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Non-visual exploration of geographic maps: Does sonification help?

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Abstract

Purpose. This study aims at evaluating the effectiveness of sonification as a mean to provide access to geo-referenced information to users with visual impairments.

Method. Thiry-five participants (10 congenitally blind, 10 with acquired blindness and 15 blindfolded sighted) completed four tasks of progressive difficulty. During each task, participants first explored a sonified map by using either a tablet or a keyboard to move across regions and listened to sounds giving information about the current location. Then the participants were asked to identify, among four tactile maps, the one that crossmodally corresponds to the sonifed map they just explored. Finally, participants answered a self-report questionnaire of understanding and satisfaction.

Results. Participants achieved high accuracy in all of the four tactile map discrimination tasks. No significant performance difference was found neither between subjects that used keyboard or tablet, nor between the three groups of blind and sighted participants. Differences between groups and interfaces were found in the usage strategies. High levels of satisfaction and understanding of the tools and tasks emerged from users' reports.

Keywords: *Sonification, blindness, mental mapping, non-visual exploration, haptics*

Introduction

There is a considerable amount of information that is not available to blind individuals, in particular the information which is encoded in spatial and graphical forms (e.g., diagrams, graphs, geo-political maps). A subject that puzzles experimental research is whether the issue is limited to a problem of access to spatial information by users who are blind or whether there are also cognitive constraints in the construction of internal spatial representation for people who have never had visual experience or who have lost their vision in early infancy.

Experimental studies provide extensive evidence that blind people experience difficulties in forming mental representations of spatial structures [1–4] and that they face difficulties in spatial imagery as well as in navigating efficiently through spaces [5]. These results support the inference that visual experience is necessary to the acquisition of spatial concepts. However, there is no general agreement about the nature of spatial processing difficulties experienced by blind people. In particular, it is unclear whether these spatial difficulties are due to performance, competence, or ability deficits [1].

Several studies question this sight-centered model of spatial processing, arguing that spatial representations generated by different sensory modalities (haptic and auditory, for instance) or by verbal input are functionally equivalent to visual representations of space [6,7]. This view supports the existence of an amodal spatial representation system that receives inputs from different sensory channels [8]. According to this orientation, blind people should be able to organize functionally equivalent spatial maps using tactile, auditory, and kinaesthetic information.

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The theoretical debate that sets a crucial role for vision against a multisensory, or amodal, spatial representation is an open question [9] and has important empirical implications for designing effective assistive tools.

In recent decades, the attempts to provide easier and full access to spatial information for visually-impaired people have considerably increased. Owing to more sophisticated integrations of non-visual perceptual stimuli and conceptual information, new possibilities of information access have been developed [10]. One of the first studies addressing the issue that whether other sensory information can compensate the lack of visual experience in forming mental spatial imagery, was carried out by Kerr. She used a mental scanning task in haptic learning. The results showed a strong relation between scanning time and Euclidean distances both for sighted and for congenitally blind people, although the response times were significantly longer for blind than for sighted subjects [11]. The same chronometric performance for blind, blindfolded, and sighted participants was found by Röder and Rösler using a similar paradigm [12]. Aleman et al. by asking participants to memorize the position of a target cube in two-dimensional (2D) and three-dimensional (3D) matrices after haptic exploration confirmed that blind participants were capable of good performance, although they made significantly more errors than sighted participants [13]. Although there is encouraging experimental evidence for effective spatial mappings in absence of vision, other evidences show that blind subjects have more difficulties than sighted ones in memorizing spatial positions of target objects [14], and in maintaining different items of spatial information simultaneously [15].

Currently, the most common solution for displaying spatial information in the absence of vision is by tactile mapping. For a long time, tactile maps were the only means for communicating spatial, particularly geographical information, to visual impaired people. The design and the production of tactile maps have involved researchers from several fields: applied geographers, computer scientists and psychologists, amongst others. Since the early work [16–19], cartographers have adopted different solutions both for designing and producing tactile maps: raised inks, thermoforming, vacuum forming, etching, and accretion for tactile maps [20]. In parallel, psychological research investigated the impact of tactile mapping on the cognitive system, quantifying accessibility, identifying problems, possibilities and limitations of tactile maps also in comparison to visually presented maps. Implementations of haptic tools within virtual navigation environments provided encouraging results, as blind participants were able to generate a verbal description and a physical model of the explored virtual environment, with a general improvement of navigation performance in real space [5].

