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Development of Navigation Skills through Audio Haptic Videogaming in Learners who are Blind

Jaime Sánchez
(Department of Computer Science and Center for Advanced Research in Education (CARE)
University of Chile, Santiago, Chile
jsanchez@dcc.uchile.cl)

Marcia de Borba Campos
(Faculty of Informatics, Pontifical Catholic University of Rio Grande do Sul – PUCRS
Porto Alegre, Brazil
marcia.campos@pucrs.br)

Abstract: This study presents the development of a video game with audio and haptic interfaces that allows for the stimulation of orientation and mobility skills in people who are blind through the use of virtual environments. We evaluate the usability and the impact of the use of an audio and haptic-based videogame on the development of orientation and mobility skills in school-age learners who are blind. The results show that the interfaces used in the videogame are usable and appropriately designed, and that the haptic interface is as effective as the audio interface for orientation and mobility purposes.

Keywords: haptic and audio interfaces, orientation, mobility, people who are blind
Categories: H.3.1, H.3.2, H.3.3, H.3.7, H.5.1

1 Introduction

For people who are blind, navigation through unfamiliar spaces can be a complex task compared to a sighted person. In order to achieve orientation & mobility (O&M) [Sánchez, 10], people who are blind need to use other resources to receive feedback from the environment, such as sounds or textures.

Blindness is not synonymous with difficulty in navigation. As the collection of environmental information in the blind is based on different sensory channels than sight, the integration of this information is different when creating mental representations of the environment. For example, learning the environment through touch means having to rely on sequential observations and building a mental image from its components and not from the whole. In general, people with visual disabilities, properly trained, are able to navigate and have a representation of the environment. In the case of blind children, whose learning process of O&M skills is in development, it may be difficult to process spatial information if they have not had enough experience to determine their own position and relationship to objects using the rest of their senses.

Various virtual environments have been designed in order to train people who are blind, and to assist them with the development of O&M skills [Lahav, 08][Lumbreras, 99][Sánchez, 09b]. To navigate through an environment it is necessary to have access to the information that can be recovered from the environment, in order to then filter out useful information in a way that is coherent and comprehensible for whoever needs it. It is for this reason that in the case of people who are blind, the use of virtual environments and appropriate interfaces allows them to improve their O&M skills [Sánchez, 09a]. This kind of interfaces can be, for example, haptics or audio based. Such resources can also be used for recreational purposes.

Overall blind children learn their environment using their own perception and experience. A factor in this learning is the motivation to interact with the environment and explore their physical properties [Warren, 94]. From small suggested receive O & M training to develop skills that enable them to travel safely and efficiently. Since they are small it is suggested that they receive O&M training to develop skills that enable them to travel safely and efficiently.

Due to the impossibility of obtaining information through sight, people who are blind must employ other senses, such as touch, in order to be able to perceive their surroundings [Lutz, 06]. In this way, it has been possible to establish two categories of perceptions used by people who are blind [Ballesteros, 93]: (i) Tactile Perception, which is information perceived exclusively by the skin, and (ii) Kinesthetic Perception, which is information provided by muscles and tendons. The combination of both concepts, in order to benefit a person who is blind regarding the acquisition of information, is called haptic perception [Ballesteros, 93] [Oakley, 00].

[Jütte, 08] discusses the use of haptic perception in health-related applications, citing for example the development of prosthesis for patients with spinal cord injuries, which can result in an extended reach of the human hand. In the case of people who are blind it is possible to simulate, through a virtual environment, a return to what was originally based on visual channels, providing a perception of space as the user interacts with the application.

Unlike the sense of sight, the functionality of haptic perception lays in the codification of the various properties of elements, objects and substances such as hardness, texture, temperature and weight. Such properties are difficult to quantify through the sense of sight [Travieso, 07].

Haptic interfaces have been provided through the use of devices that are capable of creating feedback through interaction with muscles and tendons [Lahav, 08]. This provides for the feeling of applying force over a certain object [Lahav, 08]. More recently, research on haptic interfaces has become increasingly relevant, and in particular the use of the Novint Falcon device with videogames for training and rehabilitation has enjoyed growing attention [Reuters, 09]. This device is reasonably useful for representing virtual environments, and provides force feedback in such a way that when it is used the user can feel the volume and force of a virtual object in his hand [Sánchez, 09b].

Several studies [GauBert, 11][GauBert, 12][Heller, 01][Norman, 04] have sought to compare vision with haptic perception, showing that for the perception of properties that are visible, such as a bumpy texture or porosity, haptic perception is able to match or even overcome visual perception in terms of specificity [Travieso, 07][Hu, 06], and match it in the spatial perception of objects [Rosa, 93]. From this it can be gathered that the use of haptic perception is feasible as an alternative form of providing contextual information on volumes and objects [Sarmiento, 03].

There are several studies that include the use of haptic perception by people who are blind in various contexts [De Felice, 05][Homa, 09] [Huang, 09] [Murphy, 07] [Yu, 00][Yu, 03]. In the context of O&M, one study is that of [Lahav, 02], who presents and evaluates an application that allows for the construction of a virtual environment based on the design of a layout formed by using geometric shapes. Once the design phase has been concluded, the user who is blind can interact with the virtual environment thanks to the use of a haptic device. The user takes on an aerial perspective of the environment, for which reason the feedback that the user receives is equivalent to having a hard model of the environment and tracing possible paths by using a pencil, in which collisions are transmitted through the sense of touch [Lahav, 02]. The use of the haptic perception as a strategy for understanding visual information was also discussed by [Kim, 10], who points to the importance of the idea that the heterogeneous needs of users must be considered in the design of assisted technology. This author researches the individual differences between various users' capacities for the use of haptic perception, mainly related to age differences and visual disability. She also discusses more accessible and applicable design approaches for users with visual disability based on haptic user interfaces.

Another alternative for providing information to people who are blind is through audio-based interfaces. Through the use of audio-based cues, a person who is blind is able to locate objects of interest in the same way as a sighted person [Crossan, 06]. This kind of interface requires careful design, as it is necessary to assure that the end user does not feel saturated by an excessive amount of information [Loomis, 05]. One example of audio-based virtual environments can be seen in the videogame AbES [Sánchez, 09b]. This videogame expands on the concept of the fictitious corridors used in its predecessor AudioDoom [Lumbreras, 99], in order to generate an audio-based virtual representation of real environments, thus serving as a videogame that allows for O&M training [Sánchez, 09b]. Together with a three-dimensional interface, the use of audio allows to increase the potential for various forms of interaction between the user and the computer. [Frauenberger, 03] presents an audio-based virtual reality system that allows the user to explore a virtual environment using only his sense of hearing. [Jain, 12] performed empirical evaluations of various approaches through which spatial information on the environment is transmitted through the use of audio cues. Audio-based applications are also being developed for mobile devices with users who are blind as the target audience. One example of this is a puzzle game in which the pieces with images originally used for puzzles are replaced with randomized musical patterns [Carvalho, 12].

