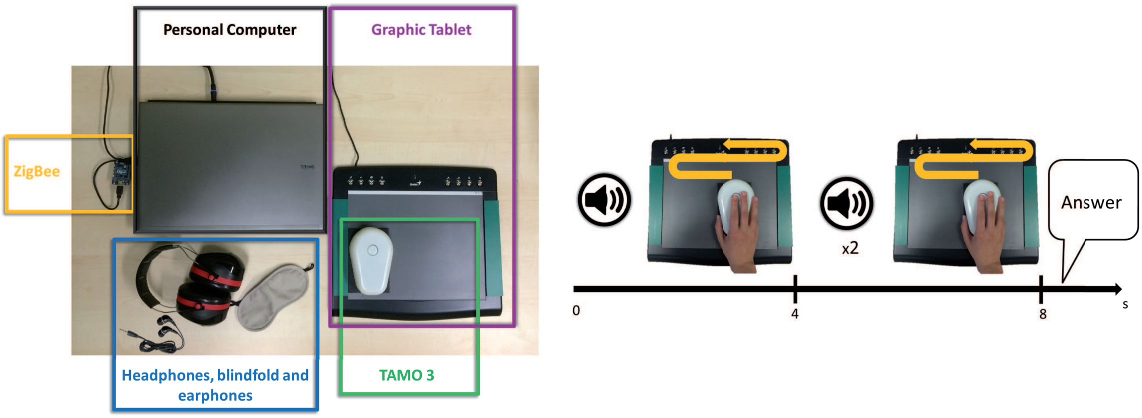


Figure 4.12: Left: experimental setup. A PC connected to the graphic tablet on which the TAMO3 was freely moved. The PC and TAMO3 communicate through a ZigBee module. Participants wore headphones and blindfold. Right: an example of a trial. A sound triggered the explorations. The scanning movement is shown with the yellow arrows.

mental workload [78] to check whether or not it modulates the precision in curvature estimation. In summary, the current section aims to answer two research questions: 1) Is discrimination of curvature modulated by the number and type of geometrical descriptors displayed with our tactile mouse? 2) Is mental workload modulated by the number and type of geometrical descriptors?

4.3.1 Materials and methods

Participants. Eight volunteers (4 females) participated in this study. Their ages ranged from 26 to 47 years (31.8 ±6.8). All of them were naïve to the task and reported to be right handed. Participants had no scars or other damages on the fingertip of their index finger. The protocol was approved by the local Ethics Committee (Azienda Sanitaria Locale 3, Genoa) and procedures complied with the Declaration of Helsinki.

Procedure. Participants were asked to explore virtual objects using the TActile MOuse 3, the TAMO3, described in section 3.3 of Chapter 3. They wore sound-isolating headphones and were blindfolded, in order to remove any non-tactile cue (see Figure 4.12 on the left side). We investigated the influence of three geometrical descriptors on the perception of curvatures. The experimenter familiarized the participants with both the device and the movements, by requiring them to move the TAMO3 back and forth on the tablet (Figure 4.12, right). Each movement, constrained in 4 seconds, allowed to perceive a single bump. The geometrical characteristics of the bumps are depicted in Figure 4.13. In the portion of space on the side of bumps, tactor was placed under the cover and thus it was difficult to reach it by participants' fingers. This particular position of the tactor was chosen to disadvantages participants choice to use the initial elevation cue as a reference to judge bump curvature. Tests were designed according to a two alternative forced-choices protocol (2AFC): two virtual curves, each having constant curvature, were represented one after the other. Participants had to judge in which of the two the radius of curvature was smaller, i.e. which one was more curved. Two different sounds triggered the exploration. Each participant performed three sessions, one for each geometrical descriptor, as shown in Figure 4.11 (right). To avoid possible learning biases, the order of the sessions and of presentation of reference stimuli, was randomized according to a Latin square design.

In all the tests, the reference stimulus had a constant curvature of 0.2 m^{-1}. All the comparison stimuli had greater constant curvature than the reference stimulus. The maximum height of all bumps was fixed at 30 mm (see Figure 4.13). In order to prevent the known bias on curvature discrimination due to bump length, all the bumps were truncated on the right and left border, as displayed in Figure 4.13, to 180 mm. To find a suitable range of curvatures allowing a reliable estimation of the psychometric function, all by minimizing the number of estimation points, we performed three steps: firstly we found the curvature perceived correctly 90% of times by the Quest method [190]. Then we derived, from this value to the reference, a list of four equally-spaced stimuli. Each of them was tested 20 times. Finally, the Just Noticeable Difference (with discrimination threshold of 75%) for each participant was computed and tested another 20 times to confirm the reliability of the estimate. A total of 2880 (3 sessions per participant X 120 trials per session X 8 participants) trials were performed. In order to minimize discrepancies in exploratory strategies among participants, their scanning movement was constrained by plastic strips as physical stops glued on the tablet (see Figure 4.12). During familiarization, we made sure that participants minimized rotations of the device around the Z-axis. After each session participants were asked to fill a questionnaire, i.e. a shorter version of NASA-RTLX (NASA Raw Task Load Index), which is an assessment tool to evaluate the subjective perception workload of a task [58], see Table 4.3. We chose to use the RTLX test because even excluding the pairwise analysis between items, it is a less cumbersome questionnaire and has similar results respect to the original TLX test [123]. We considered five items: Mental Demand, Physical Demand, Own

Table 4.3: NASA Raw Task Load Index

Factor	Range	Description
Mental Demand	Low/High	How much mental and perceptual activity,was required?
Physical Demand	Low/High	How much physical activity was required?
Temporal Demand	Low/High	How much time pressure did you feel due to the pace at which the tasks or task elements occurred?
Effort	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Own Performance	Poor/Good	How successful do you think you were in accomplishing the task?
Frustration	Low/High	How insecure, discouraged, irritated, stressed and annoyed did you feel during the task?

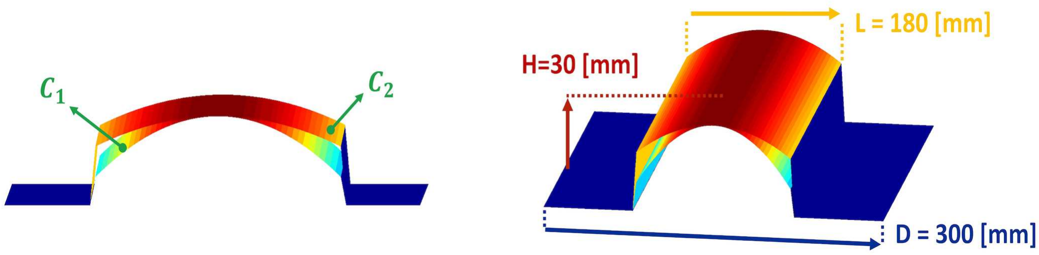


Figure 4.13: Example of two displayed virtual objects. Left: frontal view of the two bumps with different curvature, C_1 is more curved than C_2. Right: actual dimensions. All bumps shared the same maximum height, H and same fixed length L. The total extension of the space to be explored was equal to D.

Performance, Effort and Frustration; we dropped the Temporal Demand item from the beginning since time was fixed in all our trials. Each item was rated by participants from 1 to 20.

Analysis. Psychometric functions were estimated with the psignifit toolbox of Matlab which implements the maximum- likelihood method described by Wichmann and Hill. The other statistical analyses were performed using R software. Normality assumption was tested with Shapiro-Wilk test: for normally distributed data, a repeated measure analysis of variance (ANOVA) and, when necessary, an ANOVA post-hoc (Tukey HSD) analysis were performed. With non-normal distributions, Kruskal-Wallis and Wilcoxon non-parametric tests for analysis of variance and post-hoc comparisons were used, respectively. False Discovery Rate (FDR) was used to correct all p values for multiple comparisons. In each analyses, the geometrical descriptors represent the independent variable, while curvature thresholds and NASA scores are the dependent variables.

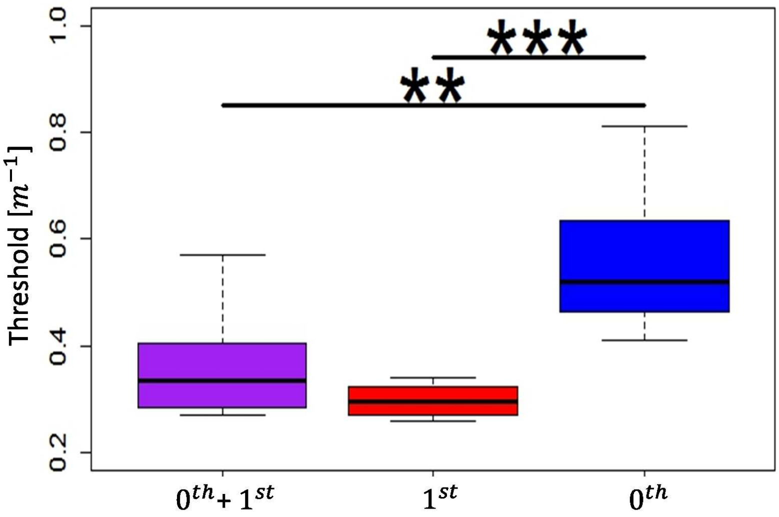


Figure 4.14: Curvature thresholds in function of geometrical descriptors. Box plots show medians (continuous lines), 25% and 75% quartiles (box limits) and whiskers embracing all the data set. Starred links join significantly different conditions: three stars stand for p ≤ 0.001, two stars for p ≤ 0.01 and one star for p ≤ 0.05.

4.3.2 Results

4.3.2.1 Curvature thresholds

Distributions of thresholds were measured for all three conditions: $0^{th} + 1^{st}$, 0^{th} and 1^{st} order. They were all normally distributed (W>0.86 and p>0.13). Curvature thresholds are shown in Figure 4.14.

For each participant there were different comparison stimuli, according to the result of the Quest method. Average values of the highest comparison stimulus were $0.45m^{-1}$ for the $0^{th} + 1^{st}$ condition, $0.36m^{-1}$ for the 1^{st} condition and $0.67m^{-1}$ for the 0^{th} condition. In Figure 4.15 is shown an example of psychometric functions of one participant, calculated for each condition. The first step was to check if geometrical descriptors modulated curvature discrimination thresholds. The ANOVA revealed a highly significant difference (F(2,21)=14.9, p<0.001, $\eta^2_{generalized}$=0.59). Post-hoc t-test showed a significant difference between the $0^{th} + 1^{st}$ and 0^{th} condition (t(23)=-3.96, p=0.002) and between 1^{st} and 0^{th} condition (t(23)=-5.25,p<0.001). Participants discriminated better the curves when inclination information was provided. In particular their precision tends to be less dispersed in the condition in which slope is the only descriptor (see Figure 4.14).

4.3.2.2 Subjective workload assessment

The RTLX computes a score by taking the sum of the each item and dividing it by six [58], in this case we divided it by five since we dropped one item (Temporal Demand). The scores of one

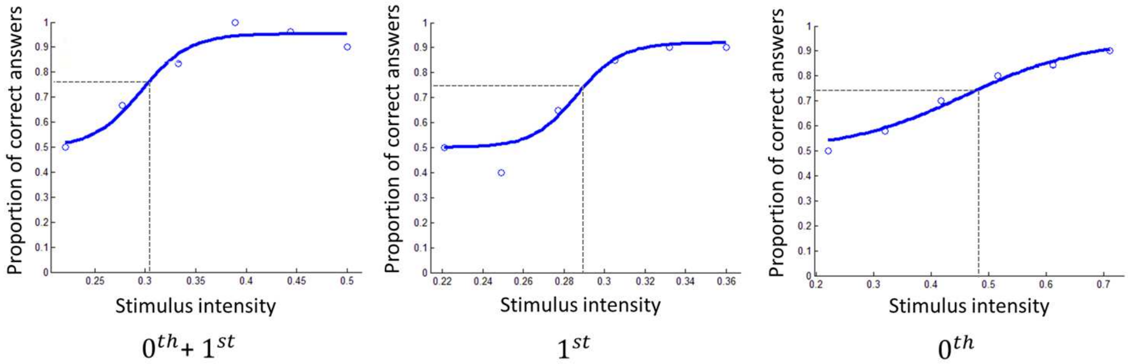


Figure 4.15: An example of psychometric functions of one participant, calculated for each condition. Reference stimulus intensity was 0.2 m^{-1} in all tests, while comparison stimuli changed according to the results achieved using the Quest method [190]. The dashed gray lines indicate the stimulus intensity correspondent to the Just Noticeable Difference calculated with discrimination threshold of 75%.

participant were discarded because only part of the questions were answered. Figure 4.16 on the left shows that the perceived workload significantly depends on the kind of haptic feedback (χ^2(2)=7.29, p=0.02). This effect is significant between the conditions 0^{th} and 1^{st} (W=5,p=0.01) and between $0^{th} + 1^{st}$ and 1^{st} (W=8.5, p=0.04). In both cases the workload was rated as higher in the 1^{st} condition. In a second step we investigated each NASA item separately, always checking for possible effects of the geometrical descriptors. Four out of five items were statistically similar among the conditions, meaning that the amount of perceived workload was similar. Those items were the Own Performance (F(2,21)=0.66, p=0.53), Mental (χ^2(2)=2.92, p=0.23) and Physical Demand (F(2,21)=0.79, p=0.46), Frustration (F(2,21)=2.51, p=0.11). In contrast, the Effort (χ^2(2)=8.28, p=0.01), was judged differently depending on the haptic condition, as depicted in Figure 4.16 on the right. Both mental and physical effort in performing the task were perceived higher in the 1^{st} than the 0^{th} condition (W=4.5, p=0.01).