Despite their effectiveness, tactile maps showed several limitations and problems both logistically and cognitively. Firstly, tactile maps are difficult and expensive to produce, are of low resolution, and rarely reach a high level of quality [21]. In comparison with the great abundance of visual maps, the variety of raised-line maps is rather scarce. Braille labeling is also a problem in small maps where there is no enough room for labeling all the countries, regions, or features within the map. Furthermore, tactile spatial exploration is necessarily a slow serial process compared with rapid visual exploration. Another limitation concerns the possibility to represent several features together (like in geopolitical maps). Multi-feature representation in tactile maps must be addressed with caution. When maps contain too much information, the discriminability of single feature can be impaired and even localization and shape acquisition can be undermined. Clark and Clark demonstrated that simplified maps, rather than exact representations, lead to a better shape recognition [22].

In order to overcome these limitations, multidisciplinary researches have been developing new ways of accessing map information, which should be easier to learn and use by blind people.

The main alternatives to haptic technologies are audio-based systems. Recent studies have demonstrated that the auditory channel, with or without tactile stimulation, can be a useful alternative for the transmission of spatial information [23,24]. Specifically, during the last few decades sonification has been used to develop new tools for transmitting spatial information. Sonification, namely the use of non-speech audio to convey information, allows the transformation of data relations into acoustical ones in order to facilitate communication or interpretation [25]. Amongst others, sonification has successfully been used to present geographical, environmental, or census data [26]. One of the first sonification systems was the *Soundgraphs* developed by Mansur et al. [27]. *Soundgraphs* allows the presentation of line graphs in sound. Time is mapped to the x-axis and pitch to the y-axis. The shape of the graph can then be heard as a rising or falling note playing over time. Mansur et al.'s initial results were very promising as users were able to identify the types of curves very easily along with maximum/minimum points. Moreover, the system allows listeners to get an overview by listening to all data very quickly, which is not easily provided using speech. Another sonification tool, *The KnowWhere™ System*, was developed by

Krueger and Gilden to present geographic information to users with visual impairments [28]. Users' hands rested upon an illuminated surface covered with a tactile grid and monitored by a ceiling-mounted video camera. The video image was analyzed by specialized processors and the location of the user's fingertip on the light table was determined. An invisible virtual map is defined on the desk surface and the feature that the user is currently pointing to is signaled by a sound which serves to identify the feature or kind of feature that has been 'touched'. Ramloll et al. found that using non-speech sound in 2D numerical tables significantly improved the ability of vision impaired users to locate and acquire data [29]. Afonso et al. implemented a virtual environment that incorporates a high quality virtual 3D audio interface [30]. The aim was to determine how a verbal description and the active exploration of an environment affected the building up of a mental spatial representation. The authors found that active exploration was better than verbal learning in generating spatial imagery. Blind participants were able to generate correct spatial representations of an environment, although they needed more time than sighted participants.

Evidence from both theoretical and empirical research seem to converge to the idea that a combination of sound and touch will work better than a single modality in non-visual displaying of spatial information [29,31] Recently, the Human Computer Interaction Laboratory of the University of Maryland developed a new sonification tool, *iSonic*, to facilitate the exploration of geo-referenced information by users with visual impairments [32] (Figure 1). In a pilot study, the authors showed that blind users were able to recognize geographic maps by using an interactive sonification system [33]. A later case study demonstrated that blind participants could perform complex tasks using combinations of sonified tables and maps [34].

Considering multisensory integration as a promising way to improve the access to spatial information to blind people, we aimed at verifying whether or not blind users are able to generate effective mental representations of geographical information when using the *iSonic* sonification tool.

In the present study, we intended to find out, both in quantitative and qualitative terms, (1) whether sonification is a useful mean to provide accurate geo-political representations (specifically choropleth maps), and (2) whether sonified map exploration is affected by different input modalities of exploration. At a theoretical level, starting from the claim that spatial representation is not mandatorily linked to visual modality, we aimed at verifying that (1) blind subjects (congenitally or acquired) do not differ from blindfolded sighted subjects in the identification of sonified maps, and (2) blind people use different perceptual and cognitive strategies, e.g., focusing more specifically on sound information than sighted subjects.

Figure 1. The *iSonic* software being used by a user with visual impairments. As the user moved her finger on the touch-tablets stereo a sound is produced representing the value of a selected variable for the state at the finger location. Commands can be issued using the keyboard, such as an automatic sweep of all the states in a region.

Method

Participants

Thirty-five subjects, 16 females and 19 males, participated in the study (mean age $=$ 32.46; SD $=$ 6.73). The sample is comprised of three groups (10 'early blind' participants, 10 'late blind' participants and 15 'sighted blindfolded'). Subjects were considered early blind when visual acuity in their better eye was below 1/300 within the third year after birth. We considered those individuals with sight at birth, and who lost sight after age 3 as late blind. Motor performance and hearing abilities were normal in all subjects.

All participants were right-handed. Subjects were all Italians and therefore likely to be poorly acquainted with the USA geographical representations used as stimulus material.