The purpose of this work was to investigate whether the use of an audio and haptic-based videogame has an impact on the development of O&M skills in school-age learners who are blind. To attain this goal, it was necessary to design, implement and evaluate the usability of Audio Haptic Maze (AHM), an audio and haptic-based videogame. We also conducted a cognitive evaluation to determine the impact of AHM on the development of O&M skills in learners who are blind.

2 Audio Haptic Maze

Audio Haptic Maze (AHM) is a videogame based on AbES [Sánchez, 09b], and was designed for use by users who are blind either autonomously or with the supervision of a facilitator in contexts of research and practice. The game includes the use of both audio and haptic-based interfaces, that can be used either together o separately. AHM is a first-person videogame in which the user must escape from a maze. In order to fulfill the mission, the player must find treasure chests dispersed throughout several corridors and rooms in the maze, which contain keys and treasures. The keys have geometric shapes that correspond to certain doors in the maze. The user must pick them up and try them out one at a time, until he identifies which key can be used to open the doors needed to get out of the maze. In order to add another entertaining component to the game, the score of the game increases with each treasure that the player finds. The time that the player takes to get out of the maze is also a factor, in which the less amount of time taken implies a higher score.

The entire process for the design and development of AHM was based on a user-centered design methodology [ISO, 99], working directly with the end-user and making the user an active participant in the design through interactions, conversations, interviews and end-user usability evaluations. The researchers' entire range of abundant team experience regarding interface design for children who are blind was also used in this design process.

AHM is based on a model for implementing educational software focused on children with visual disabilities [Sánchez, 04]. The model is centered on providing facilities for evaluation purposes and prompting feedback from the end user. It also clarifies similarities and differences between software for people with and without visual disabilities, for implementation purposes.

2.1 Development

The videogame was developed utilizing C++ language in the Microsoft Visual Studio .NET 2010 development environment, in which GLUT libraries were used for the graphic display, OpenAL for the use of spatial audio, and the SDK of the Novint Falcon was used to generate haptic feedback.

In order to execute the videogame, a computer with an Intel Core2 Duo processor or higher is needed, with 2GB of RAM and a 16MB graphic card, with at least 20MB of free space on the hard drive for installation. It is necessary to have an audio output for stereo headphones and a free USB port in order to connect the Novint Falcon to the computer from which the videogame is executed.

2.2 Interfaces

AHM includes different interfaces in order to provide feedback to the user and information to the facilitator.

2.2.1 Graphic Interface

The Graphic Interface, used by the facilitator, represents the current state of the game, using a third person perspective to show where the user who is blind is in real time. Fig. 1.i represents a screenshot of the graphic interface of AHM with the elements that can be found on the map, in which: (A) represents a treasure chest, which can have a key or a treasure inside; (B) represents the character controlled by the user; (C) represents a door in the maze. Fig. 1.ii illustrates a user who is blind interacting with the videogame.

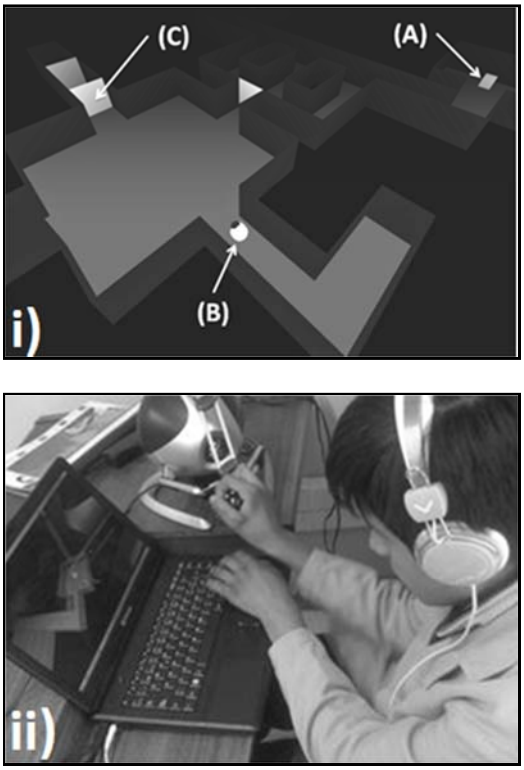

Figure 1: i) AHM graphic interface, used by the facilitator. ii) A user who is blind interacting with the videogame

2.2.2 Audio Interface

The Audio Interface is utilized by the user who is blind. AHM uses spatialized sound to represent the ambience of the corridors. For example, if the user has a corridor to the left, he can hear an ambience sound through the left-hand channel. The same kind of interaction is possible with other objects such as doors and keys, which are also represented by certain audio cues. All of the actions in the virtual environment have a particular sound cue associated to them. For example, if the user walks, a step sound cue can be heard. Examples of other possible actions are to bump into an object, turn in a specific direction, and pick up an object. In addition to this audible feedback, verbal audio is used to indicate certain situations. For example, when the user picks up a key, the context of the game changes, and the user is informed through verbal audio so that he can now listen to a sequence of beeps indicating the number of vertices on the key.

Through the audio description, the system transmits information on the environment that would normally be understood visually in real time. This procedure aids the users in creating points of reference, that help him to determine places and objects, as well as the distribution of these objects throughout the virtual environment.

Based on this information, the user is able to construct a mental map of the AHM environment.

2.2.3 Haptic Interface

The Haptic Interface is utilized by the user who is blind. By using the haptic device, the user can control a 3D cursor inside the virtual environment. All of the audio-based feedback is emulated by using haptics. Thus, haptic textures are used to represent distinct objects on the map, so if the user touches a wall with the 3D cursor, the haptic feedback of that object's texture will be different compared to that associated with touching a door. Also, the user will be able to identify shapes within the map. Regarding the feedback for actions, like walking or turning left or right, force feedback is applied, such as a vibration in the direction of the user's movement. In this way, if the user decides to walk forward, there is a vibration to the front and corresponding vibrations to either side if the user turns left or right. In this way, the audio-based information is complemented by haptic perception, facilitating the user's interaction with the system/environment.

2.3 Interaction

The interaction with the videogame is carried out through the use of a standard computer keyboard, a Novint Falcon haptic device and earphones (See Fig.1. ii).