4.3.3 Discussion

4.3.3.1 Inclination cue corresponds to higher precision in curvature discrimination

Our results show that local inclination is a sufficient cue to discriminate curvatures with the TAMO3 device. In line with previous findings [196], the presence of the inclination accounts for most of the variance of the precision. Therefore virtual curved objects can be more easily distinguished from each other when the inclination cue is present. In addition, including the elevation cue did not further increase precision. Interestingly, although the combined cues of elevation and inclination may seem more ecological and close to the geometrical structure of real surfaces, here they seem not to be additive but to average the performance in terms of

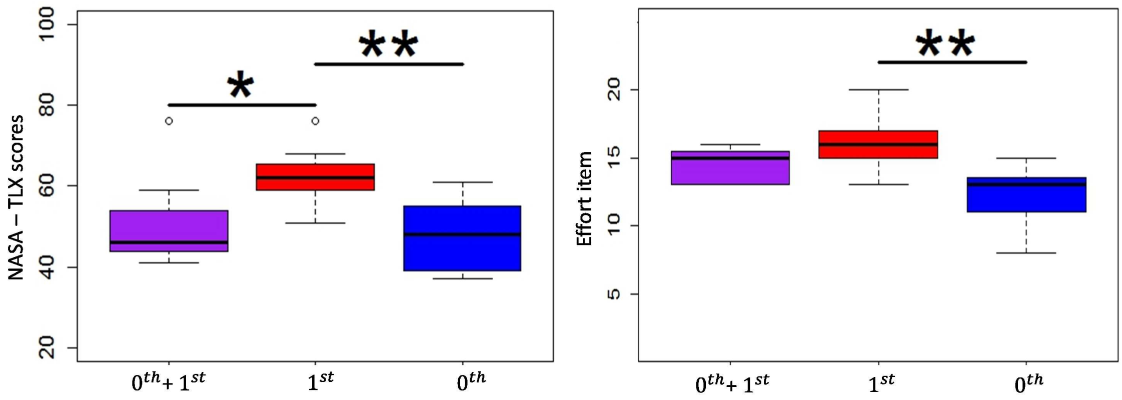


Figure 4.16: Summed scores of NASA questionnaire (on the left) and effort item (on the right) in function of the geometrical descriptor. Non-Gaussian distribution may lack one or both whiskers. Starred links join significantly different conditions: three stars stand for $p \leq 0.001$, two stars for $p \leq 0.01$ and one star for $p \leq 0.05$.

discrimination threshold. The exploratory procedure we proposed is similar to what is done in [196], where $0^{th}+1^{st}$ and 1^{st} order condition presented a statistically similar discrimination threshold ($0.5m^{-1}$), while the 0^{th} order condition had significant higher value ($2m^{-1}$). Our results are in line with previous findings. However, our values exhibit compressed magnitudes: $0.36m^{-1}$ for $0^{th}+1^{st}$ condition, $0.29m^{-1}$ for 1^{st} and $0.56m^{-1}$ for 0^{th}, meaning that discriminating curvatures with our device seems to be rather easy.

The generally lower thresholds can be explained, as compared to [196], by the fact that Wijntjes and colleagues employed a device in which the motion of a flat plate is caused by the fingertip, i.e. the sole finger is, at the same time, determining the motion and receiving the feedback. With our setup, instead, the motion of the tactor is controlled by the whole hand, and not by the index only. In our case the phalanxes of one finger only receives haptic feedback, therefore minimizing the overall feedback on the hand (which was resting on the mouse). This might have made the task easier, with lower thresholds. Therefore, to the first research question *Is discrimination of curvature modulated by the number and type of geometrical descriptors displayed with our tactile mouse?* we answer "Yes". Haptic rendering of shapes may therefore be facilitated when only essential haptic cues are displayed: the contribution of inclination and elevation may be decoupled.

4.3.3.2 Inclination cue generally makes the task more demanding

When analysing the global modified NASA-RTLX score, we found a difference among the haptic conditions, especially with inclination. This descriptor alone requires a higher workload to process curvature information. This is in some sense against what is generally reported [64]. However the load score, when inclination was rendered, was ten points above half of the maximum score, meaning that an average task load was perceived. We can still claim that discriminating curvatures by means of inclination is a "non difficult" task per se, which is supported by our data about thresholds. No high frustration was associated, indeed, to this condition, suggesting that even if the task was more demanding it was still acceptable. *Effort* is higher for the condition in which only inclination was provided, meaning that it was interpreted by participants as a more difficult haptic feedback for curvature discrimination. Importantly, contrary to the *Effort*, *Frustration* was equally perceived, indicating that the task was not causing negative emotional content. Therefore, to the second research question *Is mental workload modulated by the number and type of geometrical descriptors?* we can also answer "Yes".

4.3.4 Contribution to rehabilitation protocols

In this study, the contribution of a tactile device in the construction of mental maps via dynamic touch, was tested. The device, called TAMO3, can effectively help in the discrimination of curved virtual surfaces.

Importantly, the fact that performance and workload here provided opposite trends supports the hypothesis that performance evaluation alone may not be a sufficient [175] when designing assistive devices as the TAMO3 aims to be. When considering task load and precision together, the choice of the suitable haptic descriptor may vary: in our tests, indeed, we have seen that inclination revealed to be the best cue for precision, but adding the elevation cue might seem more natural, as it determined a significantly lower global task load (Figure 4.16). This result is therefore interesting when designing interfaces for visually impaired persons. When task load and precision have opposite trends, a trade off may be necessary to achieve high precision without increasing too much mental demand, which may put at risk the users' acceptance of a device. The separate analysis of single load items shows that *Effort* was sensitive to geometrical descriptors: *Effort* is the work to do, both mentally and physically, to reach a certain level of performance. Further work will include more complex descriptors e.g. virtual objects with curvature changing along more than one axis, as well as tests with end users.

4.4 Study 4: How geometrical descriptors help sighted and blind people to build cognitive maps of solid geometry with a 3DOF tactile mouse

People who use touch to identify object features, i.e. visually impaired, develop autonomous or guided strategies and gain experience which is different compared to who mainly exploit vision to achieve the same goal, i.e. sighted subjects. The aspect of familiarity of objects used in experimental tests is crucial in the analyses of matching performances. Regularly explored shapes or objects which have been experienced in different haptic modalities present patterns stored in terms of exploration strategies, perception and proprioception. For instance in [61] blind individuals were quite quick and accurate in mentally rotating a series of familiar stimuli (e.g., Braille characters), this is confirmed also in [81]. The number of fingers used and consequently the possibility to handle the object to recognize has also an effect on the level of accuracy achieved. In a bi-manual task in which 3D objects could be haptically manipulated blind participants showed to outperform their sighted peers [38]. Instead similar rates are achieved when participants are asked to discriminate differences between 3D unusual shapes with random orientation presentation [129]. Moreover, if object matching is done with hand-sized unfamiliar objects, the accuracy is still similar between sighted and visually impaired subjects [198]. When, on the contrary, participant have to recognize basic geometrical shapes blind are more accurate than blindfolded sighted participants. This trend is confirmed also if shapes are presented in an unusual orientation or with distorted contours, thus with no prototypical objects [171].

Here, we render a dictionary of geometrical solids by means of the TAMO3, aiming at stimulating one finger only. The choice of solids is twofold. They are unfamiliar objects, i.e. 3D abstract solids, which cannot be manipulated because we want to study if the recognition rate is influenced by the visual impairment. The solids share similar dimensions and differ only for orientation in the space and curvature changes along the main axes in order to isolate the potential sources of errors in recognition accuracy. Additionally, the exploration of shapes is modified in terms of tactile feedback: geometrical primitives of objects are evaluated separately in the process of object identification. In this section we seek whether or not the ability of matching real object with virtual objects depends on the kind and amount of geometrical descriptors and on visual impairment. Our hypothesis is that the information from elevation and local surface orientation provide complementary cues. Therefore matching abilities should perform at best when both cues are present. Moreover, we hypothesize that visual impairment will affect performances in matching real with virtual objects since objects used are unfamiliar and cannot be manipulated. Since the design of haptic devices cannot discard the mental demand associated with information displayed [185], to further evaluate the process of interaction we measured mental workload [78], also to check whether or not it was modulated by the kind of geometrical descriptor.

4.4.1 Materials and methods

Participants. The sample was composed by blindfolded sighted and visually impaired participants. Blindfolded sighted participants were twelve volunteers: 6 females, 24 to 36 years, 29.1 ±4.2 sd. Visually impaired sample matched in gender and age the sample of blinfolded sighted participants. They were twelve volunteers: 6 females, 19 to 29 years, 24.4 ±3.3 sd. According to the World Health Organization classification, 8 of them were blind belonging to the 4^{th} category and 4 were blind of the 3^{rd} category: those categories group people with acuity ranging from 1/60 to 1/20. All participants were naïve to the task, reported to be right-handed and had no scars on

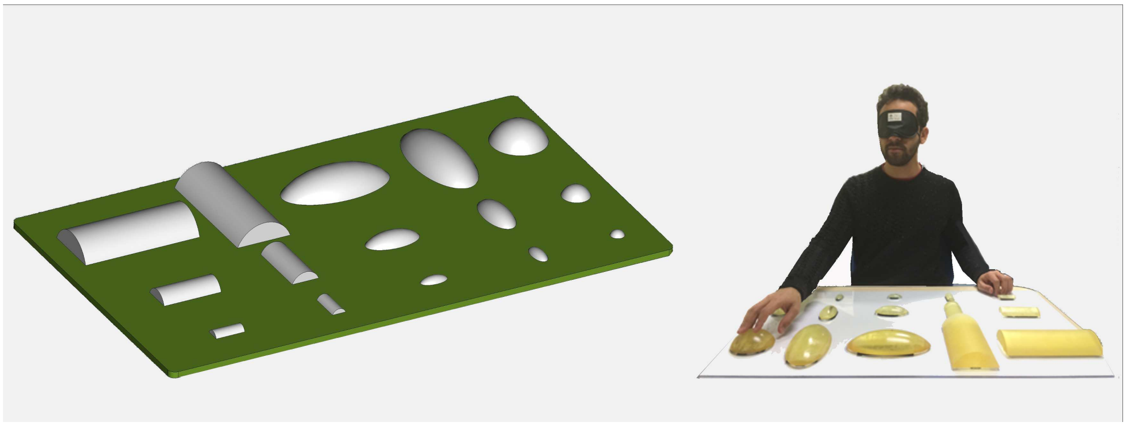


Figure 4.17: Left: CAD model of Tactile Dictionary used as verification setup, comprising five main solids: one hemisphere, two semi-cylinders and two semi-ellipses. The latter two are arranged in two orientations. Main parameters of the solids: 50 mm (equal to the diameter of the hemisphere, the smallest side of the semi-cylinder and the minor axis - the width - of the semi-ellipse) and 100 mm (equal to the largest side of the semi-cylinder and the major axis of the semi-ellipses). The height of all five objects was 18 mm. The first and last row, i.e. the nearest and the most distant to subject body, contain halved and doubled objects. Right: real scenario in which one participant is exploring the Tactile Dictionary.

the fingertip of their dominant index finger.