Materials and tasks

Four sonified auditory maps and 16 tactile plastic maps were used as experimental materials. Auditory maps represented patterns of unemployment rates in

USA. The rate for each state was sonified by a musical pitch. Three levels of pitches were used, with a high pitch (G4 at 783.9 Hz) for high unemployment, a medium pitch (E4 at 659.2 Hz) for medium levels, and a low pitch (C4 at 523.2 Hz) for low unemployment rates. Patterns of three maps were of progressive complexity, from the first being clearly divided into three areas, to the third being more varied and realistic (See leftmost maps in Figure 2).

The fourth auditory map represented the Idaho state and its counties (Figure 3). For this map, the three levels of unemployments were not provided as the map was used to assess how subjects explore and represent shape, size, and external boundaries of a map, not the pattern of values.

A total of 16 tactile plastic maps (42 cm × 30 cm) were used in the four tasks of the experiment. For each task, four tactile maps were used, with one corresponding to the sonified map (target), and the remaining three being the distractors. The distractor maps, identical in shape to the target, vary only in their pattern of unemployment (see the smaller maps in Figure 2). In order to control whether subjects were able to detect subtle variations we also included distractors presenting patterns very similar to the target's one.

State and county borders consisted of embossed lines. For the first three tasks, three different textures represented the three categories of the value (rate of unemployment) on the tactile maps: dotted texture was equal to high value, herringbone texture to medium value, and striped texture to low value (see the picture in Figure 4 for an example).

For the fourth task, four tactile maps of four different states were used: with one target map corresponding to the sonified map (Idaho see Figure 3), and the three distractors (New Hampshire, Utah, and Washington). The tactile maps represented the general shapes of the states. There were no textures inside the counties of the four tactile maps.

A paper questionnaire was given at the end about user satisfaction and general understanding of the tools and tasks.

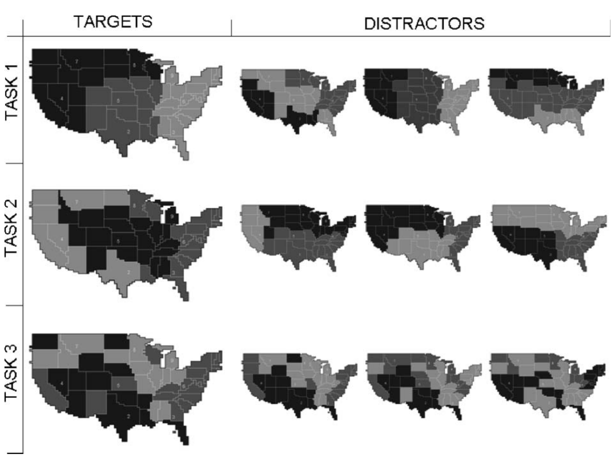


Figure 2. Maps of unemployment patterns across the USA. The unemployment value is represented by different shades of grey (the darker, the higher). In the sonified maps users would hear a high pitch tone for high values and lower pitch tones for the lower values.

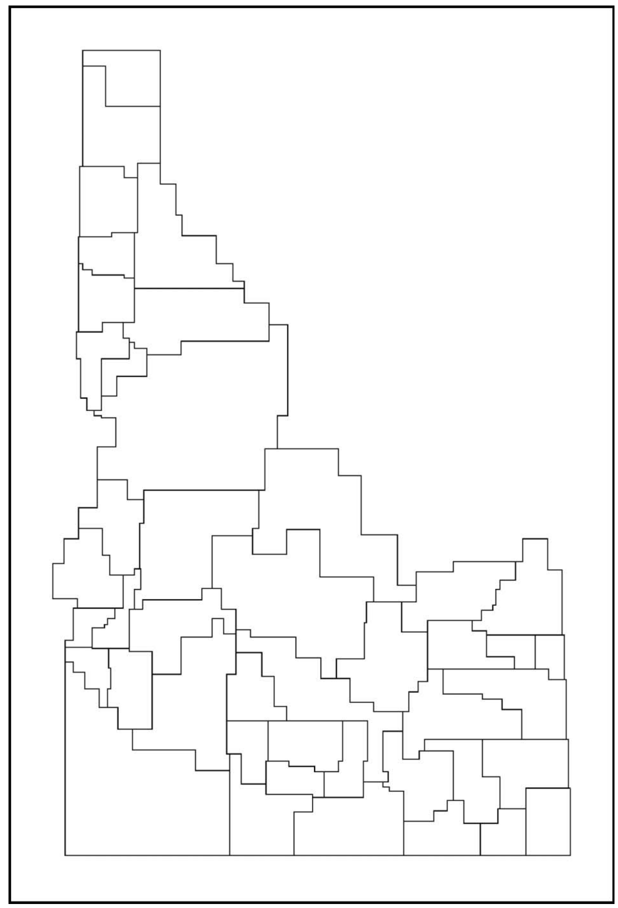


Figure 3. Auditory map of Idaho shape. The map is blank.