In the case of the audio-based interface, the entirety of the user's immersion is achieved through the use of stereo sound, in order to provide information regarding the location of objects, such as walls and doors, in the virtual environment. In this way, the user can create a mental model of the spatial dimensions of the environment. In navigating, the user can interact with each of the previously mentioned elements, and each of these elements provides feedback that helps the user to become oriented in the environment.

The Novint Falcon device was used for haptic feedback, which works as a three dimensional pointer that allows for an interaction with 3D volumes, generating force feedback.

2.4 Logging actual use

During the entire process of interaction in which the user plays with the videogame, the actions taken are stored in files that can then be visualized by the facilitator through a special application called "Path Analyzer", which marks the places on the map through which the user has navigated (Fig. 2). This allows for a more complete user route analysis, session after session, in order to show the evolution of the user's movements as the various areas of the map that have been navigated are integrated into the user's mental map.

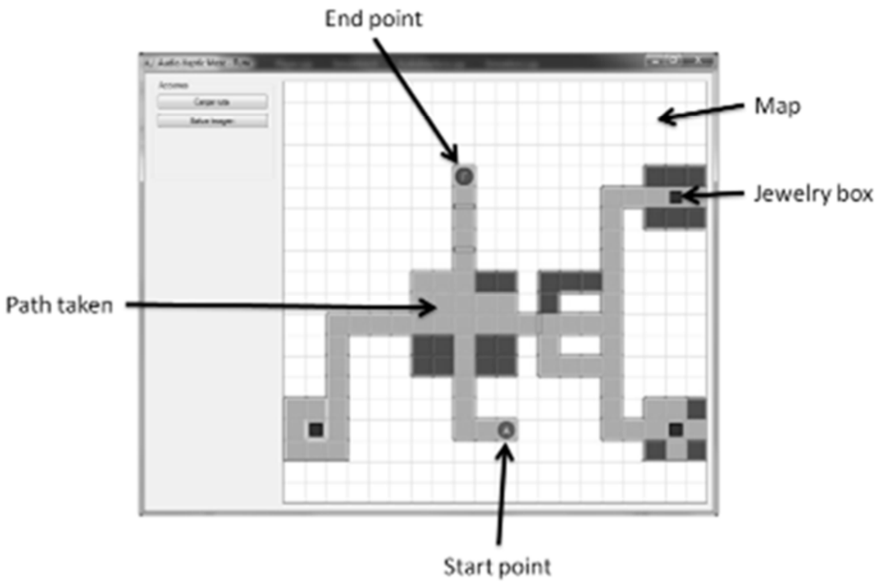

Figure 2: Screenshot of the Path analyzer application

3 Usability Evaluation

First, we conducted a usability evaluation with end users to validate the design of the game. Below is the methodology used and the results obtained.

3.1 Sample

For the usability evaluation of AHM, a sample consisting of 10 learners who are blind with ages ranging from 10 to 15 years old was selected. None of these research participants have any additional, associated disabilities other than visual impairment.

3.2 Instruments

For usability testing, several key instruments were used. The Software Usability Elements questionnaire (SUE) allows for quantifying the degree to which the audio and haptic feedback used in the videogame were recognizable. The Open Question Usability questionnaire (OQU) that was applied to the users included questions such as: Was it possible to perceive the relative position of the objects? Did you like the audio/haptic interface used for feedback in the software? The idea was to collect knowledge regarding aspects related to O&M that represent the focus of the AHM videogame, as well as regarding the use of the controls, the information provided by the software, and the user's navigation of the virtual environment. The results of this evaluation allowed researchers to redesign and improve the user interfaces. Once the corrections and redesign of the software had been carried out, Sánchez's Software Usability for Blind Children (SUBC) [Sánchez, 03] questionnaire was administered.

This questionnaire consists of 14 items for which the users had to define to what degree each item was fulfilled, on a scale ranging from 1 ("a little") to 10 ("a lot"). The results allowed for an evaluation of the software's usability according to the user's level of satisfaction, using sentences such as, "I like the software" and "The software is motivating".

3.3 Procedure

The first step was to establish an activity revolving around the usability of each of the proposed interfaces. To these ends, two 20-minute sessions were held with each user. During these sessions the users were asked to listen to a set of 40 sounds, identifying or relating the object or action that each sound represented, and focusing their attention mainly on the contextual sounds to be used in the videogame such as footsteps and bumping sounds. Also, a set of 20 high relief objects and a set of the same 20 objects with low relief were used, and users were asked to interact with these objects through the haptic device to establish the haptic characteristics regarding shape and texture, in order to identify the object or element that was represented.

The SUE questionnaire was completed by the facilitators after each work session, in order to identify which of these audio and haptic elements were easier for the users to recognize and associate. Based on these results, the most appropriate sounds and elements were selected for use in the videogame.

Afterwards, the users interacted with AHM in a 40-minute session, in which they were asked to take a path from point A to point B on the map. During this process, the facilitator observed the user's position on the map through a graphic interface in order to detect if there were any difficulties regarding their navigation, and whether or not they were able to perceive the audio and haptic elements within the maze and use them as references for orientation and mobility.

After having finished this activity, the users completed the OQU questionnaire with the help of a facilitator during a period of 10 minutes.

Finally, the users proceeded to respond to the SUBC questionnaire with the help of the facilitator, who read the questions out loud and filled in their responses. Based on the results of these questionnaires, the team proceeded to make all of the changes and redesigns that would allow for an improved version of the videogame, in order to make it even more usable.

3.4 Results

Initially, it was planned that the sounds utilized in the videogame would represent a "metallic" environment, which would create a spatial maze atmosphere in order to make the game more attractive to the students. However, according to the results obtained from the application of the SUE questionnaire for the evaluation of iconic sounds, it was observed that the sounds, which were altered in order to achieve the desired effect, confused the users. For this reason it was decided to use pure sounds.

For the usability evaluation of shapes through the use of didactical materials, the results obtained from the questionnaire showed that the students correctly identified simple geometric shapes, but had problems identifying complex shapes. In the same way, in evaluating shapes through the use of the haptic device, it was observed that the majority of the users identified regular shapes with the device, but not complex shapes. Finally, in evaluating the usability of the virtual textures represented through the use of the haptic device, the results showed that most users correctly described the textures.

When the users responded to the question “Did you like the videogame?” on the OQU questionnaire, all users answered positively, with phrases such as: “I liked the environment that the videogame generates, it is very realistic”, “It is fun to move around in the corridors and escape from the maze”. In response to the question “Do you want to add something else to the videogame?”, in general the users replied that they would like the maze to include enemies to fight against. According to the results of this questionnaire, the videogame was generally well accepted, and in the future it would be possible to consider adding other components that would make it even more attractive. One relevant aspect regarding the use of the interface based on audio and combined sounds was the users’ comments that the experience was very enriching, but not necessarily because of the ability to transmit information from the virtual environment to the user; rather they noted that, in part, the sound helped to generate an environment that is more associated with what they would expect from a videogame.