Procedure. Sighted participants were blindfolded, then familiarized with the Tactile Dictionary by touching all fifteen solids. The participants, through the use of TAMO3, perceived virtual objects in three conditions and related sessions, i.e. different tactile modalities (see Fig. 4.11 on the right) associated with geometrical descriptors: elevation alone (0^{th} order), inclination alone (1^{st} order) or both ($0^{th} + 1^{st}$ order). To avoid possible learning biases, the kind of virtual object was randomly shuffled and the order of geometrical descriptors presented was randomized according to a Latin square design. After the familiarization, one virtual object was displayed: its virtual dimensions matched only the physical dimensions of the *matched size objects* of the Tactile Dictionary. The participants were not aware of this detail. Participants were requested to construct the mental map of the object as accurately as possible, then to indicate which one among the fifteen real objects best matched the explored virtual object. No time limit was given. The experimenter recorded the answer on a PC right after it was given, to allow an approximated measure of the reaction time. Each session was composed by 5 trials of training and 15 trials of the actual experiment (each object was presented three times). A total of 1440 (20 trial per session * 3 sessions per participants * 24 participants) trials were performed. After each session, participants were asked to fill the NASA-TLX, NASA Task Load Index questionnaire, which is an assessment procedure to evaluate the participative perception of the workload of a task [58]. The list of items of NASA-TLX are in table 4.3.

Analysis. We measured how well and how fast participants matched shape and size of virtual

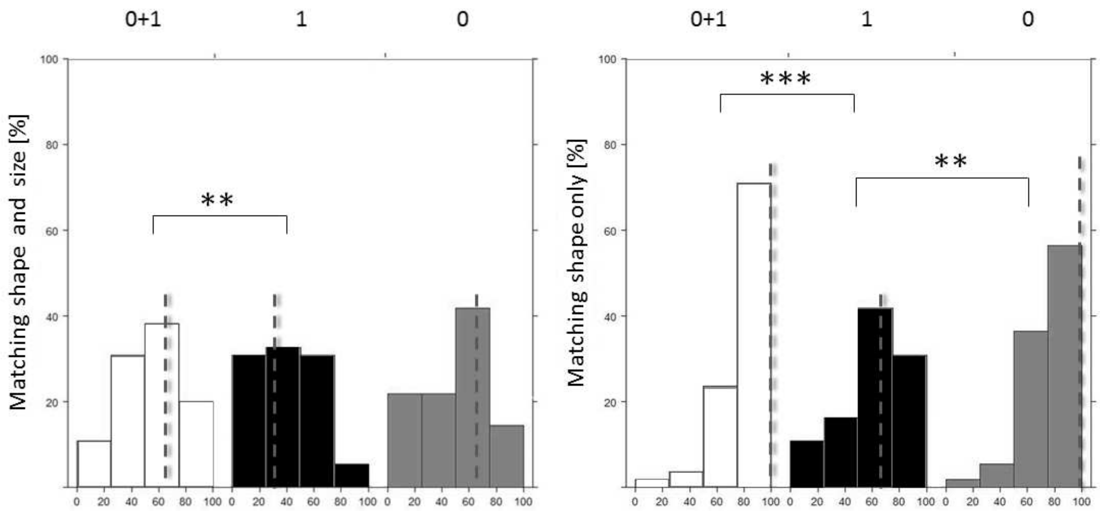


Figure 4.18: *Blindfolded sighted sample.* Ability in matching virtual with real objects. Histograms have matching percentages on the x axis and frequencies on the y axis. Left: correctness defined as guessing shape and size. Right: correctness is defined as guessing shape only. Vertical dashed lines represent medians. Starred links join significantly different conditions: *** for $p < 0.001$, ** for $p < 0.01$ and * for $p < 0.05$.

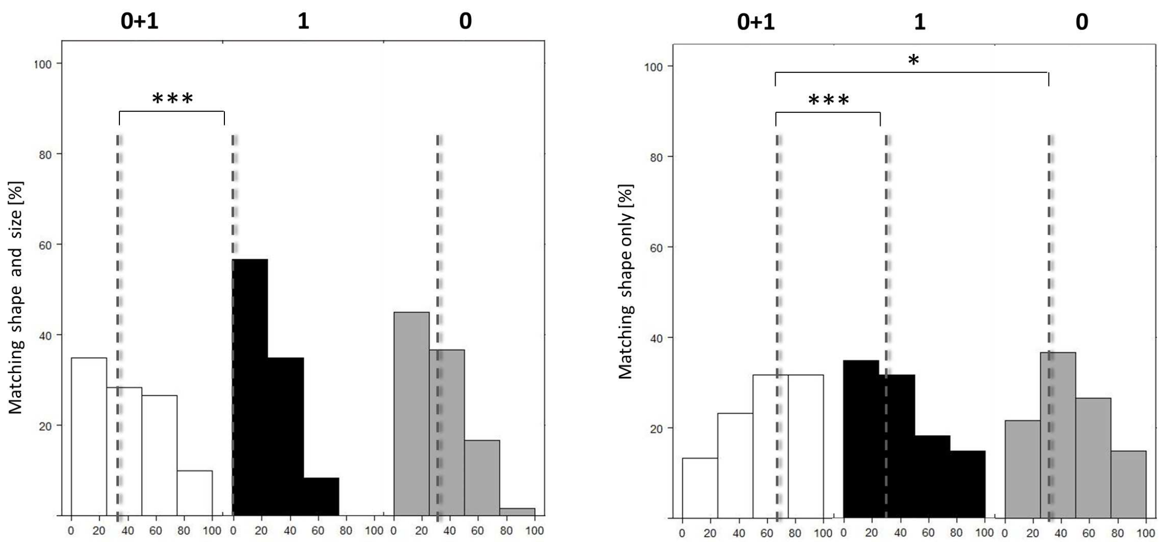


Figure 4.19: *Visually impaired sample.* Ability in matching virtual with real objects. Histograms have matching percentages on the x axis and frequencies on the y axis. Left: correctness defined as guessing shape and size. Right: correctness is defined as guessing shape only. Vertical dashed lines represent medians. Starred links join significantly different conditions: *** for $p < 0.001$, ** for $p < 0.01$ and * for $p < 0.05$.

objects displayed with the TAMO3 to that of real objects displayed on the Tactile Dictionary. Mental workload for each tactile condition was then measured. Therefore, our independent variables are the *Geometrical Descriptors* (0^{th}, 1^{st} and $0^{th}+1^{st}$ order), our dependent variables are *Matching Ability* (measured as recognition rate), *Mental Workload* (measured with the NASA-TLX) and *Reaction Time*. Normality assumption of the dependent variables was tested with Shapiro-Wilk test: in case of data normally-distributed it was performed a repeated measure analysis of variance (ANOVA) and, when necessary, an ANOVA post-hoc (Tukey HSD) analysis. On the other hand, for non-normal distributions, Friedman Rank Sum test and Wilcoxon non-parametric tests for analysis of variance and post-hoc comparisons were respectively used. R software [146] was used for the analysis.

4.4.2 Results

In order to check if auditory stimuli influenced the task, a pilot study was conducted with participant wearing sound-isolating headphones. Three right-handed persons (blindfolded sighted participants)were recruited and perform the same task of object recognition described in the *Procedure* section. Results of this study were statistically similar to those achieved in the present study, suggesting that noise associated to the exploration of virtual stimuli did not have an effect on the performance achieved.

The *Results* section describes the achievements of this study firstly for the blindfolded sighted and visually impaired samples separately and then comparing them.

4.4.2.1 Ability in matching virtual and real objects

Blindfolded sighted sample. First, we considered the case in which matching was defined correct when both shape and size were guessed. In Figure 4.18 (left) we show performance distributions of matching ability, displayed as histograms, using each of the three geometrical descriptors. Data were not normally-distributed ($W > 0.85$, $p < 8*10^{-6}$). Friedman non-parametric test revealed a significant effect of the Geometrical Descriptors on Matching Ability ($\chi^2(2)$=11.33, p=0.003). Specifically, Wilcoxon post-hoc for pairwise comparisons showed that the difference was statistically significant between the $0^{th}+1^{st}$ and 1^{st} condition (W=11.33, p=0.007). The conditions in which the elevation cue was presented (i.e. $0^{th}+1^{st}$ and 0^{th}), exhibited the highest values of performances, having a median value of 66.7% (with mean values of 55.8% for $0^{th}+1^{st}$ and 49.7% for 0^{th}) respect to the 33.3% of 1^{st} condition (with mean value of 37%).

Second, we considered the case where guessing only the shape was sufficient to define the matching as correct, neglecting size. In Fig. 4.18(right) the distribution of the shape-only matching ability is shown depending on geometrical descriptors. Distributions were not normal ($W > 0.6$, $p < 6.9*10^{-5}$). Friedman test showed also in this case a significant effect of the Geometrical Descriptors ($\chi^2(2)$=20.3, p=0.00003). Post-hoc revealed a difference between $0^{th}+1^{st}$ and 1^{st} condition (V=699, p=0.00001), but this time also between 0^{th} and 1^{st} (V=643.5, p=0.002). Also in this case performances of $0^{th}+1^{st}$ and 0^{th} are higher than 1^{st}, showing a median value of

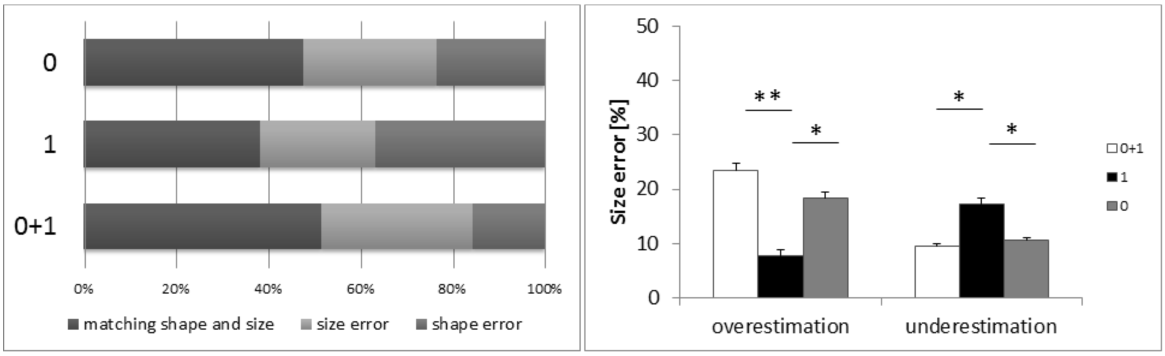


Figure 4.20: *Blindfolded sighted sample.* Left: on the horizontal axis there are the percentages of matching shape and size, error in size and errors in shape performed; on the vertical axis there are the geometrical descriptors. Right: percentages of size errors depending on geometrical descriptors used. Percentages are split in overestimation and underestimation errors. Whiskers represent standard deviations from the average values. Starred links join significantly different conditions.

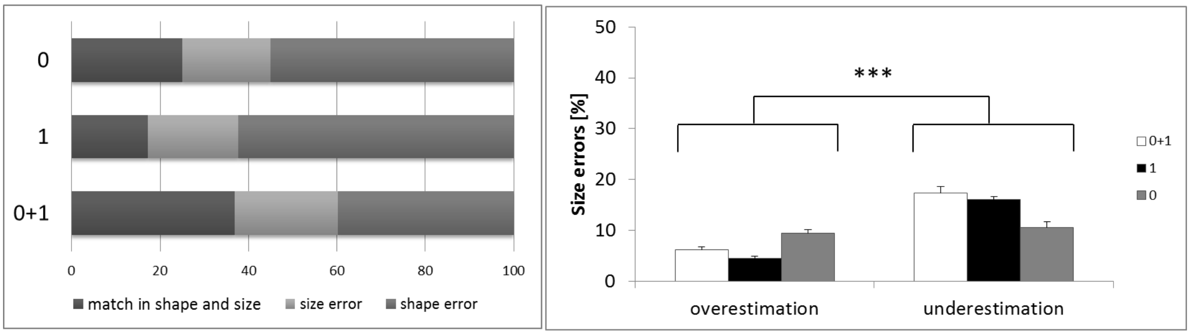


Figure 4.21: *Visually impaired sample.* Left: on the horizontal axis there are the percentages of matching shape and size, error in size and errors in shape performed; on the vertical axis there are the geometrical descriptors. Right: percentages of size errors depending on geometrical descriptors used. Percentages are split in overestimation and underestimation errors. Whiskers represent standard deviations from the average values. Starred links join significantly different conditions.

