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USER-CENTERED TECHNOLOGIES FOR BLIND CHILDREN

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Abstract*: The purpose of this paper is to review, summarize, and illustrate research work involving four audio-based games created within a user-centered design methodology through successive usability tasks and evaluations. These games were designed by considering the mental model of blind children and their styles of interaction to perceive and process data and information. The goal of these games was to enhance the cognitive development of spatial structures, memory, haptic perception, mathematical skills, navigation and orientation, and problem solving of blind children. Findings indicate significant improvements in learning and cognition from using audio-based tools specially tailored for the blind. That is, technologies for blind children, carefully tailored through user-centered design approaches, can make a significant contribution to cognitive development of these children. This paper contributes new insight into the design and implementation of audio-based virtual environments to facilitate learning and cognition in blind children.*

Keywords: *blind children, user-centered design, audio-based interfaces, learning and cognition.*

INTRODUCTION

The increasing pace of technological growth and development has been difficult to follow for the average citizen. This situation is more critical for people with disabilities, since many of them do not have easy access to new technologies. The possibilities for them to access information and to work with technological devices are highly restricted, preventing them from becoming more active in a globalized world.

Although sighted users have many different mental models[1], similarities exist among people from the same culture and with similar experiences. Moreover, digital natives[2] and digital immigrants[3] have varying intuitive mental models that determine the pace at which they can access information and develop a diverse array of strategies, but they do not have any major difficulties in the long run.

Children with visual disabilities have entirely different ways to structure, order, and perceive the world, assuming a singular mental model quite distinct from sighted children. This

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is a major issue affecting access to digital technologies based on graphical user interfaces: Children with nonvisual mental models have to cope with devices designed for children with visual mental models. In this paper, the term *blind* refers to children who are either totally blind or have some residual vision (known collectively as legally blind).

Some research initiatives have incorporated screen readers and text-to-speech technology into diverse computing environments for people with visual disabilities, but these are not sufficient because the core applications are designed for a user with a rather different mental model (Pitt & Edwards, 1996; Weber, Kochaneck, Stephanidis, & Homatas, 1993). Virtual environments with three-dimensional (3D) sound[4] have been developed to help legally blind users construct a mental representation of a virtual environment and to develop cognitive abilities (Mereu & Kazman, 1996). Loomis, Lippa, Klatzky, and Golledge's (2002) field study sought to understand the spatial updating of locations specified by 3D sound and spatial language. Savidis, Stepanidis, Korte, Crispien, and Felbaum (1996) incorporated a direct manipulation system for hierarchical navigation in nonvisual interaction. Schneider and Strothotte (2000) studied the constructive exploration of spatial navigation by blind users. Kurniawan, Sporka, Nemec, and Slavik (2004) designed and fully evaluated a spatial audio system for blind children. The work of Morley, Petrie, O'Neill & McNally (1998) presented blind users with the task of developing navigational strategies in order to represent complex spatial structures that pose cognitive difficulties to these users. This system was developed for use with various output devices, such as a concept keyboard, tablets, haptic interfaces (Lange, 1999), and joysticks with force feedback (Ressler & Antonishek, 2001).

In response to the issue of developing user-centered technology for blind children, diverse interface designs have been implemented for users with visual disabilities that allow them to utilize the technology more fully. One initiative in this line of research is centered on sound-based interfaces used to enhance cognition in blind children. This researcher's group has been using 3D sound to convey information and knowledge by exploiting users' auditory senses to cope with their loss of vision. Systematic usability evaluations have been performed during the development of the interface in order to inform the design of user-centered interfaces. Specifically, the research group has identified key interface issues used to map the blind users' mental models, needs, and ways of thinking (Sánchez, Baloian, Hassler, & Hoppe, 2003; Sánchez & Lumbreras, 1999; Sánchez & Sáenz, 2006a, 2006b, 2006c).