The results provided by the Software Usability for Blind Children (SUBC) questionnaire showed that AHM is usable for users with visual disability (see Fig. 3).

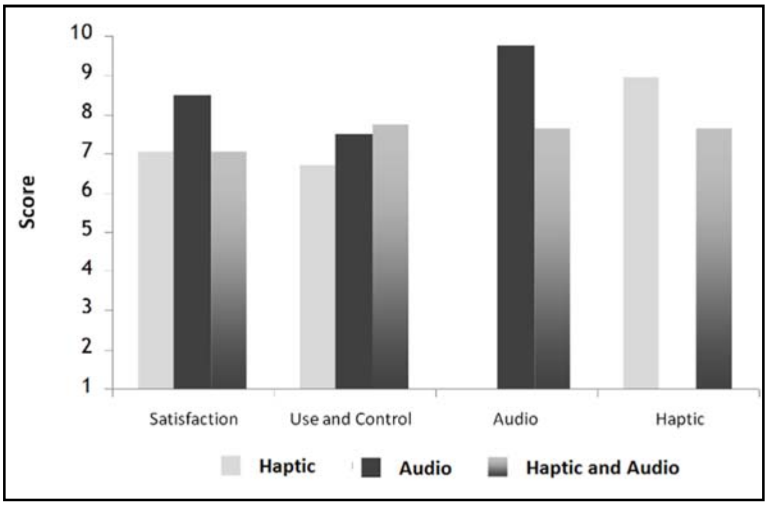

Figure 3: Results of the Software Usability for Children Who Are Blind, SUBC

In order to perform the evaluation, the three kinds of interfaces involved in the videogame were analyzed: haptic, audio and haptic plus audio. The results showed that the mean level of the “users’ satisfaction” was 7.0, 8.5 and 7.1 points respectively for each kind of interface, on a scale with a maximum of 10 points. For the “Satisfaction” category, the sentence with the highest score across the board for all three interfaces was “I would play this game again”, with a score of 7.6 for the haptic interface, 9.2 for the audio and 7.5 for the audio and haptic combined. This aspect is fundamental, as it shows that users maintain an interest in the videogame, and did not become bored too quickly. This result was consistent with the results obtained from the OQU questionnaire as well.

The “Control and Use” category obtained a score of 6.7, 7.5 and 7.8 points respectively for haptic, audio and haptic plus audio interfaces, respectively, on a scale with a maximum of 10 points. As all of these scores are above 6.0, they are considered to be acceptable. The score is lower for the haptic interface, as for the users the exclusive use of the Novint Falcon in order to obtain feedback from the game required a certain learning curve, as none of the participants in the sample had ever used this device before.

In the “Audio” category, a score of 10 points was obtained for the audio interface regarding the sentence “The sounds of the videogame provided me with information”, while for the haptic interface the sentence “I like the sounds of the videogame” obtained a maximum of 8 points. This variation of maximums was due to the fact that in the case of the audio-based interface, this was the only way to obtain feedback from the videogame, while for the haptic plus audio interface, the users felt that the sounds were complementary to the haptic elements, which made the videogame more exciting.

Within the “Haptic” category, the highest score was obtained in the haptic and haptic plus audio interfaces, for the sentence “The tactile sensation of the device provided me with information”, which obtained 10 points and 8 points respectively. It is clear that the higher score is associated with the haptic interface, as in this case it was the only means of obtaining feedback from the videogame.

Importantly, the results of the haptic plus audio interface were lower than the audio interface in the dimensions Satisfaction and Audio. This could be explained by the fact that use of the device implied an adaptation period and therefore an additional difficulty in the development of the evaluation activities. This is probably why the use of audio-based interface was more relevant.

4 Cognitive Impact

Once validated the interfaces of the game, we proceeded with the assessment of the cognitive impact on end users as a result of using the tool. Below is the methodology used and the results obtained.

4.1 Sample

An intentional sample was selected, made up of 7 learners who are blind with ages between and 10 and 15 years old, including four males and three females, all from the Metropolitan Region of Santiago. All of the participants attend the Santa Lucia School for the Blind. The requirements to participate were: 1. Being between 10 and 15 years of age, 2. Presenting Total Blindness, 3. Being enrolled in between Third and Eighth grade of General Elementary Education. The details of the sample can be seen in Table 1.

To perform the analysis of the results, the sample was segmented into two user groups. The first group considered users of 10-12 years of age, and the second group considered users of 13-15 years of age.

Gender	Ophthalmological Diagnostic	Degree of Vision
F	Blindness Caused by Brain tumor	Totally Blind
M	Retinopathy of prematurity	Totally Blind
M	Bilateral Blindness	Totally Blind
F	Microphthalmia	Totally Blind
M	Leber's congenital amaurosis	Totally Blind
M	Congenital amaurosis	Totally Blind
F	Retinopathy of prematurity	Totally Blind

Table 1: Sample description

4.2 Instruments

In order to study the degree of the videogame's impact, together with the cognitive tasks performed, on the development of the participants' O&M-related skills, an O&M skills checklist was created for children with visual disability between 10 and 15 years of age. This checklist was designed by special education teachers who are specialists in visual disabilities. The validation of the instruments was performed by these teachers applying the O&M skills checklist to users who are blind other than those involved in the sample, in order to detect errors in comprehension and the measurement of results.

This evaluative instrument was applied individually to each user at the beginning and at the end of the cognitive intervention, in order to determine in what way the use of the videogame had affected the development of O&M skills.

The dimensions contained within this instrument are:

- **Sensory perception.** The perception of information through the auditory and haptic channels are evaluated, taking into account the fact that sensory capacities are the primary functions that are developed to pick up on, integrate and react to information and stimulus from the environment.
- **Tempo-spatial development.** The users' knowledge regarding their position in space is evaluated, in being able to understand the distribution and location in space of various elements based on their own bodies, while at the same time being able to establish a relation between these aspects in order to navigate through the space.
- **O&M skills.** The skills regarding navigation based on O&M training is evaluated, either through use of the cane as a technical aid in order to detect obstacles in the environment or not. The purpose of this was to show whether or not the users are able to navigate both real and virtual environments based on these techniques, thus validating them for facilitating and strengthening their navigation.

4.3 Cognitive Tasks with the use of Audio Haptic Maze

These tasks sought to develop and/or strengthen O&M Skills in learners who are blind, based on the use of Audio Haptic Maze and its audio and/or haptic-based interfaces.