100% and mean values of 87.9% for $0^{th} + 1^{st}$ and 82.4% for 0^{th}. Therefore, the $0^{th} + 1^{st}$ and 1^{st} conditions were different when correctly guessing both shape and size or shape alone.

Third, we analysed the relative contribution of shape and size errors, for each Geometrical Descriptor. On the left side, Fig. 4.20 shows the percentages of complete matching (matched size and shape) and errors in size and shape discrimination. From the analysis of error histograms, it is apparent that the tactile condition biases the kind of error done. Object size was misunderstood more in $0^{th} + 1^{st}$ and 0^{th} than in the 1^{st} condition. The situation is reversed in case of shape errors. Size errors can be decoupled in overestimation and underestimation ones. Data were normally distributed (W<0.97, p>0.29). ANOVA test revealed that both overestimation and

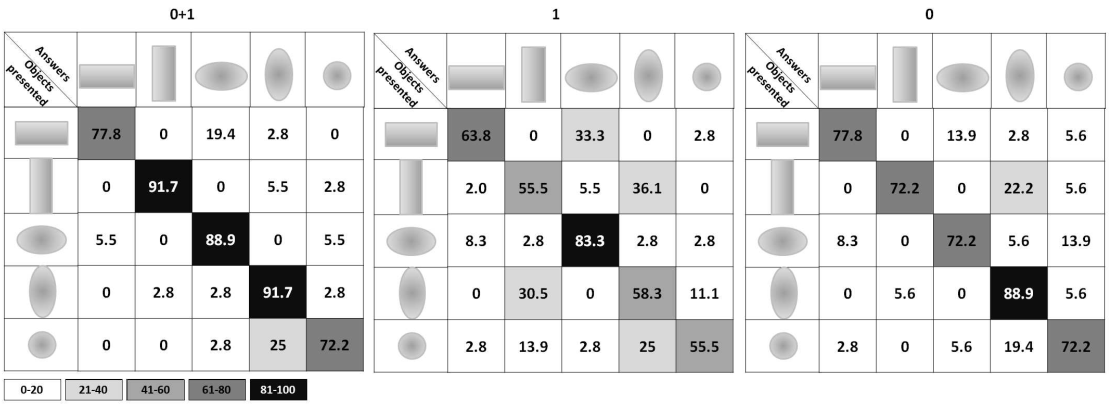


Figure 4.22: *Blindfolded sighted sample.* Confusion matrices of performances in matching shapes, depending on the three Geometrical Descriptors. Cells contain recognition rates: in this case shape mismatch was not considered an error.

underestimation depended on the tactile condition, (showing p<0.03). In both cases $0^{th}+1^{st}$ and 0^{th} conditions were significantly different from 1^{st}.

Fourth, we analysed the nature of shape errors. Figure 4.22 shows the confusion matrices for each condition of Geometrical Descriptor: in this case shape mismatch was not considered an error. In $0^{th}+1^{st}$ condition, all the values on the diagonal are higher than those outside (p<0.001) meaning that shape is well recognized for all the objects (mean value is 84.4%). In 1^{st} condition, values of performance on the diagonal (mean value is 63.3%) are still higher then those outside (p<0.05) but the difference is less evident: specifically, horizontal semi-ellipses are confused with horizontal semi-cylinders; vertical semi-ellipses are confused with vertical semi-cylinders and vice versa. In practice, a chess-like appearance denotes that confusion occurs with objects having similar orientation with respect to the body of the participant. In the 0^{th} condition, the prevalence of correct values on the diagonal still occurs (p<0.001), although the confusion with objects of similar orientation is still apparent. Overall on the three confusion matrices, semi-ellipses appear to have been better recognized on average (vertical: 81.5%, horizontal: 79.6%), followed by cylinders (73.1% both for vertical and horizontal) and spheres (66.6%) which are mainly confused with vertical semi-ellipses.

Finally, Geometrical Descriptors did not had a significant effect on the measured reaction time. Mean values and relative standard deviations of reaction time were 37.9s ±13.5 for the $0^{th}+1^{st}$, 41s ±19 for 1^{st} and 38.6s ±15.8 for the 0^{th} condition.

Visually impaired sample. In this section there are the same analysis steps of the previous section.

First, we considered the case in which matching was defined correct when both shape and size were guessed. In Figure 4.19 (left) we show performance distributions of matching ability, displayed as histograms, using each of the three geometrical descriptors. Data were not normally-distributed ($W > 0.7285$, $p < 2*10^{-9}$). Friedman non-parametric test revealed a significant effect

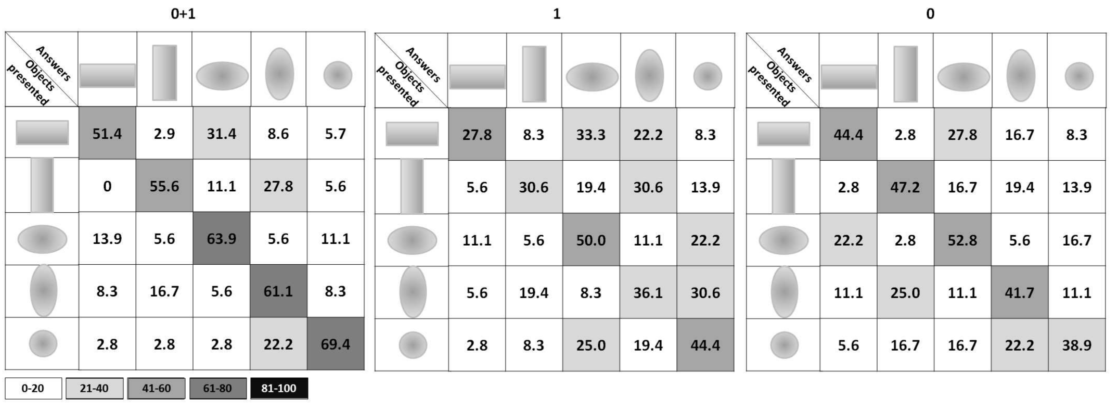


Figure 4.23: *Visually impaired sample.* Confusion matrices of performances in matching shapes, depending on the three Geometrical Descriptors. Cells contain recognition rates: in this case shape mismatch was not considered an error.

of the Geometrical Descriptors on Matching Ability (χ^2(2)=12.67, p=0.002). Then, Wilcoxon post-hoc for pairwise comparisons showed that the difference was statistically significant between the $0^{th}+1^{st}$ and 1^{st} condition (W=2393.5, p=0.0008). The conditions in which the elevation cue was presented (i.e. $0^{th}+1^{st}$ and 0^{th}), exhibited the highest values of performances, having a median value of 33.3% (with mean values of 37.2% for $0^{th}+1^{st}$ and 25% for 0^{th}) respect to the 0% of 1^{st} condition (with mean value of 17.2%).

Second, we considered the case where guessing only the shape was sufficient to define the matching as correct, neglecting size. Figure 4.19 (right) shows the distribution of the shape-only matching ability depending on geometrical descriptors. Distributions were not normal (W > 0.83, p< $1.4*10^{-6}$) and Friedman test showed also in this case a significant effect of the Geometrical Descriptors (χ^2(2)=13.88, p=0.001). Post-hoc revealed a difference between $0^{th}+1^{st}$ and 1^{st} condition (V=2442.5, p=0.0005), but this time also between $0^{th}+1^{st}$ and 0^{th} (V=2262.5, p=0.01). In this case performances of $0^{th}+1^{st}$ and 0^{th} are higher than 1^{st}, showing a median of 66.7% and mean value of 60.5% for $0^{th}+1^{st}$ and respectively median of 33.3% and mean value of 45% for 0^{th} . Therefore, the $0^{th}+1^{st}$ and 1^{st} conditions were different when correctly guessing both shape and size or shape alone.

Third, we analysed the relative contribution of shape and size errors, for each Geometrical Descriptor. Figure 4.20, on the left side, shows the percentages of complete matching (matched size and shape) and errors in size and shape discrimination. From the analysis of error histograms, it is apparent that the tactile condition biases the kind of error done. Object size was misunderstood in all the three tactile conditions similarly. Then size errors can be decoupled in overestimation and underestimation ones. Since data were normally distributed (W<0.98, p>0.13) an ANOVA test was performed. It revealed that neither overestimation nor underestimation depended on the tactile condition, but there was a bias in perceiving object size: objects were felt significantly smaller(F(1) = 18.25, p=0.0002).

Fourth, we analysed the nature of shape errors: Figure 4.23 shows the confusion matrices for each condition of Geometrical Descriptor, in this case shape mismatch was not considered an error. In $0^{th}+1^{st}$ condition, all the values on the diagonal are higher than those outside (p<0.02) meaning that shape is well recognized for all the objects (mean value is 60.3%). In 1^{st} condition, values of performance on the diagonal (mean value is 37.8%) are statistically similar to those outside (p>0.05): horizontal and vertical semi-ellipses are confused with hemispheres and vice versa; horizontal semi-cylinders are mainly confused with horizontal semi-ellipses and vice versa; vertical semi-cylinders are confused with vertical semi-ellipses. In the 0^{th} condition, the prevalence of correct values on the diagonal does not occur (p>0.05), although the confusion with objects of similar orientation is still apparent. In practice, a chess-like appearance denotes that confusion occurs with objects having similar orientation with respect to the body of the participant. Overall on the three confusion matrices, cylinders appear to have been better recognized on average (vertical: 66.7%, horizontal: 41.2%), followed by semi-ellipses (vertical: 46.3%, horizontal: 55.6%) and spheres (50.9%) which are mainly confused with semi-ellipses.

Finally, Geometrical Descriptors biased the measured reaction time. The trial duration was not normally distributed (W<0.86 ,p>$4.8*10^{-6}$): mean values and relative standard deviations were 31.3s ±24.1 for the $0^{th}+1^{st}$, 38.4s ±24.5 for 1^{st} and 28.6s ±13.7 for the 0^{th} condition. The 1^{st} condition appears to be the longest and statistically different from the $0^{th}+1^{st}$ (V=615 ,p=0.03) and from the 0^{th} (V=476 ,p=0.001) conditions.

Comparison between groups. This section describes the comparisons between the blindfolded sighted and visually impaired sample: from now on, the Group variable will indicate the two samples.

First, it were considered the distributions of matching ability when both the shape and size were guessed, see Fig. 4.18 and 4.19 on the left. A Friedman non-parametric test showed that the distributions of matching ability were statistically different between the samples: $\chi^2(1)$=34.57, p=$4.1*10^{-9}$. This difference was true also considering the Geometrical Descriptors separately, with both elevation and inclination (W=2234.5, p=0.02), with only inclination (W=2513, p=$6.2*10^{-5}$) and with only elevation (W=2493,p=$1*10^{-4}$). These differences have an univocal direction, in all cases the blindfolded sighted perform better than visually impaired participants.

Second, the definition of Matching ability was reduced at the case in which only size mismatch was considered an error, see Fig. 4.18 and 4.19 on the right. Friedman test revealed that, also in this case, the Group had an effect on the Matching ability: $\chi^2(1)$=41.79, p=$1*10^{-10}$. This difference was true also considering the Geometrical Descriptors separately, with both elevation and inclination (W=2539.5, p=$6.2*10^{-5}$), with only inclination (W=2531, p=$7.6*10^{-5}$) and with only elevation (W=2738.5, p=$4.3*10^{-7}$). These differences have an univocal direction, in all cases the blindfolded sighted perform better than visually impaired participants.