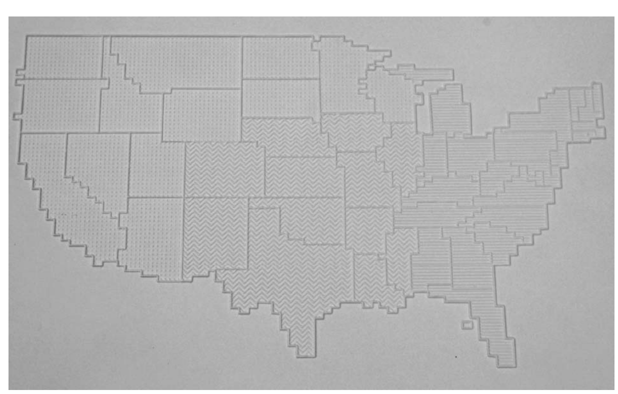


Figure 4. An example of tactile maps with different textures representing the three values of unemployment rate.

Apparatus

Map exploration was conducted using an operational interactive software, *iSonic*, an environment to assist users with visual impairment in exploring geo-referenced data using coordinated maps and tables, augmented with nontextual sounds and speech output [34]. Only a fraction of the features of *iSonic* were used to conduct this study. In *iSonic*, different pitches of a violin timbre indicate different levels of the chosen variable (such as scholarization, unemployment, or crime rate statistics). Stereo sounds provide information about the left–right location of the geographical area. Table I lists the sonification features of *iSonic* that we used.

iSonic can be operated using two input devices: a computer keyboard and a touch-tablet. The keyboard interface allows a combination of techniques to navigate the map. Users can perform the following actions: start an automatic sweep to obtain a quick overview of the data patterns; perform a relative navigation using arrow keys to move from one region to the neighboring ones; use the numerical keypad to explore the 3×3 zones into which the map is divided (see Figure 5), with pressing 1 to play the left-bottom zone, pressing 9 to play the right-top zone, and so on; request details of a data item (e.g., the name of the current state). The modality of keyboard exploration was structured as shown in Table II.

The touch-tablet interface allows users to point to and explore the display in a more direct way: when users touch the smooth surface they hear the sound whose pitch indicates the value for the region at the finger position. They can also drag their finger on the surface and hear as a continuous sound plays when their finger moves within the region. The sound stops when the user lifts her/his finger. When the finger crosses a region border, a border sound is played. Another sound is played when the user moves outside the map. In both interfaces, by pressing ‘0’ on the number pad (as shown in the Table II) participants could hear a sweep of the entire map.

The two interfaces show important differences: keyboard exploration could be defined as qualitative, discrete, and symbolic whereas touch-tablet exploration as quantitative, continuous, and analogical. More precisely, keyboard exploration is: qualitative, because it informs about the state values; discrete, because it progresses by means of all-or-nothing steps; symbolic, because arrow-keys typically move in only four directions. In contrast, the touch-tablet interaction is: quantitative, because each movement gives information about shape and size of each state; continuous, because it keeps informing users also when they stay still on a spot; analogical-proprioceptive, because the movement of a part of the body mirrors an analogous movement on the map.

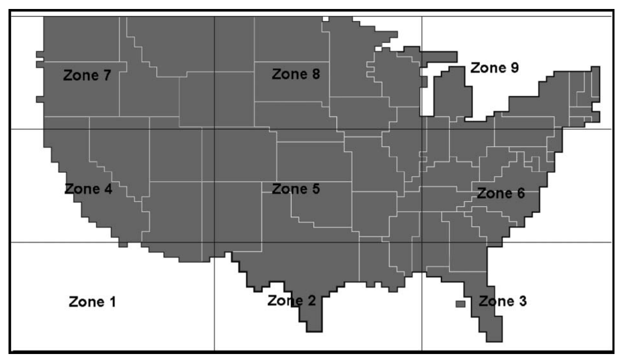
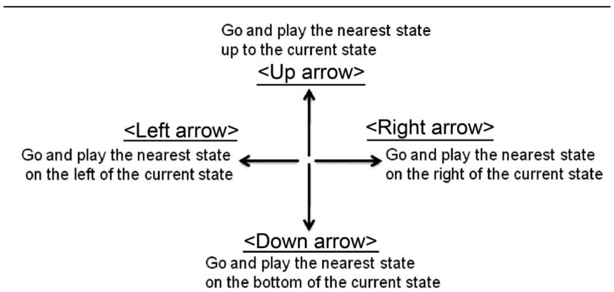


Figure 5. Participants were asked to indicate which level of unemployment (low, medium, high) was the most represented within each one of the nine above depicted map zones.

Table I. Sound and their corresponding parameters.