4.3.1 Tasks regarding the Comprehension of Dynamic Components

These tasks were sub-divided into:

- **Integration of Elements.** In this task, it was sought to integrate each of the audio and/or haptic elements used in the videogame into the user's mental map, in order to establish the dynamics of the videogame that are related to movement.
- **Establishment of Distances and Sizes on the Map.** This task sought to solidify the establishment of the relationship of equivalence between one step and one cell. The maze is made up of a certain number of cells, corresponding both to rooms and hallways. By integrating knowledge of this dynamic, the user can establish distances to doors and keys, and can determine the size of the various environments by counting the cells while moving from one place to another.
- **Directionality and Movement on the Map.** This task sought to strengthen the establishment of relations between the segments on the map and the direction in which the learners are facing and moving, so that the user is able to locate the various elements on the map. In addition, players were asked to delimit their movements regarding the direction that they took, mainly in order to verify whether or not they noticed when they moved forwards or backwards, or turned in one direction or another.
- **Composition and Distribution of the Map.** This task was related to all of the map-based sessions, and sought to work on the identification of hallways, rooms, elements represented through the use of audio and/or haptics, and the search for these elements based on the character's location on the map.

4.3.2 Map Appropriation and Navigational Tasks

These tasks were centered on establishing a mental representation of the navigated environment based on the videogame's dynamics that strengthen the establishment of relationships useful for orientation and mobility in the virtual space.

The maze in the videogame was divided into different sectors (see Figure 4), which determined the following tasks:

- **Sector A.** This task sought to establish the number of hallways, rooms and/or elements available in this area. In addition, it sought to establish the direction of movement, relationships of distance and size pertaining to the elements, hallways and rooms, in order to facilitate the formation of movement strategies. Afterwards, each player was asked to represent the space he had navigated with representative material of the elements of the videogame.
- **Sector B.** This task had as an objective that through the audio and/or haptic-based interfaces, the players would move through sector B in the maze, locating the different hallways and elements. After navigating this sector of the maze, each player was asked to represent the space that had been navigated, describing the route taken and the elements that the player had located on that route, in

addition to describing whether or not the user was walking down a hallway or through a room.

- **Elements and Size Dynamics.** This task consisted of comprehending the videogame's dynamic regarding the execution of actions, and the interaction with various elements in the videogame such as doors and differently shaped keys that could be used to open specific doors. Based on this, the learner had to resolve problems such as inferring the need to find a specific key in order to open a particular door, understanding if he was walking down a hallway or through a room, determining the number of steps taken when moving about, and based on the latter, establishing the size of the space in which the user is located. In addition, the users had to comprehend the functionality of the Novint Falcon, the buttons on the keypad, and learn to orient themselves based on audio and/or haptic cues, in order to determine and identify the elements within the videogame.
- **Sectors A, B and C, Directionality and Movement.** The objective of this task was to establish the relationships of movement performed by the player when moving through the 3 sectors of the maze, using the respective interface assigned to each particular work group. Each user had to identify each sector (based on characteristics that had already been established during prior navigational exercises), and the directions and elements located both in a hallway and/or a room. Once the route had been navigated, each player was asked to represent the space that had been navigated with representative material, requiring knowledge of the number of cells for each hallway and room, and the elements such as intersections, doors, treasure chests and keys.
- **Total Navigation of the Map.** This last task was based on navigating freely throughout the entire maze, applying all of the strategies and dynamics involved in the videogame that are needed in order to successfully complete the mission of opening all of the doors and navigating between the 3 sectors of the virtual environment. In addition, the need to establish the directions in which the learner was moving was emphasized, as well as the need to establish the relationships of size regarding hallways and rooms, the relationship between the audio and/or haptic elements of the videogame as associated with concrete objects, and the verbal description of everything the player had identified and the routes taken. In this task, the learners were also asked to graphically represent the environment that had been navigated, adding arrows to indicate the directions that had to be followed in order to move from one sector to another.

4.4 Procedure

Initially, the O&M skills checklist was applied as a pretest, in 45-minute sessions with each user. During these sessions, the users were provided with a set of materials in order to perform some of the actions required by the instrument (see Fig. 5).

In a second stage, the users performed cognitive tasks through the use of the videogame in which each of the dimensions contained in the O&M skills checklist was worked on (Perceptual development, Temporal-spatial development, O&M skills) in order to strengthen the development of these skills by using AHM (see Fig. 6). This stage involved a total of twelve, 40-minute sessions with each user.

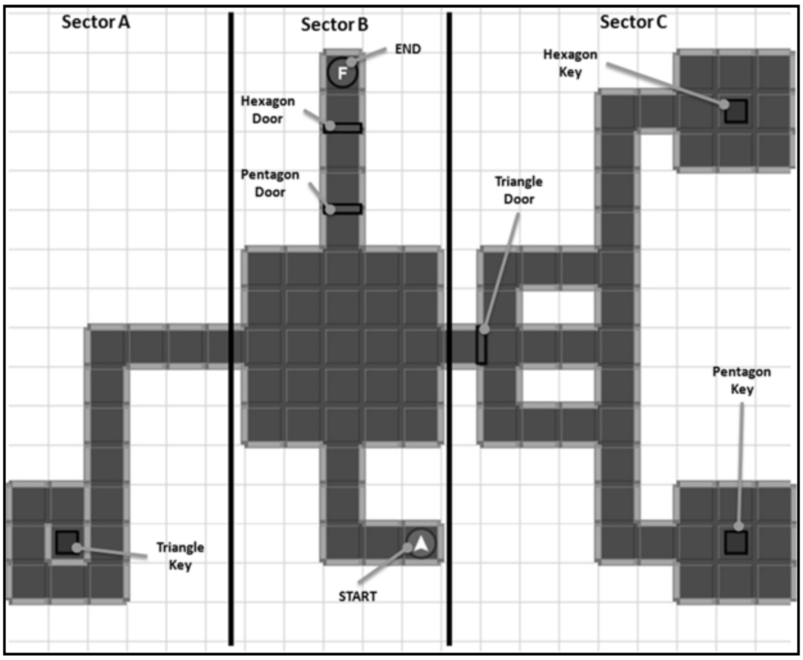

Figure 4: Sectors within the Maze of Audio Haptic Maze

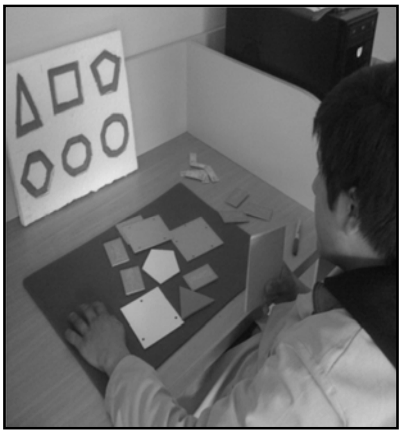

Figure 5: Activities performed by the user during the pre-test

Once the user had finished navigating through the maze, he was asked to create a graphic representation of the environment through representative material of the elements of the videogame, in order to determine if the mental image created coincided with the spaces that had been navigated virtually while interacting with the videogame. This does not mean that the representation was made through a freehand drawing, but through manipulative materials by the learner, who should place them according to his personal perception of the environment.