Third, the errors were analysed and divided into two main categories: the errors due to mismatch in size judgements and the errors due to mismatch in shape judgements. A t-test

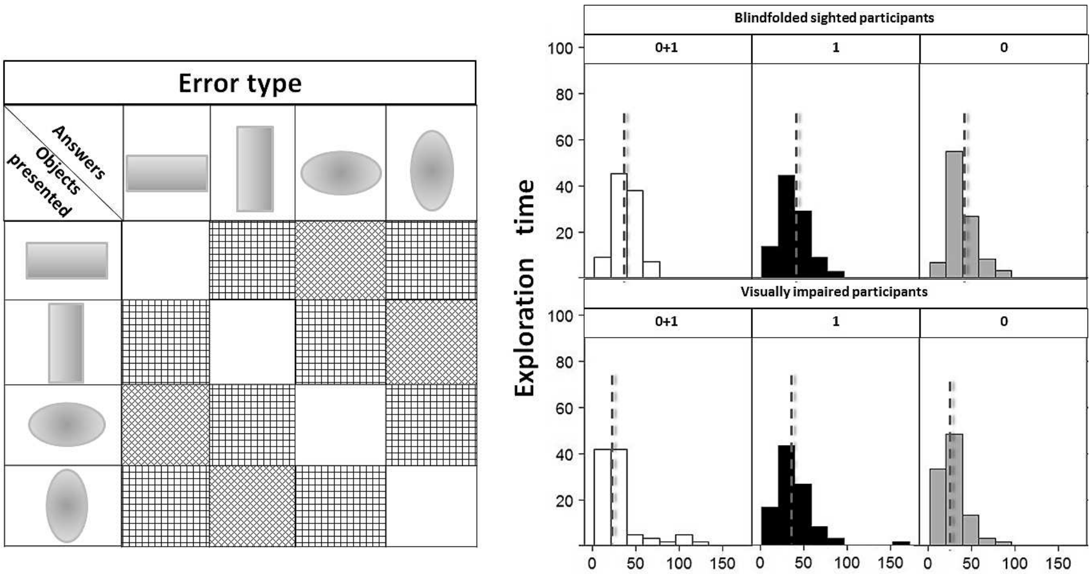


Figure 4.24: Matrix indicating the two kind of shape errors analysed. Squared texture indicates errors in orientation, while rhomboidal texture represents contour errors (left). Distributions of reaction times depending on the Group and on Geometrical Descriptors. Dashed lines represent mean values (right).

was performed to know the possible effect of Group in the estimation of object size. It revealed a significant difference in the Group variable (t(1)=31.6, p=0.005): sighted participants misunderstood object sizes more than visually impaired people. The mismatch in size could be due to an underestimation or overestimation. The t-test showed that the Group has an effect only in overestimating the size (t(1) = 23.1, p=0.002) and not in the opposite direction (t(1) = 1.2; p=0.3). As a result, sighted participants tend to perceive the size of objects as bigger than what it really is and more frequently than visually impaired participants. As shown in Figures 4.20 and 4.21 (on the right) the amount of size errors, mostly for sighted participants, is changing depending on the Geometrical Descriptor. Considering each Geometrical Descriptor separately, a significant difference according to the Group was found in the $0^{th} + 1^{st}$ (p=0.007) and in the 0^{th} (p=0.04) condition for overestimation. Furthermore, the nature of the shape errors was investigated. In Figure 4.24, on the left, are shown the two kind of errors which have been analysed. Cells containing squared texture indicate the errors in orientation, i.e. a horizontal confused with a vertical object and vice versa. Cells with rhomboidal texture represent the errors in misjudging object contours , i.e. a a cylinder confused with an ellipse. White coloured cells indicate an exact matching. To evaluate the quantity of the errors in orientation respect to the errors in contour the *Error type ratio* was calculated. The *Error type ratio* has the sum of errors in orientation on the numerator and the sum of errors in contour on the denominator. Table 4.4 shows values of the *Error type ratio* depending on the Group and the Geometrical Descriptors. Blindfolded sighted participants showed lower *Error type ratio* than visually impaired, with all Geometrical

Table 4.4: Error type ratio

	0+1	**1**	**0**
blindfolded sighted	$\frac{5.5}{33.3} = 0.16$	$\frac{13.9}{108.3} = 0.13$	$\frac{8.3}{50} = 0.16$
visually impaired	$\frac{47.5}{89.8} = 0.53$	$\frac{86.1}{94.4} = 0.91$	$\frac{69.4}{94.4} = 0.73$

Descriptors. Thus, visually impaired sample misjudged orientation more than their peers: in condition $0^{th} + 1^{st}$ half of their errors were in orientation, in condition 0^{th} it was 73% and in condition 1^{st} there was the same quantity of contour and orientation errors.

Finally, the reaction time was compared, see Figure 4.24 on the right. Blindfolded sighted appeared to be slower than visually impaired participants. Their reaction times were divided according to the Geometrical Descriptor used and also in this case the visually impaired participants were faster. Furthermore, these differences were statistically significant for condition $0^{th} + 1^{st}$ (V=1277, p=0.008) and 0^{th} (V=1360,p=0.001).

4.4.2.2 Subjective evaluation

Blindfolded sighted sample. After completion of the NASA-TLX questionnaire for each Geometrical Descriptor, the overall task load was calculated by merging the items weighted by the participants: the complete procedure is described in [59]. Mean values of the overall workload and their standard deviations are shown in Fig. 4.25 (left) depending on the Geometrical Descriptor. The perceived workload significantly depended on the Geometrical Descriptor (F(2,20)=5.52, p=0.01): its effect is significant between the conditions 0^{th} and 1^{st} (t(10)=-5.42, p=0.0003) where the workload was rated as higher in the 1^{st} condition. Additionally, the effect of Geometrical Descriptor was investigated for each NASA factor separately.

Figure 4.25 (right) depicts mean values and standard deviations of these factors. Since half of the distributions were not normal, mean values should be considered as indicative. Four out of six factors were statistically different, meaning that geometrical descriptors used efficiently differentiate the task. Factors showing a statistical difference were Mental Demand (χ^2(2)=8.87, p=0.01), Performance (χ^2(2)=6.68, p=0.03), Effort (χ^2(2)=8.06, p=0.01) and Frustration (χ^2(2)=8.7, p=0.01). In agreement with the global workload, the condition 1^{st} was generally judged as more mentally demanding, required more effort and caused more frustration.

Visually impaired sample. The overall task load was calculated by merging all the items of NASA-TLX questionnaire weighted by the participants. Mean values of the overall workload and their standard deviations are shown in Fig. 4.26 (left) depending on the Geometrical Descriptor. The perceived workload did not depend on the Geometrical Descriptor. Additionally, the effect of Geometrical Descriptor was investigated for each NASA factor separately.

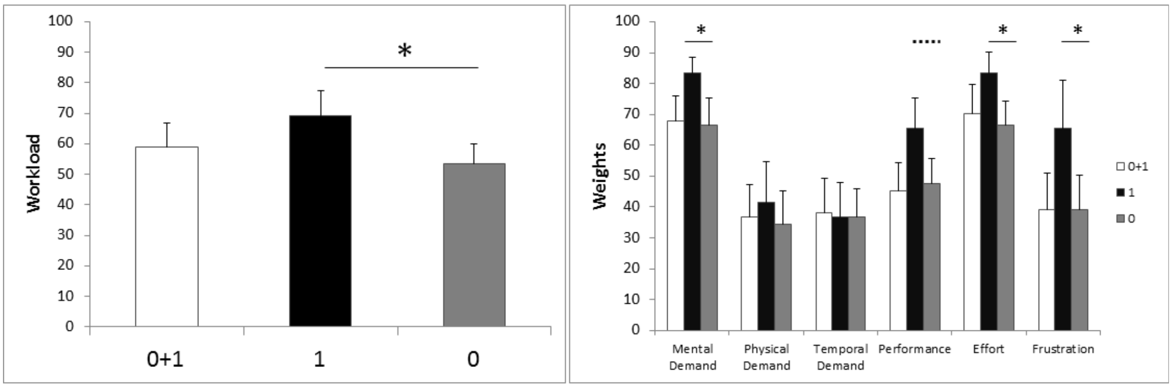


Figure 4.25: *Blindfolded sighted sample.* Overall task load values(left) and its factors(right) for different tactile feedbacks. Whiskers represent standard deviations from the average value of factors. Starred links join significantly different conditions: three stars stand for p < 0.001, two stars for p < 0.01 and one star for p < 0.05. Dashed lines indicate a trend, i.e. p<0.1.

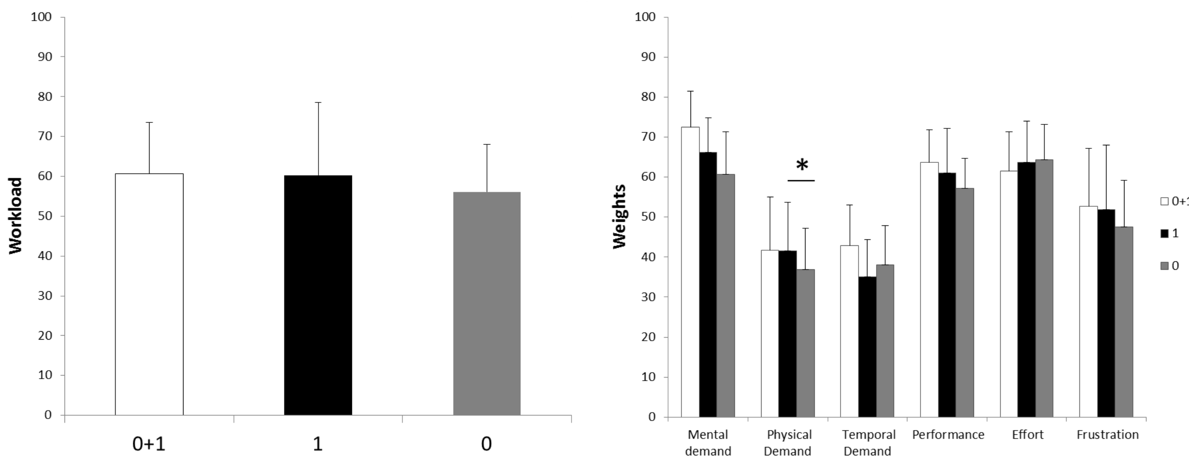


Figure 4.26: *Visually impaired sample.* Overall task load values(left) and its factors(right) for different tactile feedbacks. Whiskers represent standard deviations from the average value of factors. Starred links join significantly different conditions: three stars stand for p < 0.001, two stars for p < 0.01 and one star for p < 0.05. Dashed lines indicate a trend, i.e. p<0.1.

In Figure 4.26 (right) are shown the mean values and standard deviations of these factors. Since one third of the distributions was not normal, mean values should be considered as indicative. One out of six factors was statistically different, meaning that geometrical descriptors used did not influence the workload associated to the task. The only factor showing statistical difference was the Physical Demand (V=21, p=0.03).

Comparison between groups. A two-way ANOVA was performed with the workload as dependent variable and Group and Geometrical Descriptors as independent variables. ANOVA showed a significant trend only for Geometrical Descriptors, F(2,66)=3.41 with p=0.04. Moreover, considering the two samples together, a Post-hoc t-test revealed that condition 1^{st} had significantly

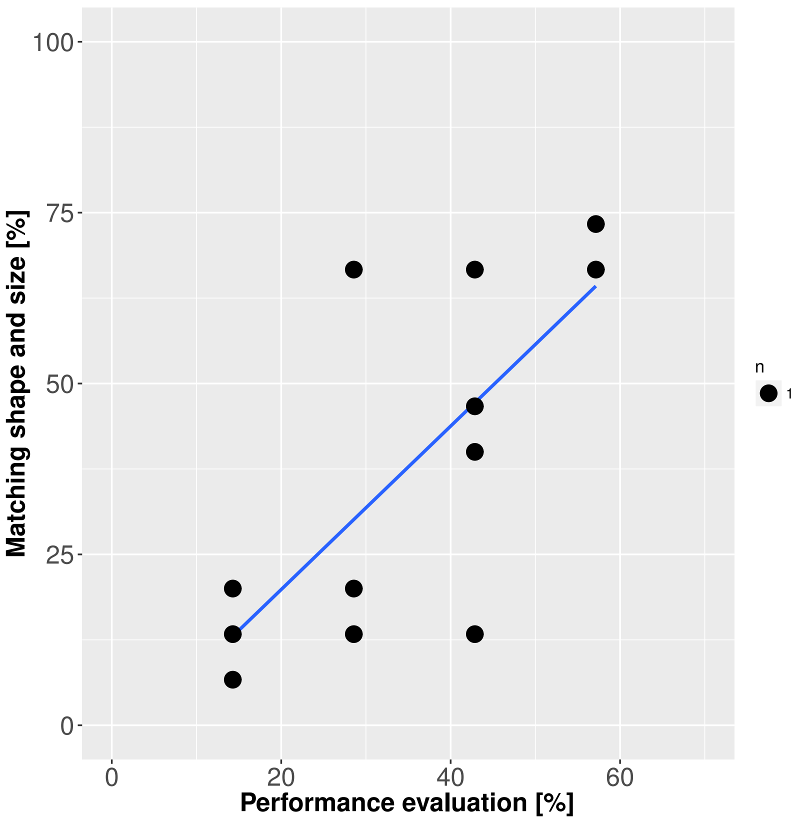


Figure 4.27: Linear prediction of matching ability from visually impaired participants in the condition $0^{th} + 1^{st}$. Matching ability in both shape and size predicted by subjective evaluation of the performance.

higher values than 0^{th} (t(23)=3.22,p=0.004) and $0^{th} + 1^{st}$ (t(23)=2.58,p=0.02) conditions.