Sound parameter	Map feature
Violin pitch	
High	state with a high level of unemployment
Medium	state with a medium level of unemployment
Low	state with a low level of unemployment
Single click	region border
Fret guitar	background (area out of the map borders)
Stereo panning (relative loudness of left and right channels)	Horizontal eccentricity (position on the left-right axis)

Table II. Keyboard exploration.



<0> →	Play an automatic sweep of all states, proceeding rightwards from the up-left corner position to the bottom-right corner position
Number pad from 1 to 9 →	Play an automatic sweep of those states pertinent to one of the 9 quadrants in which the map is divided

Procedure

Each experimental session was conducted in a soundproof and dimly lighted room and lasted for ~1 h and 30 min. The whole session consisted of three phases: a pre-experimental phase, the experiment, and a post-experimental questionnaire. Subjects were randomly assigned to either the keyboard or the touch-tablet interface condition.

In the *pre-experimental phase*, participants were tested for their basic auditory discrimination abilities with an auditory localization task and a pitch discrimination task. Then, in a training session of about 10 min, they could explore sonified training maps (different from the ones used in the experimental tasks) to practice with the interface and the logic of the experimental tasks.

In the *experimental phase*, subjects performed four tasks. Each task consisted of auditory exploration, tactile recognition, and questionnaire filling. The interface condition (keyboard or touch-screen) for the exploration depended on the experimental group each subject was assigned to. Subjects were instructed to explore the sonified map in order to learn the overall data pattern. The first three tasks were to explore the patterns of unemployment rate across states. The fourth task was to explore the general shape of the map. The purpose of the first three tasks was to investigate the exploration and representation of geo-referenced data patterns on maps, whereas the fourth task was designed for assessing how subjects explore and represent shape, size, and external boundaries of the map. For each task, immediately after exploring the auditory map, subjects were presented with four tactile maps, one target and three distractors. Subjects were invited to rate each of the four tactile maps for its correspondence with the sonified map, along a scale ranging from 0 to 10 (0 standing for 'no correspondence at all' and 10 standing for 'perfect match'). Finally, participants answered questions about the distribution of values across the states (for task1, 2, and 3), or about the approximate shape of the map (rectangular, L-shaped, triangular, squared, circular, or rectangular) and the number of regions (for task 4). There was a 5-min break between the tasks.

In the *post-experimental phase*, participants answered a questionnaire about their satisfaction and understanding of the tool and tasks, based on a 6-point Likert scale (from 0 completely in disagreement to 6 completely in agreement). The questionnaire covered the following aspects: pitch sound detection, usefulness of stereo-panning, map shape discrimination, discrimination of the shape of the regions inside the Idaho map and their numerosity, understanding of unemployment level distribution, software usability, software easiness, pleasantness of the software.

Results

Accuracy

During each task, we asked participants to rate (from 0 to 10) the level of matching of each one of the four tactile maps with the sonified map they explored. Only one of the tactile maps (target) matched the sonified map, whereas the other three were distractors.

An analysis of variance was performed for each one of the four tasks, using the factor map(target and three distractors) as the independent within-subjects factor. High rates of matching between the target tactile map and the sonified map (mean = 7.30, SD = 0.14) and low rates of matching between distractors and the sonified map (mean = 3.75, SD = 0.49) indicated high accuracy.

The effect was significant in all four tasks with the following values: $F(3, 102) = 19.33$, $p < 0.01$ in task 1, $F(3, 102) = 14.08$, $p < 0.01$ in task 2, $F(3, 102) = 12.40$, $p < 0.01$ in task 3 and $F(3, 102) = 25.03$, $p < 0.01$ in task 4. The *post hoc* analyses (Fisher's LSD) showed that in all tasks the target tactile map was rated higher than all distractors. Considering that the differences between the patterns of target and distractors are in some cases very subtle (see for example the second distractor map of task 1 and all the distractors of task 3 in Figure 2), subjects demonstrated to have a clear representation of the unemployment pattern of target maps.

A separate analysis was conducted considering Interface (keyboard or touch-screen) and the Group (sighted *vs.* late blind *vs.* early blind subjects) as between factors and Task as within factor. The algebraic difference between the target tactile map matching rates and the distractors map matching rates was used as a measure for subject's accuracy. This measure was the dependent variable of the analysis.

The results showed that congenitally blind, acquired blind, and sighted blindfolded subjects did not differ in discriminating targets in all four tasks: $F(2, 29) = 2.25$, $p = 0.12$.

Regarding the influence of the interface, the use of keyboard or touch-tablet during the exploration did not lead to significant differences in discriminating targets from distractors: $F(1, 29) = 0.075$, $p = 0.78$.

The influence of TASK is not significant, $F(3, 87) = 1.39$, $p = 0.25$, indicating that the discrimination of target maps from distractors was of comparable difficulty in the four different tasks.