Spatial, sound-based virtual environments have been oriented toward assisting the cognitive development of children with visual disabilities through the development of tempo-spatial structures, short-term and abstract memory, haptic perception, problem solving, mathematics learning skills, and orientation and mobilization skills. Relevant data from these studies are helping to map the role that spatial sound can play in the cognitive development of blind children. Researchers are progressively accepting the hypothesis that computer-delivered spatial sound has a critical impact on the cognitive development of blind children (Baldis, 2001; Cernuzzi, Paniagua, & Chenú, 2004; Lahav & Mioduser, 2004; McCrindle & Symons, 2000; Sánchez & Flores, 2004, 2005; Sánchez, Flores, & Sáenz, 2005; Sánchez & Sáenz, 2005; Winberg & Helltrom, 2000).

Interfaces without visual cues for blind children have been critical for exploring the auditory means for enhanced cognition. In such research, digital applications for sighted children have not been embedded with audio, nor have screen readers been used in applications intended for blind children. As a result, through continuous testing in usability practices, researchers have been able to define the particular mental models that blind users employ to perceive their real surroundings. Such research allows designers to improve embedded interface tools that help blind users to map their own virtual surroundings and access opportunities to become more fully integrated into their societies that are relying more regularly on technological access.

The purpose of this paper is to review, summarize, and illustrate the work on four audio-based games designed to assist blind children in mapping[5] their virtual environments and to improve their cognitive development. The development process of this research employed a user-centered design methodology through successive usability tasks and evaluations.

RELATED WORK

Hardware for Blind Children

One of the most traditional techniques blind people use for transferring and storing information comes from the creation of tactile-explored characters. Louis Braille created a system based on dots arranged in two columns of three points each and forming a cell that represents an alphabetic character. Paper or plastic sheets printed with these characters constitute permanent reading sources for visually impaired people, such as traditional books for sighted people. Today, Braille cells have been developed technically as a set of elements electrically configured in such a way that, when organized in lines, constitute a Braille line. When this line is used with a computer terminal and with appropriate software and interfaces, it is capable of reproducing a line of conventional text in Braille. The user reads the line by moving his or her finger over these Braille cells as if it were a printed line. Once read, a new set of characters takes the place of the previous one and the process continues in this way until a given text is completed. The use of bidimensional mechanisms, such as using Braille lines and haptic devices, is also seen as a viable alternative to help improve the social integration and inclusion of sight-impaired people (Ramstein, 1996).

Virtual reality systems often lack significant tactile stimulation. Currently, interaction is used primarily through visual cues. Likewise, no standard mechanisms exist that prohibit or help users avoid virtual collisions with objects in the digital world (since there is no sensation of contact). Recent literature proposes some possible alternatives to solving this problem by using haptic interfaces (Tan, 2000). Haptics relates to the sense of touch. It is applied in the digital environment by combining the tactile abilities with virtual reality.

Some haptic devices are capable of providing feedback through interaction with muscles and tendons, and, in this way, a feeling of applying force over a certain object is provided. Moreover, some devices use tactile terminals to provide information about temperature, texture, and pressure. For example, PHANToM is a pointer device that provides force feedback in such a way that the user can feel the volume and force simulated inside the virtual environment with his or her hand (Yu & Brewster, 2002). This provides for greater feedback during the interaction with objects inside a certain application, from menus to entire virtual worlds. Among the many diverse uses of this device is the design of regular and irregular geometrical figures, represented in order to allow blind users to identify shapes, reliefs, and textures. The PHANToM also allows for the modeling of a virtual environment with corridors, streets, rooms, buildings, and so forth, through which the user can navigate, assisted by the same device.

In a similar vein, the use of force feedback joysticks in software interaction introduces a new field of action for blind people. Such devices produce a decreased need for audio stimuli, which lowers the acoustic contamination. Force feedback joysticks are devices with a high potential for use, as they provide a sufficient number of buttons, button arrangements, sizes, and the like, to facilitate software interaction (Sánchez et al., 2003). The increased tactility provided through these joysticks and other haptic interfaces, coordinated with audio assistance, represents an important complement for user interaction and immersion in the virtual world.