Figure 6: Learner performing cognitive tasks with Audio Haptic Maze

Complementary to the cognitive evaluation, during each work session, once navigation through the virtual environment had been completed, each user was asked (in order of age) to form a graphic representation of the virtual environment they had navigated, in order to determine the adoption and restructuring of the mental model based on audio and haptic cues (see Fig. 7).

Finally, in a third stage the same O&M skills checklist used in the first stage was applied as a post-test.

Figure 7: Learners forming graphic representations of the environments navigated

4.5 Results

The results obtained from the evaluation of the 10-12 year old age group from the sample showed an increment in the pretest/posttest performance means in all dimensions. Based on a T Test that was performed with this data, it was found that the differences in the pretest/posttest means for the “Sensory perception” (pretest mean = 65.75 points; posttest mean = 70.75 points; range of scores from 0 to 72 points) and

"Tempo-spatial development" (pretest mean = 24.45 points; posttest mean = 28.75 points; range of scores from 0 to 34 points) dimensions were not statistically significant. However, for the "O&M skills" (pretest mean=32.31 points; posttest mean=48.75 points; range of scores from 0 to 52 points) dimension the difference between the two means was statistically significant ($t = -4{,}323$; $p < 0.05$).

The results obtained for the evaluation of the 13-15 year old age group from the sample showed increments in their pretest/posttest performance means in all dimensions as well. Based on a T Test that was performed with this data, it was found that the differences in the pretest/posttest means for the "Tempo-spatial development" (pretest mean = 33.33 points; posttest mean = 34.00 points; range of scores from 0 to 34 points) and "O&M skills" (pretest mean = 34.00 points; posttest mean = 43.76 points; range of scores from 0 to 44 points) dimensions were not statistically significant. However, for the "Sensory perception" (pretest mean = 59.00 points; posttest mean = 68.00 points; range of scores from 0 to 68 points) dimension the difference between the two means was statistically significant ($t = -5{,}197$; $p < 0.05$).

Also, the users were able to navigate through all of the areas that make up the maze designed, making intelligent decisions regarding what direction to follow in order to go from point A to point B based on the information provided.

Evidence of this point is reflected in Fig. 8, which shows the result of a behavioral analysis of one of the 13-15 year-old user's navigations through the environment. It can be observed that the user integrates both interfaces in order to completely navigate all of the areas on the map of the maze in the virtual environment.

As for the graphic representations of the users' mental maps after having finished the navigation sessions, these representations included all of the elements involved in the videogame's virtual environment, but lacked precision regarding specific dimensions and the orientation of the corridors and rooms (see Fig. 9). The problem associated with spatial dimensions is due to the users' tendency to perform a peripheral exploration while navigating in real life, a tendency that is transferred to their navigation in the virtual environment. This situation is only visible through the representations with representative material, in that virtually the users were able to successfully establish the dimensions that correspond to each area of the maze.

5 Conclusions

The purpose of this study was to design, implement and evaluate the Audio Haptic Maze (AHM) videogame and determine whether the use of an audio and haptic-based videogame has an impact on the development of O&M skills in school-age learners who are blind. The results showed that playing and training with AHM improved the development of O&M skills in learners who are blind.

The contribution of this work is to show how through the integration of multimodal interfaces into a video game the development of O&M skills can be promotes in blind learners. The playful aspects of the game and its associated technology positively influenced the motivation of end users.

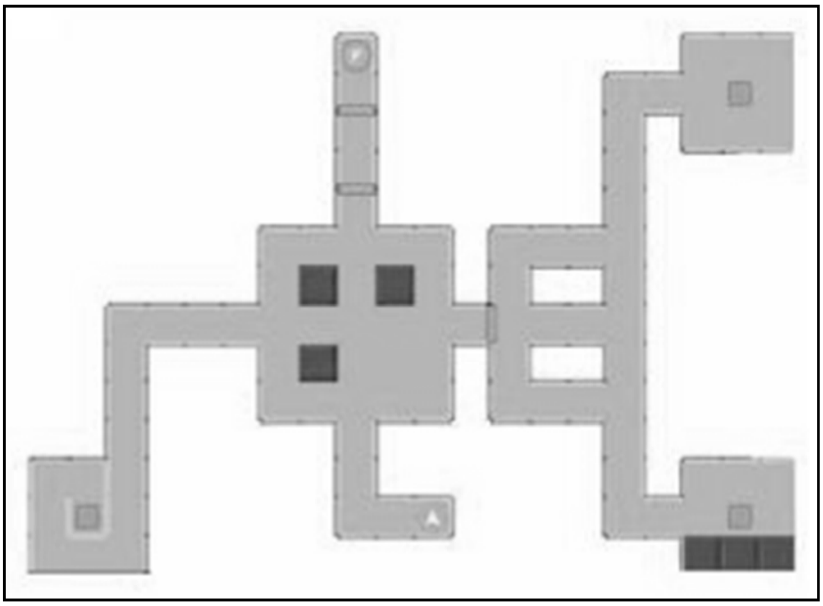

Figure 8: Result of the Path Analyzer for one of the user's navigations. The clear cells correspond to the places visited by the user

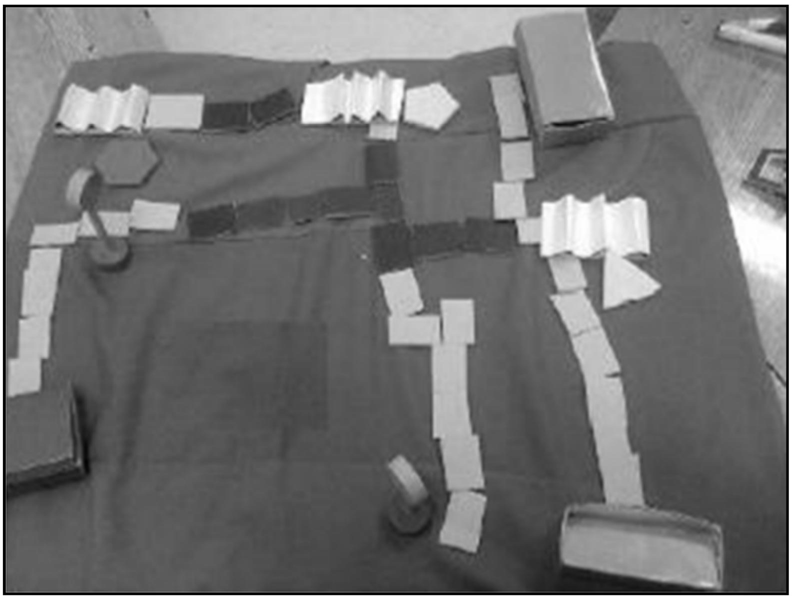

Figure 9: Graphic representation of the mental map of the virtual environment navigated.