Questionnaire

After each one of the first three tasks, subjects were asked to report the level of value (low, medium, high unemployment, or water/background) that was the most represented in each one of the following nine zones of the map:

For task, four subjects were asked to estimate the number of regions included in the map. Subjects were particularly accurate in the first task (about 80% of correct identification), in which the levels of unemployment were clearly organized in three big patterns, while in tasks 2 and 3, where the spatial organization was more complex, they performed progressively more poorly (62% and 53%, respectively). A one-way within ANOVA confirmed that this difference is statistically significant $F(2, 16) = 8.34$, $p < 0.01$. Task 1 differed from task 2 and task 3 which in turn did not differ from each other (*post hoc* Fisher's Least Significant Difference (LSD): $p < 0.05$).

We did not find any difference, $F(2, 24) = 1.7$, $p > 0.05$, in the percentage of correct identification of values into quadrants among sighted, congenitally blind, and acquired blind subjects.

Interestingly, in task 4, when subjects had to estimate the number of regions inside the map, there was, in all conditions, a general tendency to underestimate the number of regions (mean = 25.02; SD = 14.02), reporting < 44, the actual number of Idaho counties.

Final questionnaire

After all tasks were completed, participants answered a set of questions (Likert-scale from 0 to 6) regarding the general features of the task and the sonification tool. A two-factor between-subject ANOVA was performed, considering *Interface* and *Group* as independent variables. Table III shows the complete list of the questions and the level of significance both for *group* and *interface* factors.

Subjects reported high levels of understanding and satisfaction of the tool and the tasks, even though less in the more specific aspects and features of the maps (particularly for the number and shape of regions and general shape of the maps). We found no statistically significant difference between sighted and blind participants and between the two interface groups except for a few exceptions. Regarding the stereo panning feature, (which set the proportions of the left and right signal amplitude as a function on the position of the source), blind subjects paid more attention to stereo panning than sighted participants. Both groups of blind subjects reported being helped by the stereo panning more than sighted subjects (*post hoc* LSD: $p < 0.05$).

The groups differed also in their perception of the easiness of the interface: blind subjects (both early and late blind) rated the interface higher for ease of use than the sighted participants, probably due to their experience with non-visual interfaces.

Finally, no significant difference was found in blind and sighted subjects' answers about the effectiveness of the interface.

Exploration modalities and strategies

From the log files of tasks 1 and 3, the easiest and the hardest tasks respectively, we extracted several quantitative parameters to analyze modalities and strategies of exploration.

Regarding the number of steps, (where step is defined as a move from a state to another), the data showed that touch-tablet users performed more steps than keyboard users (295 *vs.* 118, respectively in average). This difference is significant, $F(1, 43) = 17.66$, $p < 0.001$. The higher number of steps performed by touch-tablet users is reflected in higher exhaustivity, measured with the percent number of states explored. In fact, we found that touch-tablet users explored more states (83.20%) than keyboard users (62.98%), and this difference is significant, $F(1, 39) = 27.93$, $p < 0.001$. There is no significant influence of *group* either on the number of steps, or on the exhaustivity of exploration. However, grouping together late blind and sighted participants, they showed greater exhaustivity than those early blind, $F(1, 41) = 4.49$, $p < 0.05$.

Table III. Questions and significance level of the final questionnaire.

Question	Rate (from 1 to 6)	Group	Interface
It is easy to distinguish the different sounds	5.1	$F(2,29) = 0.26$, $p = 0.76$	$F(1,29) = 0.00$, $p = 0.99$
Stereo panning is useful for the orientation	4.6	$F(2,29) = 6.22$, $p = 0.00$**	$F(1,29) = 1.10$, $p = 0.30$
The shape of the maps is clear to me	3.7	$F(2,29) = 0.18$, $p = 0.83$	$F(1,29) = 0.63$ $p = 0.43$
The shape of the single regions was clear to me	3.7	$F(2,29) = 0.18$, $p = 0.83$	$F(1,29) = 0.63$ $p = 0.43$
The number of the region into the maps was clear to me	2	$F(2,29) = 0.02$, $p = 0.97$	$F(1,29) = 0.47$ $p = 0.49$
I could understand the distribution of the level of unemployment during the exploration	4.2	$F(2,29) = 1,96$, $p = 0.15$	$F(1,29) = 0.04$ $p = 0.83$
The tool is easy to use	5.4	$F(2,29) = 4.05$, $p = 0.02$*	$F(1,29) = 1.54$ $p = 0.22$
The tool is fun to use	4.4	$F(2,29) = 0.98$, $p = 0.38$	$F(1,29) = 8.8$ $p = 0.00$**
The tool is easy to learn	5.1	$F(2,29) = 1.53$, $p = 0.23$	$F(1,29) = 1.61$ $p = 0.21$

*The levels of significance at 0.05.