Finally, we were interested in knowing if participants were aware of performance achieved. Data about self-evaluation of the performance, collected with NASA questionnaire, were compared with the matching ability. Between the two groups, only visually impaired population showed to properly rate the matching ability. In fact, a significant correlation was found between the ability of matching virtual objects and the subjective evaluation of their performance, F(1,10) = 13.09; p=0.005; R^2 = 0.57 (see Figure 4.27). This correlation is valid only for the condition in which both Geometrical Descriptors are present, suggesting that a good evaluation of performance is helped by a better understanding of the task. In order to evaluate the consistency of the successful self-evaluation of performance, we checked if also other NASA factors were correlate with objective performance achieved by blind individuals in the complete tactile condition. Results confirmed that only self-assessed performance is a reliable predictor since none among mental demand (F(1,10)=0.22, p=0.65), physical demand (F(1,10)=0.03, p=0.87), temporal demand(F(1,10)=0.26, p=0.62), effort (F(1,10)=3.37, p=0.09) and frustration (F(1,10)=2.8, p=0.12) showed a significant effect on objective performance .

4.4.3 Discussion

Our results show that when tactile feedback approximates real touch, performances in matching virtual with real objects are higher. This result is true for both blindfolded sighted and visually impaired participants. The way tactile feedback is provided by our experimental setup allows to combine local tactile cues, given by elevation and inclination of a tactor in 3DOF, to global kinesthetic cues, given by proprioceptive feedback coming from hand and arm motion. In other words, the metaphor induced by our device is that of touching objects as if a coin was put between an object and the fingertip. We hypothesized that elevation and inclination cues could have different effects on the ability to match real with virtual objects and could also have effects on the mental workload in performing such matching task.

4.4.3.1 Merging elevation and inclination cues facilitates object recognition

Blindfolded sighted sample. The distributions of matching rates are skewed towards high performances and confusion matrices are mainly diagonal. However, inclination cue led to worse performance mainly because of shape errors. When elevation cues are present, size errors are more prominent. In other words, the sole inclination gave more ambiguous information about the shape: in fact, qualitative observations from our participants reported that when elevation only is displayed, the zones of the objects where the gradient is null (e.g. peaks of spheres, peaks of ellipses and the highest line of the cylinders) could be confused with the zones surrounding the object. This explains both the lower performance and the higher cognitive load. The combination of elevation and inclination cues revealed to be best for matching virtual and real objects. Interestingly, when performance are at best, overestimation errors become prominent. Although we do not show the complete confusion matrices (where size errors are also displayed), the kind of size error was biased: participants tended to significantly overestimate the size of all five objects. The shape of the TAMO3, which is closest to our largest objects on the Tactile Dictionary, might have played a role. However, for practical applications this bias could be recovered by decreasing the overall size of the virtual objects and allow a more precise matching. The objects with the highest score were the ellipses (see Fig. 4.22): as cylinders, ellipses have axial symmetries that, on the surface of the tablet, are different along the vertical axis, i.e. the line joining the elbow to the proximal and distal parts of the hand, and along the horizontal axis, i.e. the line parallel to the shoulders. Therefore, perceiving different major and minor axes may have led to clearer mental constructions, while an object with central symmetry such as the sphere was frequently confused with an ellipse. This result is in line with previous studies demonstrating that hand's scanning movements [52] and their direction [186] affect haptics judgements. The main source of error, contour-wise, was the estimation of inclination in more than one dimension: in fact cylinders were mainly confused with ellipses (and viceversa), but object orientation was almost always perfectly guessed. Proprioceptive cues, leading to estimate orientation, were therefore very well decoded, while tactile cues, leading to estimation of curvatures, were integrated with more issues.

Yet, past works have shown that inclination cues are successfully perceived [196]: it might be that perceiving curvatures in multidimentional spaces may require more effort. This aspect needs further research. Interestingly, spheres were frequently overestimated along the distal direction (therefore confused with vertical ellipses), as if perception on distal and transversal planes undergo different precision [113].

Visually impaired sample. The presence of both geometrical descriptors increases performances as shown in the distribution of matching rates: the condition in which both inclination and elevation are present has a higher matching rate respect to the distributions in which only one geometrical descriptor is present. Moreover the percentages of matched objects in the confusion matrix (elements in the diagonal) are statistically higher than the quantity of shape errors (elements outside the diagonal), see Fig. 4.23. If rendered alone, elevation or inclination, are not sufficient to elicit a comprehensible mental map of the objects: in fact in the confusion matrix, the shape errors percentages are comparable to those of matched objects. Therefore, in visually impaired people, simplifying tactile information led to confusions when constructing mental representations from virtual objects. Again the main source of error was the evaluation of changes in curvature along two dimensions: the vertical and the horizontal axes. Therefore, objects with curvature changes only on one axis, i.e. cylinders, were confused with objects with curvature changes on two dimensions, i.e. ellipses. Jointly with the impaired estimation of curvature, when only inclination was present, also the integration of proprioception cues failed since ellipses were confused with hemispheres. Moreover, since cylinders were confused with ellipses of the same orientation and vice versa, we can affirm that object orientation was almost easily matched. The cylinder is the most recognizable object in all tactile conditions even if the sphere has the highest percentage when approximating real touch, i.e. in the tactile condition containing both geometrical descriptors. The condition in which only inclination is displayed was verbally described as the less intuitive, confirming the lowest performances achieved. When considering mismatches in size estimation, participants showed a bias on *under size* objects. Visually impaired sample appears to systematically underestimate the size of virtual objects, independently from the kind and amount of geometrical descriptors displayed. This result has an important consequence if, in a more practical scenario, visually impaired people will independently use the TAMO3. In this case, size of virtual objects used in the experiment represent the lower limit: passing this limit could penalize object understandability.

Comparison between groups. The use of all geometrical descriptors is source of good comprehension of virtual object explored by touch, both in presence of visual impairment or not. Interestingly, the difference between the two populations arises in the *way* geometrical descriptors are combined. While sighted participant could even use only elevation descriptor without losing matching precision, visually impaired population need both inclination and elevation in order to achieve a good match between real and virtual objects. Comparing matching ability in the tactile condition in which both visually impaired and sighted participants performed at best, i.e. the one in which both elevation and inclination were present, a difference in accuracy rate can be found. Visual impairment is a cause of lower accuracy in matching real with virtual objects. Therefore, sighted participants showed to be almost always successful in understanding virtual object shapes (median value of matching ability was 100%) instead, blind participants matched a bit more than the half of all presented objects (median value was 66%). It follows the achievements of previous studies indicating that exploring objects without manipulating them results in an impaired performance of blind population [129]. The nature of errors shows a differences between the two populations. Sighted participants misjudged more the size of objects than visually impaired, because they tended to feel virtual objects bigger than they were. Besides size errors, we analysed also confusions in judging contour and orientation of virtual objects. As described in the *Introduction* section, the shapes of virtual objects were created with the aim of being unfamiliar objects and similar among each other. The understanding of shape contour is mainly due to perception of curvatures and to the way of exploring the borders of objects. On the other side, the vertical and horizontal orientations could be discriminated depending on strategy used to move the arm and integrate tactile feedback. The two populations showed different trends in doing errors: visually impaired participants showed to confuse more the orientation of objects than sighted. This result is in line with previous studies demonstrating that haptic orientation discrimination is impaired in absence of vision [54]. One reason of this confusion between horizontal and vertical axes (and vice versa) could be that visually impaired participants did not easily estimate the length and width of virtual objects as demonstrated in [113]. This was true also with blindfolded sighted participants but to a less extent. Admittedly, to deepen the comparison between the two samples, further analyses regarding exploration strategies and speed used should be added.

4.4.3.2 Rendered alone, inclination cue increases the perceived workload

Blindfolded sighted sample. The kind of geometrical descriptor influences the perceived workload. The highest global workload, as well as the highest mental demand, effort and frustration are found with inclination cues only. This result matches with the poorest performances achieved in this condition. When displaying elevation only, the task is less mentally demanding and entails less effort, frustration and less global workload. These two observations suggest that simplifying the tactile feedback does not necessary mean increasing the complexity of the task, but the *way* this is done is important. When both cues are present, the workload sets to an average value (and performance grows at best). The relation between performance and workload is therefore highly task dependent, as also shown in [17].

Visually impaired sample. The kind of geometrical descriptors has no effect on the workload perceived by visually impaired participants, meaning that the subjective evaluation of the task does not correlate with the performance achieved: even if the tactile condition resembling real touch has statistically higher performances respect to the other tactile conditions, it is perceived as equally demanding. Surprisingly, the condition verbally rated as the less intuitive, i.e. the one in which only inclination was depicted, was evaluated as challenging as the other. One possible explanation is that the three conditions were equally perceived as abstractions of reality and tactile feedback changes were not sufficient to differentiate those levels of abstractions.

Comparison between groups. Belonging to a group, blindfolded sighted or visually impaired participants, has not an effect on the perception of workload associated to the task. On the other side, only the amount of Geometrical Descriptors makes a difference in evaluating how the task is demanding. Therefore, grouping the two samples, the condition in which there was only the inclination was perceived as the most challenging.

Blind population showed a particular sensitivity to the evaluation of their own performance. Their subjective evaluation clearly reflects the objective accuracy in matching objects: subjective and objective variable can be linked by a linear correlation as already demonstrated in [16]. On the contrary, blindfolded sighted population failed in this estimate. This is a precious result in perspective of the independently use of TAMO3 by visually impaired population. Users, aware of performance achieved, can potentially tune task difficulty in order to challenge themselves in more complex scenarios.

4.4.4 Contribution to rehabilitation protocols

In conclusion, this section showed that it is possible with a portable device delivering limited tactile feedback, to convey information about solid geometry. In principle, this method can be proposed, in rehabilitation context, as complementary learning tool when geometrical concepts have to displayed, and potentially manipulated, by persons with visual loss. Visual impairment causes less accurate performances in matching real and virtual objects, thus, exercises planning should be targeted consequently. Moreover, since the presence of the kind and number of geometrical descriptor has a strong effect on matching ability, rehabilitators could decide to tune task difficulty changing the haptic feedback. Those changes will not be source of frustration or effort for participants and at the end of the exercise they likely will be able to predict their own ability, making comparisons with previous tests and thus be actively involved in the process of learning. Data organization, acquisition, storage and analyses, mostly in this last experiment, have been planned to be automatically run. The idea comes from the context of *serious games*, i.e. a kind of game designed to be primarily didactic but adding entertainment to the phase of learning. Game framework let players, or in this case learners, to automatically know their achievements right after each task and eventually practise more avoiding the time limit of rehabilitation schedule. Moreover, supporting rehabilitation process with a serious game structure allows learners to freely access their data: they can therefore consult them, analyse their trends and possibly plan future activities.

Chapter 6

Conclusions and future work

6.1 Conclusions

Our goal is contributing to solve the problem of accessing digital information non-visually, by demonstrating that bidimensional user interfaces, enriched with 3D content, can be used by blind people. The system proposed in this thesis is targeted to assist and potentially enhance spatial abilities of visually impaired people, taking advantage of the tactile residual sense.

The first achievement is that our system provides an appropriate stimulation to elicit the learning of simple geometrical objects to which, in principle, it is possible to associate a semantic content. We used two tactile stimulators, TAMO1 and TAMO3, with different purposes in several studies.

The *metaphor* is that TAMO1 provides a minimalistic local tactile cue, that integrated with active exploration can elicit a mental map: much like touching and exploring an object with one finger only, TAMO1 mimics real perception of an object when a small *stick* is attached to the finger and mediates interaction. The stick being smaller than the fingertip size and not being capable to elicit tangential cues, but mainly normal, to the skin. When the finger lies still on an arbitrary object, this is equivalent to feel the height of the object, but the information the brain derives from skin indentation is *discarded*.

The second, TAMO3, is meant to enhance the similarity to real tactile exploration. Elementary geometrical primitives, i.e. *local elevation* and *local inclination*, are used to approximate a *global* tactile scalar field.