Regarding the usability associated with the videogame, it was found that the use of appropriate audio icons is crucial to be able to provide correct information. For this reason, applying sound effects to these audio cues could generate a kind of special environment that can have a negative effect on usability.

Both the haptic and the audio-based interfaces are able to transmit the same information on the user's state within the virtual environment. However, it is necessary to reiterate that both interfaces were complemented with the use of Text-To-Speech, used in order to indicate contextual and/or status changes, which would have been difficult to transmit to users through either audio or haptic icons. These contextual changes have a favorable effect on the associations that the users make between the elements that make up the different areas in the maze, as through the use of these elements users are able to determine the specific sector of the maze in which the various elements are located, and the actions that they must take in order to resolve the videogame's dynamics and continue with their navigation into other sectors of the virtual environment.

The use of audio and haptic interfaces together showed that, more than just complementing the provision of information regarding the user's state within the virtual environment, this combination allows for the creation of an environment that is much closer to what the user would expect from a videogame. The users utilized the haptic interface to navigate and the audio interface to imagine the situation in which they were immersed within the videogame's maze.

As such, the use of the haptic and audio interfaces together allows the user who is blind navigating the videogame's virtual environment to be able to form a better perception of distances, shapes and the orientation of the objects on the map when updating his position.

Regarding the cognitive impact, the results of this study show that all the audio and haptic icons are useful for establishing navigational paths in the virtual environment. The icons that allow the users to measure the spaces that they navigate are especially helpful for this process, not only to establish a mental map of the virtual environment, but to apply this information to real navigational contexts as well. This was corroborated by the results regarding the effect that the intervention had on the users in the "O&M skills" dimension.

The results allow for the confirmation that all of the users within the 10-12 year old age group presented significant development of their O&M skills as a result of their interaction with the AHM videogame. The results also indicate that the "O&M skills" dimension was that which experienced the most significant quantitative development, which is directly related to the efficiency of the user's movements when navigating within the videogame's virtual environment.

As far as the results for the 13-15 year old age group, all of the users presented a development in their O&M skills after having completed the cognitive tasks. There was an important increase in their scores as a result of their interaction with the videogame, although this increase was not statistically significant in the "O&M skills" dimension. Case studies were observed in which some users were seen to develop the skills involved in entire indicators that had not been present in the pretest. One example of this is the development of techniques for the search and location of objects in the environment, which became visible in the videogame when the users had to locate the treasure chests that contained the keys needed to open the doors of the maze.

The game presented limitations in the development of abstract representation that end users could achieve working with the proposed interfaces. We attempted to overcome these limitations by proposing the use of low and bounded complexity spaces in the game (number of items, size of the maze, and choices of paths to follow). As future work plans, we intend to expand the complexity of the virtual environment.

It is proposed as future work to explore how learners construct their mental models. In this paper, the evaluation criteria of the graphic representation of the navigated virtual environment, was based on the accuracy of representation achieved by learners. However, it will be pertinent and appropriate to study how users represent mental maps, focusing the analysis on the utility for themselves related to the functional elements of the environment.

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References

[Ballesteros, 93] Ballesteros, S.: Percepción Háptica de Objetos y Patrones Realzados: Una Revisión. Departamento de Psicología Básica. Universidad Nacional de Educación a Distancia. Psiocthema, 1993, vol.5, nº2, 311-321.

[Carvalho, 12] Carvalho, J., Guerreiro, T., Duarte, L., Carriç, L.: Audio-Based Mobile Puzzle Gaming for Blind People. In: MOBACC 2012: Mobile Accessibility Workshop at MobileHCI 2012, San Francisco, USA, September 2012.

[Crossan, 06] Crossan, A., Brewster, S.: Two-Handed Navigation in a Haptic Virtual Environment. In Proceedings of International Conference on Human Factors in Computing Systems, pp.676-681, Montréal, Québec, (Canada), 2006.

[De Felice, 05] De Felice, F., Renna, F., Attolico, Distante, A.: Haptic fruition of 3D virtual scene by blind people. In Proceedings of the 18th international conference on Innovations in Applied Artificial Intelligence (IEA/AIE'2005), Ali M & Esposito F (Eds.). Springer-Verlag, London, UK, 269-278, 2005.

[Frauenberger, 03] Frauenberger, C., Noisternig, M.: 3D audio interfaces for the blind. In: Proceedings of the 2003 International Conference on Auditory Display, Boston, MA, USA, July 6-9, 2003, pp. 1-4.

[Gaißert, 11] Gaißert, N., Bülthoff, h. h., Wallraven, C.: Similarity and categorization: From vision to touch. Acta Psychologica, Volume 138, Issue 1, September 2011, Pages 219–230. http://dx.doi.org/10.1016/j.actpsy.2011.06.007

[Gaißert, 12] Gaißert, N., Waterkamp, S., Fleming, R. W., Bülthoff, I.: Haptic Categorical Perception of Shape. PLoS One. 2012; 7(8): e43062. Published online 2012 August 10. doi: 10.1371/journal.pone.0043062

[Heller, 01] Heller, M. A., Brackett, D. D., Scroggs E., Allen, A. C., Green, S.: Haptic perception of the horizontal by blind and low-vision individuals. In: Perception 30, 5, 601 – 610, 2001.

[Homa, 09] Homa, D., Kahol, K., Tripathi, P., Bratton, L., Panchanathan, S.: Haptic concepts in the blind. Attention, Percept & Psychophys. 2009 May;71(4):690-8. doi: 10.3758/APP.71.4.690.

[Hu, 06] Hu, W., Lin, T., Sakai, K., Imamiya, A., Omata, M.: Setup Consistent Visual Textures for Haptic Surfaces in a Virtual Reality World. In Proceedings of the 9th conference on User interfaces for all (ERCIM'06), Stephanidis C & Pieper M (Eds.). Springer-Verlag, Berlin, Heidelberg, 78-87, 2006.