**The levels of significance at 0.01.

We analyzed whether participants tended to exhibit linear movements by keeping a clear direction for more than two steps and whether they maintained specific directions while moving. The percentage of 'keep-a-direction steps' on the total number of movements is high (54.69%). Through a uni-factorial ANOVA, considering *keep* (percentage of steps that does not change direction for at least two movements) as the dependent variable and interface as the between factor, we observed that keyboard users tended to keep a direction more than touch-tablet explorers, $F(1, 39) = 17.64$, $p < 0.001$. There was not a significant influence of group on *keep*, $F(2, 39) = 2.01$, $p > 0.05$.

There was significant preference for specific directions, $F(3, 117) = 8.43$, $p < 0.001$. The *post hoc* analysis showed that rightward movements (39.31%) were the most performed, followed by leftward movements (30.60%), whereas downward (18.08%) and upward (11.99%) movements were performed less frequently. There was no influence of the group on the direction preference, $F(6, 117) = 1.96$, $p > 0.05$, but there was influence of the interface, $F(3, 117) = 8.43$, $p < 0.001$. As shown in Figure 6, while touch-tablet users showed clear preference for rightward movements (which in the *post hoc* is significantly higher than all the other directions), keyboard users showed that they prefer horizontal movements (both rightward and leftward) to vertical ones (both upward and downward).

Discussion

In all four tasks, participants showed high accuracy in recognizing the tactile map corresponding to the sonified map explored. This result indicates that, at least to some extent, auditory stimulation can be effectively used to present geo-referenced information. Considering the abovementioned limitations of traditional tactile maps, our findings have relevant empirical implications for the accessibility of blind individuals to geopolitical data and, more in general, to spatial information.

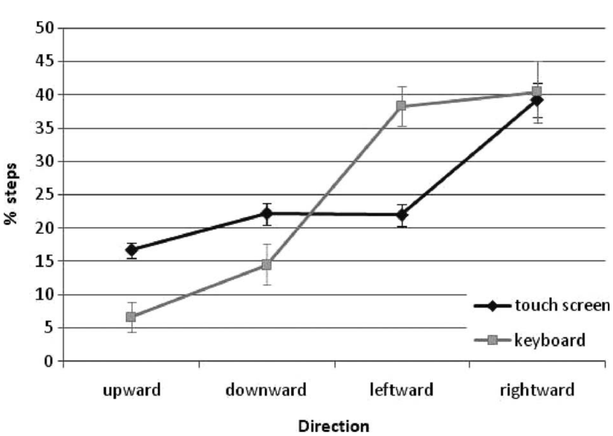


Figure 6. Percentage of movements towards the four directions in function of the interface.

Considering the differences between blind and sighted subjects, according to the hypothesis that claims that vision plays a crucial role in setting up spatial mapping during a critical or sensitive period of development [35], we would expect early blind subjects to perform poorer than late blind and blindfolded ones. However, our results go against this theoretical expectation, suggesting the possibility of equivalent performance of blind and sighted subjects in spatial representation and orientation obtained through modalities other than vision. In fact, the three groups do not differ in performing the map recognition task. Our results are consistent with the hypothesis of an equivalence between sensory modalities in transmitting spatial information [6,7] and with the amodal theory of spatial representation [8,36].

Nevertheless, we should consider that subjects, both sighted and blind, had difficulties in recognizing specific details of the map. In particular, all participants had difficulty remembering the distribution of the values in complex patterns (task 2 and task 3) and the number of regions inside a map (task 4). In accordance with experimental evidence, it seems that sonification, like other non-visual display tools [37], at least in its present modalities, is more indicated for navigating and learning the macro-structure of a spatial configuration than for transmitting spatial details. The latter would require a higher engagement of working memory. Moreover in the specific case of our experiment, the mandatorily sequential information acquisition may have progressively shadowed previously acquired details. Future research has to take into more direct account the relationships between display characteristics and cognitive processes involved in task exploration.

Regarding the relative effectiveness of the two interfaces, we found that touch-tablet and keyboard users showed no significant difference in the performance. Both *keyboard* (exploring the map by moving step-by-step with the arrow keys) and *touch-tablet* (exploring the map by touching the screen with a finger) exploration seem to lead to an effective overall spatial representation. Consistent with the amodal theory of spatial representations [8,36], this result supports that different perceptual experiences may result in comparable representations of the same spatial configuration. However, the presence of representational differences, not detectable at a performance level, cannot be excluded.