The *metaphor* here is that TAMO3 provides a local tactile cue (wider than that rendered with TAMO1), that integrated with active exploration can elicit a mental map: much like touching and exploring an object with one finger only, TAMO3 mimics real perception of an object when a small *coin* is attached to the finger and mediates interaction. The coin is of the same dimension as the fingertip. When the finger lies still on an arbitrary object, this is equivalent to feeling the height of the object and what is its local inclination, and the information the brain derives from skin indentation is partly *preserved*.

With inclination being a geometrical property that depends on hand orientation, TAMO3 also adapts tactile feedback to hand orientation, i.e. the tactor is inclined in an absolute reference system.

Both devices display local features of virtual objects combining local tactile cues to global kinesthetic cues, given by proprioceptive feedback coming from hand and arm motion. Applications span from access of graphics and scientific content on the web to the learning of 3D maps of real environments.

Secondly, this research 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. Visual impairment effect has been analysed introducing variables which belonged to multiple domains: subjective and behvioral. In the quest for obtaining metrics able to measure spatial abilities, in fact, the evaluation of the sole performance may lead to only partial understanding about what is behind the quality of cognitive mapping. Knowing the strategies to merge local tactile content in a global percept helps in the comprehension of mechanisms which lead to create a mental map. On the other hand, subjective variables such as gender, mental status and perception of task difficulty have a role in understanding the effort done to create a mental map. Investigating the underpinnings of a certain performance can complement and potentially improve O&M rehabilitation protocols.

Finally, the ability to actively manage virtual content through touch modality was investigated. Visually impaired people demonstrated to be able to exploit their imagery to interact with virtual content and manipulate it by means of a haptic device. Dynamic manipulation of virtual content can be a practical means to verify if a map has been understood, i.e. a verification setup, meaningful in a rehabilitation context.

As a conclusion, the answers to the following research questions will be provided:

1. How do visually impaired persons react to the stimulation mode, as compared to sighted persons?

2. Is it possible to find an appropriate stimulation mode that helps to effectively build mental models from virtual geometrical primitives?

3. Can visually impaired people manipulate dynamic virtual content through touch?

Considering the construction of virtual maps with minimal touch information provided by TAMO1, it is possible to affirm that:

- Blind and blindfolded sighted people seemed to share a similar abstract level of mapping process. Since in the creation of a mental map similar mechanisms are involved, visual convention used by sighted people, might be similarly given by touch to blind persons. This is an additional proof that visually impaired people can effectively process graphical information through touch [198] but the novelty is that it happens also with virtual objects.

- Only task difficulty and not visual deprivation modulated both the amount of information acquired (behavioural measure), the related cognitive load (subjective measure) and performance. This result highlights the similarity between blind and sighted persons also in domains different from the sole performance, meaning that blind people achieve the same results of sighted exploiting similar mental resources and strategies. However, only an objective variable as the task difficulty is able to coherently affect all the measures introduced (behavioral, subjective and performance): it demonstrates that even if tasks are created by sighted subjects they are sufficient to elicit the same reactions in visually impaired people.

- A measure of anxiety revealed a systematic decrease after the use of TAMO1, suggesting that assessments of this kind of assistive devices may consider a set of diverse variables, including mood.

- The effect of visual deprivation together with blindness onset modulated performance only for a particular class of participants (congenitally blind women), thus early or temporary loss of sight looks to be irrelevant for maps to be efficiently developed, at least with our system.

- Both men and women share a similar acquisition process to learn tactile maps, but we found gender differences in mental effort and in efficiently integrating tactile cues into geometrical concepts. This is important when modelling user behavior: O&M practitioners may apply corrected metrics, or adapt them, or present a different set of tasks, when testing different genders.

With the introduction of TAMO3 the number of geometrical descriptors to be displayed increased. Virtual maps consisted in global tactile scalar fields approximated with local elevation and local inclination only, while missing information was delegated to spontaneous proprioceptive behavior. The possibility to explore a virtual environment instead of a real one, as it happens using TAMO3, gives the possibility to diversify the tactile feedback in terms of geometrical descriptors of the explored surfaces: presenting elevation, inclination or both. In this way, the role of each descriptor can be isolated and evaluated.

Therefore considering the enriched tactile feedback provided by TAMO3, the following results have been achieved:

- It is possible with a portable tactile device to convey information about solid geometry, while observing how different geometrical descriptors separately contribute to the percept. Since the most sensitive geometrical descriptor (inclination) was perceived as the most demanding, in a curvature discrimination task, a trade off may be necessary to achieve high precision without increasing too much mental demand, which may put at risk the users' acceptance of an assistive tool.
- Visual deprivation leads to less accurate performances in matching real and virtual objects, thus, the planning of exercises should be targeted consequently. Visually impaired people need local inclination information more than sighted, since the addition of inclination and elevation led to better performances. On the other hand, for sighted people it is sufficient to provide elevation cue to match real and virtual objects. Moreover, since the presence of both inclination and elevation as geometrical descriptor has a strong effect on matching ability, rehabilitators could decide to tune task difficulty changing the haptic feedback. Those changes will not be source of additional frustration or effort in blind individuals. Moreover at the end of the exercise they may be able to predict their own ability, adding a precious source of comparison with operators evaluations.
- Enriching tactile exploration with a higher degree of interaction with the environment showed that visually impaired people can actively update mental maps as a consequence of their manipulations. A measure to predict accuracy in achieving the task was found and it was independent from subjective parameters: rehabilitators therefore, using this measure, can train and stimulate the acquisition of strategies to improve trainee accuracy. The gender of the participants should be considered only for setting rehabilitation time, since it was found that women are slower than men in completing the task.

6.2 Future work

A possible application of virtual surfaces is to represent tactons linked with web-based content: the context is that of graphical user interfaces for visually impaired people. Using inclination and elevation to express different contents may help with creating a taxonomy of virtual objects. For example, displaying stacked parallelepipeds (as we have shown in [15]) may require elevation only, while displaying parts of spheres may require inclination only. Figure 6.1 shows such a scenario, matter of future work, in which different virtual objects can be displayed by the TAMO3. However, the employ of this object taxonomy should not be limited to the tactile icons but it can change depending on the semantic associated with it. As an example, tactile objects can represent elements of a real geographic map.

The phase of object and map (composed by the simultaneous presence of multiple objects) learning could be organized in steps of a longitudinal study. Since the assistive tool we propose entails the understanding of a metaphor, as a first step, the trainees should be trained to its

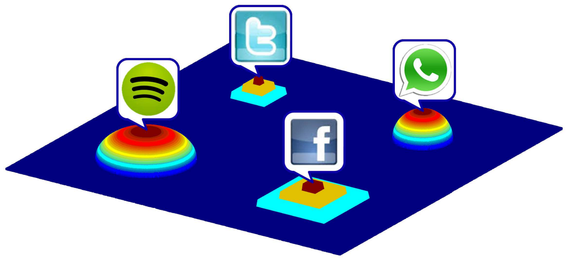


Figure 6.1: Representation of a possible tactile desktop to guide visually impaired persons in a virtual environment.

use. Considering the assistive tool delivering the richer tactile feedback, the TAMO3, a set of exercises to learn the three degrees of freedom should be created: virtual ramps changing in orientation and parallelepipeds can be used. The assistive tool should become 'transparent' [4], that is, trainees should not be aware of manipulating the device since they feel immersed in the task the device allows. In a following step, more complex objects should be explored, such as virtual surfaces created for the experiment in Chapter 4 and their combinations using additive and subtractive actions to compose new surfaces. For example, an hemisphere can be subtracted to a cylinder and consequently the new surface will have the profile of the cylinder and a hole shaped as an hemisphere. Then the virtual scene could be populated with not only one, but multiple objects. The skill to be acquired by the trainee thus is how to relate one object to another in terms of position and distances. This skill is required for navigating in real environments: when a point of interest has to be reached and the trainee has to decide the path, it is essential to know the arrangement in the space of the starting and the final position. Finally, the semantic should be added to the virtual objects and a set of exercises to memorize the elements should be created. Speaking about geographical maps, there are already examples of visual abstractions, i.e. symbols, which represent real elements. The sketch of a bed usually represents a hotel, the cross a pharmacy, the letter 'i' an information point etcetera. The same idea, therefore, could be applied in a tactile scenario.

The conclusions described in the previous section are a further contribution to the view [63] that performance alone is an insufficient measure of a rehabilitative protocol, if not coupled with metrics linked to behavioral, subjective, mental and emotional status. Considering the heterogeneity of visually impaired people, aspects as the education and the use of technology might also have an impact on spatial abilities and thus require to be evaluated [27]. For this purpose, a questionnaire was created to collect information about:

- Braille reading techniques and understanding;
- orientation and mobility training;
- use of multisensory information to orient themselves in a new or known environment;

- expertise and use of existing assistive tools as white cane, smartphones, screen magnifier and Braille bars.

The information collected with the questionnaire will be analysed and added to the results discussed in the previous chapters.

In a desirable future, the expertise and experience of rehabilitators could be integrated with data collected with this assistive tool, possibly enhancing the process of the evaluation of users' abilities.

In Figure 6.2 it is shown, on the left, the actual process of rehabilitation in which the operator evaluates rehabilitation trends of visually impaired people based on the experience achieved or on the general national guidelines and decides if and how protocols should be varied. With this method, the evaluation of rehabilitation process strongly depends on the operator and on the level of his/her expertise. The operator plans the exercises according to what he/she thinks is the potential of the visually impaired trainee and depending on the skills to be enhanced. During the exercises, the operator has to investigates or infer, with not-standardized methods, the performance achieved and the level of stress and effort done by the trainee. An important consideration is that, with this method, the visually impaired person is a passive agent of the exercises.

What it is proposed in this thesis is shown in Figure 6.2 on the right. Operators can co-evaluate the visually impaired people by means of behvioral and subjective data. The difference with the traditional evaluation (Figure 6.2 on the left) is in the way information is collected: behvioral data are automatically collected by the device proposed and subjective data are asked to the visually impaired trainee and not inferred by the operator. Here, the operator has the possibility to change task difficulty choosing the appropriate device (the minimalistic TAMO1 or the enhanced TAMO3) and the adequate task (object recognition, object matching or interaction task). Importantly, once the exercise has been chosen, the operator knows in advance which will be the potential performances of the visually impaired person, adding the information of gender and blindness onset. Moreover, the device allows to automatically record behvioral data which will be evaluated after the exercise and together with additional parameters. An important consideration is that, with this method, the visually impaired person is more involved in the rehabilitation process because he/she self-evaluates the difficulty of the task and his/her feelings during the exercise. In addiction, the visually impaired trainee is more autonomous in the completion of the exercise. In fact, mostly for the interaction experiment, the trainee is independent from the operator: this is a crucial improvement for standard protocols because it allows to perform rehabilitation at home and not specifically in the specialized centres. The final evaluation of the operator then is done collecting data from the device and from the trainee, and comparing them with the existing results reported in this thesis. Finally, depending on the performance achieved and on the level of effort done by the visually impaired person, the operator can plan the following steps of the rehabilitation in a more conscious way: if the workload perceived is low,

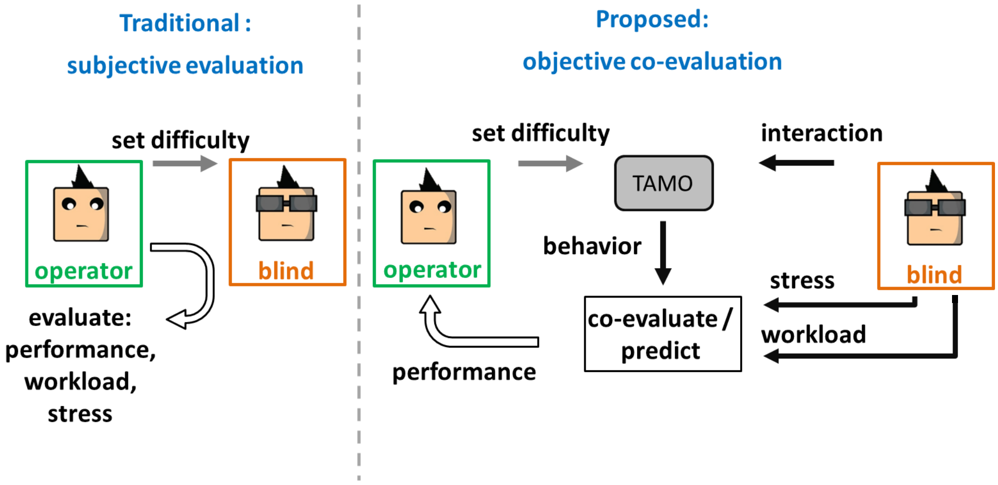


Figure 6.2: (Left) The existing rehabilitation process based on subjective evaluation of operators. (Right) The rehabilitation methodology and technology introduced in this thesis: a novel assistive device, TAMO, to automatically collect behvioral data and a more active trainee (visually impaired person). Final goal of the proposed method is to help operator to co-evaluate multiple aspects of trainee performance in a more objective way.

the operator has a higher freedom to set the task difficulty and viceversa.