[Huang, 09] Huang, Y. Y.: Exploration of interface usability in a haptic 3D virtual labyrinth for visually impaired users. In: proceeding of IADIS Interfaces and Human Computer Interaction (IHCI). ALGALVE, Portugal, June 17-23, 2009.

[ISO, 99] ISO: Human centered design processes for interactive systems. International Organization for Standardization, ISO 13407. Available from: http://www.iso.org/iso/catalogue_detail.htm?csnumber=21197 (accessed 19 August 2011).

[Jain, 12] Jain, S.: Assessment of audio interfaces for use in smartphone based spatial learning systems for the blind. Master of Science Thesis in Spatial Information Science and Engineering. University of Maine, 2012.

[Jütte, 08] Jütte, R.: Haptic perception: an historical approach. In: Matin Grunwald (Ed.). Human haptic perception: basics and applications. Leipzig (Alemanha), 2008, 3 - 13. ISBN 978-3-7643-7611-6

[Kim, 10] Kim, H. N.: Usable accessibility and haptic user interface design approach. Doctoral Thesis in Industrial and Systems Engineering. Virginia Polytechnic Institute and State University, 2010.

[Lahav, 02] Lahav, O., Mioduser, D.: Multisensory Virtual Environment for Supporting Blind Person's Acquisition of Spatial Cognitive Mapping, Orientation, and Mobility Skills. In Proceedings of the International Conference on Disability, Virtual Reality and Associated Technologies, ICDVRAT 2002, Veszprém, Hungary, 213-220.

[Lahav, 08] Lahav, O., Mioduser, D.: Haptic-feedback support for cognitive mapping of unknown spaces by people who are blind. Int. J. Hum.-Comput. Stud. 66, 1, Jan. 2008, 23-35.

[Loomis, 05] Loomis, J., Marston, J., Golledge, R., Klatzky, R.: Personal guidance system for visually impaired people: Comparison of spatial displays for route guidance. In Journal of Visual Impairment Blindness 99, 4, 219-232, 2005.

[Lumbreras, 99] Lumbreras, M., Sánchez, J.: Interactive 3D sound hyperstories for blind children. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems: the CHI Is the Limit, CHI '99, Pittsburgh, Pennsylvania, United States, May 15 – 20 1999, 318-325.

[Lutz, 06] Lutz, R.: Prototyping and evaluation of landcons: auditory objects that support wayfinding for blind travelers. SIGACCESS Access. Comput. 86, September 2006, 8-11. Available from: http://doi.acm.org/10.1145/1196148.1196150.

[Murphy, 07] Murphy, E., Kuber, R., Strain, P., McAllister, G., Yu, W.: Developing Sounds For A Multimodal Interface: Conveying Spatial Information To Visually Impaired Web Users. In Proc. of the 13th International Conference on Auditory Display (ICAD 2007), Montréal, Canada, June 26-29, 2007.

[Norman, 04] Norman, J.F., Norman, H.F., Clayton, A.M., Lianekhammy, J., Zielke, G.: The visual and haptic perception of natural object shape. In: Perception & Psychophysics 66: 342–351. 2004 Feb; 66(2):342-51.

[Oakley, 00] Oakley, I., McGee, M. R., Brewster, S., Gray, P.: Putting the feel in ’look and feel‘. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. CHI '00. ACM, New York, NY, 415-422. 2000.

[Reuters, 09] Reuters: Novint Awarded Subcontract to Develop Physical Rehabilitation Game for Military, Edition U.S., Tue Sep 1, 2009 8:02am EDT. Available from: http://www.reuters.com/article/2009/09/01/idUS132915+01-Sep-2009+MW20090901 (accessed 19 August 2011).

[Rosa, 93] Rosa, A., Ochaita, E.: Psicología de la ceguera. Alianza editorial, Madrid (España), ISBN 84-206-6539-8, 1993.

[Sánchez, 03] Sánchez, J.: Software Usability for Blind Children Questionnaire (SUBC), Usability evaluation test, University of Chile, 2003.

[Sánchez, 04] Sánchez, J., Baloian, N., Flores, H.: A methodology for developing audio-based interactive environments for learners with visual disabilities. In Proceedings of the World Conference on Educational Multimedia, Hypermedia & Telecommunications ED-MEDIA 2004. June 21-26, 2004. Lugano, Switzerland, 540-545.

[Sánchez, 09a] Sánchez, J., Sáenz, M., Ripoll, M., 2009. Usability of a Multimodal Videogame to Improve Navigation Skills for Blind Children. In Proceedings of the Eleventh International ACM SIGACCESS Conference on Computers and Accessibility, Pittsburgh, PA, USA, October 26-28, 2009, 35-42.

[Sánchez, 09b] Sánchez, J., Tadres, A., Pascual-Leone, A., Merabet, L.: Blind children navigation through gaming and associated brain plasticity. In Virtual Rehabilitation International Conference 2009, June 29-July 2, 2009, Haifa, Israel, 29-36.

[Sánchez, 10] Sánchez, J., Tadres, A.: Augmented reality application for the navigation of people who are blind, In Proceedings of the 8th International Conference Series on Disability, Virtual Reality and Associated Technologies, ICDVRAT 2010, Viña del Mar, Chile, August 31-September 2, 2010, 51-60.

[Sarmiento, 03] Sarmiento, L.C.: Ayudas aumentativas en discapacitados visuales para la representación espacial utilizando las tecnologías de la información y las comunicaciones. Tesis de Maestría en TIAE. Bogotá: UPN, 2003.

[Travieso, 07] Travieso, D.: Haptic and proprioceptive experience. Fundación Infancia y Aprendizaje. Estudios de Psicología, Vol.28, number 2, June 2007, 141-153(13).

[Warren, 94] Warren, D.H.: Blindness and Children: An Individual Differences Approach. Cambridge: Cambridge University Press. (1994) Mentioned in Ungar, S.: Cognitive mapping without visual experience: in Kitchin, R. & Freundschuh, S. (eds) Cognitive Mapping: Past Present and Future. London: Routledge (2000).

[Yu, 00] Yu, W., Ramloll, R., Brewster, S.: Haptic Graphs for Blind Computer Users. In Proceedings of the First International Workshop on Haptic Human-Computer Interaction, Brewster S & Murray-Smith R (Eds.). Springer-Verlag, London, UK, 41-51, 2000.

[Yu, 03] Yu, W., Kangas, K., Brewster, S.: Web-Based Haptic Applications for Blind People to Create Virtual Graphs. In Proceedings of the 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, HAPTICS'03. IEEE Computer Society, Washington, DC, USA, 318-325, 2003.