Some differences in strategies and modalities emerged from the log file analysis. Touch-tablet users performed more steps than keyboard ones, moving faster along the map. This data could be due to the positional spatial feedback in proprioceptive exploration (by touch-tablet) which is lacking in discrete exploration (by keyboard). It seems that a more direct, analogical, on-line spatial processing is guaranteed by touch-screen and that keyboard exploration, being strictly symbolic and discrete, requires a more conspicuous working memory involvement for reconstructing the position after each step. Exploring by arrow keys requires spatial reasoning, thus it is slower. It is possible that the greater cognitive effort with the keyboard interface may have an effect on the duration of learning. This aspect needs further investigation. Keyboard users also tended to be less exhaustive and may have missed some parts of the map when moving by discrete steps through states with irregular shapes. The fact that arrow exploration is discrete, symbolic, and less sensitive to irregularities leads keyboard users to keep a specific direction more than touch-tablet users. On the contrary, touch-tablet exploration, which provides information about the shape of states, can promote a more dynamic exploration behavior, and consequently, more frequent changes of direction.

Data show that there was a general preference for rightward movements. In particular, touch-tablet users preferred to move to the right more than the other directions and this may be tied to hand lateralization and reading direction that is a well acquired way of processing space and acting in it by both blind and sighted individuals. Keyboard users, instead, showed a general preference to horizontal movements (both rightward and leftward). It must be noted that the two keys (rightward and leftward) are on the same row and may allow rapid backward/forward control along the writing direction while the hand maintains the same posture.

To summarize the analysis of exploration modalities and strategies, the touch-tablet interface seems to foster better exploration compared with the keyboard interface. With proprioceptive cues, the touch-screen interface allows subjects to have constant awareness about the current exploration position. On the contrary, with the keyboard interface, subjects were forced to construct a mental mapping by maintaining in memory and interpolating a large amount of data that are only partially present and mostly extracted by previous positions. Moreover, the lack of information could cause shape and location distortions in subjects' mental maps. In fact, as subjects had no information about state size, they could tend to normalize the dimensions of each state, and as a consequence, to misplace the centre of the map. This problem is particularly relevant in cases like the USA map, considering the concentration of small states in the North-East and the presence of the biggest states in the South-West, distribution unfamiliar to Italian subjects. Another limitation of keyboard exploration is that the absolute position is only obtainable by the rehearsal of the previous steps while with the touch-tablet it is immediately inferable following the proprioceptive feedback. However, a possible advantage of keyboard exploration is that it allows a simpler categorization of the map division into states. For example, it is easier to categorize the number of states along the left–right and bottom–up axes. Obviously this is an advantage only for regular maps. On the contrary it seems that touch-tablet is more adapted for exploring more complex maps and for detecting finer scale details.

Regarding the influence of vision in exploration modalities and strategies, we did not find differences between early blind, late blind, and blindfolded subjects: the equivalent performances by our three groups are further evidences for the amodal theory of spatial representations [8,36].

When rating the efficiency and the manageability of the sonification tool and the tasks, our subjects reported high levels of understanding and satisfaction, even when they had difficulties in comprehending some specific features of the maps. We noticed that blind subjects reported to be helped by the stereo-panning more than sighted subjects. This result is comprehensible, as, thanks to their experience, blind people pay more attention to non-visual environmental information and perform better than sighted people in sound localization [38,39]. Groups differed also in their perception of the easiness of the interface. Blind subjects (both early and late ones) rated the tool easier to use than sighted ones. This could again be due to their previous greater experience and attention with non-visual events and environments.

Conclusion

To conclude, the sonification tool *iSonic* is useful to transmit geo-referenced information in the absence of visual information confirming the hypothesis that visual experience is not necessary for an efficient spatial cognition [40]. Consistent with Millar [1], our results show that different senses are able to transmit spatial information, as spatial representations are not necessarily linked to any specific sensory modality. However, all participants, both blind and sighted, found difficulties in acquiring fine details of sonified maps. Such difficulties seem to be linked to the greater amount of time necessary to acquire data by touching and hearing, compared with by seeing and to a heavy working memory load [41,42].

Touch-screen exploration seems to be preferable to keyboard exploration for several reasons: among others, it allows direct integration between haptic-spatial cues and sonification, promotes more exhaustive explorations, causes less representational distortions than keyboard, and finally is considered by users as easier and funnier than keyboard.

Future research

The results, limited by the specificity of the empirical applied research and by the use of a restricted ecological cartographic pattern, should be generalized by further studies. The design of more articulated experimental paradigms implying a controlled manipulation of number, size, and shape of states inside the map could improve the external validity. Moreover, finer grained dependent measures allowing a finer description of how the spatial patterns and mentally represented are needed.

Despite of the limited generalizability of our data, this research confirms the importance of multimodal integration in the transmission of spatial information. In fact, jointly with evidence from both theoretical and empirical research, our research supports the idea that a combination of sound and touch will work better than a single modality for non-visual display of spatial information. In particular, the dynamic integration of auditory and haptic capabilities could represent a new frontier for the study of new effective non-visual displays allowing users to access spatial information in more flexible ways.

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