APPENDIX A

Appendix A: demo and media content

In this appendix there are the links to media related to the devices of TAMO1 and TAMO3. The description of how TAMO1 works can be found at this link. Media content of TAMO3 encompass its features and functionality (hyperlink) and the general description of the project (hyperlink).

Furthermore it is reported the article in [120] presenting the demo of Asiahaptic conference 2016 in which TAMO3 worked together with a head mounted display [39] to guide participants in a tactile virtual environment. A video of how the demo works can be see here.

A.1 Tactile Treasure Map: Integrating Allocentric and Egocentric Information for Tactile Guidance

A.1.1 Introduction

Navigation skills involve the ability of localizing yourself and travelling in a space. In addition, it requires updating spatial information related to the environment and efficiently employ such information in emergency cases, such as getting lost or accessing interrupted roads. The previous knowledge of the navigation path facilitates the reaching of the desired destination. To store data about the itinerary, our brain has to collect and elaborate information on spatial landmarks, on position and orientation of geographical reference points.

This process leads to the creation of a mental schema representing a simplified version of the real itinerary. The creation of mental representations of a map involves spatial reference systems, such as allocentric and egocentric [1]. There is evidence showing that the performance

[1] Allocentric representation encodes object locations with respect to other objects in a global coordinate system (i.e. top-view perspective). Egocentric representation defines spatial landmarks in relation to the viewer's body in a self-referred coordinate system (i.e. ahead, behind, to the right, to the left respect to viewer's position).

of subjects on different spatial tasks are based on input from both egocentric and allocentric reference frames [35]. However, the preference for using one spatial reference frame over the other, or a combination of different spatial reference frames depends on the participant[56],[74]. The prevalence of one over the other affects the decoding of spatial information [162], but there are no definitive understanding about the adoption of those systems in absence of vision using only haptic modality as it happens for the visually impaired population.

The role of visual experience in the creation of spatial inferential representations is still a debatable topic. Some studies report the superiority of visually impaired people respect to blindfolded sighted subjects [173],[119], while other authors affirm that they actually present impaired performances [157],[153]. One possible reason for this discrepancy is the lack of a method to sequentially verify the use of allocentric and egocentric perspective in the creation of a mental representation of space.

Moreover, visually impaired people encode space mainly through the exploration of tactile maps. The use of printed tactile maps, however, is limited for a number of reasons. For instance, the amount of information that can be presented on a tactile map is limited by its physical dimensions. Moreover, to update the information of the tactile map a new version must be printed. Therefore, there are tactile systems made for blind exploration of virtual environments and maps [91],[135],[161]. Such systems can be used as a learning tool for enhancing orientation and mobility (O&M) training. However, those interactive tactile maps are still mostly explored from a top-view. That hinders the user autonomy for adopting a convenient spatial reference frame.

We propose a new haptic system to provide both egocentric and allocentric cues through the tactile modality.

The setup we propose is meant to improve spatial processing in O&M training by providing more information and autonomy to the subject while exploring dynamic tactile maps. In addition, the same setup can be used as a platform to study how each reference frame is applied to understand space during the exploration of tactile maps.

A.1.2 A System for Haptic Guidance

Our haptic system is composed by the TAMO3 [116] and a Vibrotactile Head-mounted Display [39] (Figure A.1).

The TAMO3 is a *TActile MOuse* sensitive to changes in wrist orientations and providing feedback on three degrees of freedom: height, roll and pitch (Figure A.2). TAMO3 offers a top-view perspective of a virtual map. Users can create a mental map of the explored space by integrating the tactile perception of one finger with the proprioception of the arm.

The vibrotactile HMD is composed by seven electromechanical tactors and renders directional cues on the user's head [39]. It offers a higher resolution on the forehead (such as a "Tactile Fovea"), to ease the detection of objects of interest around the user and to support an egocentric exploration (Figure A.2).

a b

Figure A.1: (a) TActile MOuse 3 (TAMO3), and (b) a vibrotactile HMD.

Figure A.2: Haptic system composed by the TActile MOuse 3 (TAMO3), and a vibrotactile HMD. While the TAMO3 supports the exploration of tactile maps from a top-view, the vibrotactile HMD provides an ego-referenced directional cue updated as a function of the TAMO3 movement.

Figure A.3: The complementary feedbacks of our haptic system: vibrotactile HMD egocentric representation(right) and TAMO3 allocentric one (left).

In our system, the HMD can provide the direction of an object, but does not provide details about the environment. Additionally, the TAMO3 does not provide directional cues, but provides important cues about the explored area (e.g. shape, dimension, and elevation). Therefore, we hypothesize that only coupling the feedback of both devices, the user can integrate egocentric and allocentric frame systems to perform the task easily and rapidly.

A.1.3 Tactile Treasure Hunt

To show how simple it is to use this haptic system, we have built a blind treasure hunt with several treasure boxes hidden inside virtual dips. That simple task can demonstrate how subjects are able to go from a start point to a desired destination just by following the haptic cues provided by the system. Moreover, it will function as a serious game. In this entertaining task, the participants will play as pirates, seeking out for as many treasure boxes as they can in a given time. While the position of the dip is signaled by the vibrotactile HMD, the slope of the terrain can be felt with the TAMO3 (see Figure A.3).

A.1.4 Aimed Results

The integrated haptic system provides both egocentric and allocentric cues, in tactile modality. The system should give autonomy to the subject in order to chose when to receive each cue. Even if the use of both cues should make the tactile exploration richer, the subject's autonomy would support the study about the preferences for different reference frames during haptic exploration. Thus, a set of contributions is expected from this setup:

- The integrated haptic system can provide complete support for tactile exploration of virtual maps;
- It should be used to improve O&M training and the acquirement of spatial information;
- The system should provide more autonomy to the user when choosing a convenient reference frame;

- The system should allow the user to perform O&M training remotely (e.g. at home);
- The components of the system can work together and separated, so the HMD can also be used during the actual navigation task to recover the direction of landmarks;
- The system can provide a setup to sequentially verify the use of allocentric and egocentric perspective in the creation of a mental representation of space;
- The system can also be used for different applications, such as the exploration of virtual environments and a virtual desktop application.

Further experiments would allow us to verify the usability of the system and the adoption of reference frames during tactile exploration.

APPENDIX

A

APPENDIX B: TIME CONSTRAINTS FOR WIRELESS COMMUNICATION ON THE TAMO3

In this section it is described the validation of wireless handshaking protocols with the TAMO3. The technology we propose should have a sufficient level of autonomy to let people achieve a certain independence in its use. In the context of wireless connection, a stable and fast communication is required. Two experimental tests were done in order to improve these features.

In a first step the speed of wireless communication was tested using two different modules, XBee and Bluetooth: technologies usually used for building personal area networks (PANs). The comparison was meant to find the fastest wireless communication module. The maximum level accepted for the communication latency was in the order of 20 ms, which is the value for 4G mobile/cellular networks. Once the fastest communication module was found, the stability of its connection was tested with a further experiment.

A.0.1 Latency using XBee

The experiment consisted in the measure of time latency between the module connected to the PC and the module on-board, i.e. connected with TAMO3, during the phase of command reception by the TAMO3. XBee is a wireless mesh network standard operating in the industrial, scientific and medical radio (ISM) frequencies, in particular at 2.4 GHz. The module used in the experiments was XBee 802.15.4 and the association was made between two of them: one connected to a computer via USB cable and the other to the TAMO3 by means of a connector integrated in the board. The test consisted in sending one command to the XBee placed on the TAMO3 and to measure, by means of an oscilloscope, the time needed to receive it. Figure A.1 shows the result of this test: the yellow signal represents the command sent, the light blue the command received . The distance between points a and b is the time latency in receiving the command: in this case it is 7.3 ms and the average value found after 5 repetitions was 7.1 ms.

A.0.2 Latency using Bluetooth

Bluetooth is a packet-based protocol having a master-slave structure. All slaves connected to the master share the same clock. Similarly to the XBee it operates in the ISM short-range radio frequency band. The test was performed between one dongle bluetooth connected to the computer and the bluetooth module RN42XVP-I/RM inserted in the TAMO3. In this case the time latency measured was much higher than with the XBee module: the average value was 50 ms.

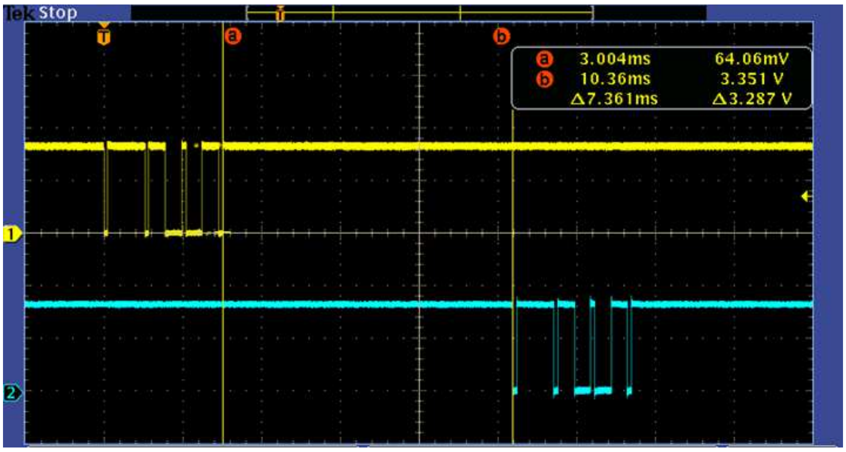


Figure A.1: Test on XBee speed in receiving commands. The yellow line is the sending command, the blue line is the command received on the board of TAMO3.

Given the superiority of XBee in terms of time latency, this technology was adopted for all the studies described in chapter 4 and its stability was analysed with the following test.

A.0.3 Stability of the XBee wireless protocol

This test consisted in sending continuously, for a fixed time (time t_2 in the Figure A.2), the same command to the servomotors of TAMO (where TAMO stands for both TAMO1 and TAMO3). The movement done by the tactor was a displacement on the z axis corresponding to an angle of 25 degrees of servomotor levers. Tactor movement was detected with the Vicon motion capture system, by means of a passive marker placed on it. A parallel port signal was used in order to precisely know when the command was sent to TAMO and when servomotors completed each movement: the signal of the parallel port was synchronized with those moments respectively represented with green and red LPT signals in Figure A.2. In the schema of Figure A.2 the time t_2 was fixed to 2 seconds and the time t_{1i} was calculated i-times during the cyclic movement. Average value of the t_{1i} was 30 ms with a standard deviation of 0.6 ms. The little value of standard deviation suggests that the variability inside a loop is negligible and thus it ensures a good and definite level of connection stability.

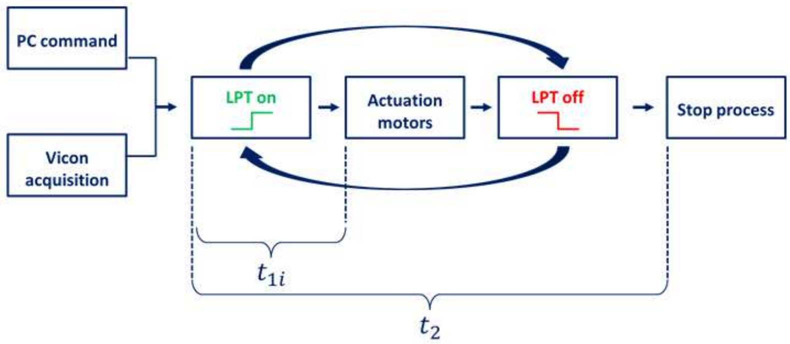


Figure A.2: Schema of stability test conducted with XBee module.

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