Finally, tablets are devices used in conjunction with a pen and operate in a way similar to a mouse. They are very helpful in aiding interfaces for users with visual disabilities (Van den Doel et al., 2004). It is very easy to design objects and guide the interaction by locating spaces represented on screen areas of the tablet. The use process is similar to that of a mouse, but the tablet includes a grille with reliefs on it that permit the blind user to locate and select certain screen areas.

Software for Blind Children

Even though mental models are different for each human being, there are several similarities between people with similar lifestyles, cultures, experiences, training background, and knowledge. Digital immigrants and digital natives have intuitive mental models for accessing information via technologies without major problems. On the contrary, however, the way users with visual impairments shape, order, and perceive the world is completely different from sighted users, and thus they approach the virtual and real environment through an entirely different mental model. This is, without a doubt, the most critical challenge that blind users face when using technologies with interfaces that have not been designed and planned specifically for them. It is not enough to simply give them accessibility to information technology: They cannot interact with games in the same manner as their sighted peers. Such access must be designed from the beginning for users with visual impairments.

Tactile input/output hardware is not the only way to provide blind people with the information from codified texts in the computer's memory. Voice synthesizing software, known as text-to-speech (TTS), allows for the interpretation of written information through hearing it spoken aloud. There are many applications known as screen readers that allow users to navigate through a visual screen and to have access to software based on text mode and graphical interfaces that are supported by the operating system's message system. The main concern with this type of support is the proper design of the dialog between the sight-impaired user and the computer, because when the usability is not appropriately created, it may become useless (Pitt & Edwards, 1996).

Simply adding TTS to the software is not sufficient to achieve an adequate management of tools, due primarily to the distinctiveness between the blind and sighted users' mental models. As a consequence, some interface designs and developments for users with visual disabilities adopt a rather different paradigm in order to orient these special users to the management of technology, which would imply important achievements for blind users in the management of computer and mobile devices.

Audio-based virtual environments have helped to improve learning and cognition in blind children. They have assisted the development of tempo-spatial skills (Sánchez & Lumbreras, 1999), haptic perception, and abstract memory (Sánchez et al., 2003). The development and practice of short-term memory skills has also been attained during interactions with virtual environments (Sánchez & Flores, 2004).

Based on this research, a game based on the board game Memory was designed (Sánchez & Flores, 2004). By considering the specific needs of blind children and their level of psychological development, educational topics were also included in order to go beyond entertainment and sociability and to delve more deeply into their learning. The cognitive emphasis of this software was on boosting short-term and long-term memory. Another software program helped blind children to identify and differentiate sound-enhancing orientation, navigation, and mobility skills in their everyday life (Sánchez and Sáenz, 2006a).

In this paper, the research emphasizes the results obtained after use of the four games specially designed for legally blind children: *AudioMath, The Farm of Theo & Seth, AudioVida,* and *AudioChile*. These games include both audio (for the totally blind) and visual (for those with residual vision) interfaces that were adapted to the specific needs and characteristics of the blind children.

THE METHODOLOGY OF THE STUDIES

For more than a decade now, researchers have developed software and games for blind users under the criterion that interfaces are appropriate for—that is, tailored—to the needs and interests of the user's mental model. In designing and developing software for blind people, researchers have established a methodology and instruments for usability and cognitive evaluation of software. These methods provide relevant data that can be used to redesign virtual environments and produce pertinent user-oriented interfaces. In this paper, four games are presented that were especially designed and implemented for children with visual disabilities and targeted to enhance specific cognitive skills (see Figure 1).

Participants

A total sample of 67 learners who were attending the Santa Lucia School in Santiago, Chile, was selected, although not all learners tested the games. All learners were classified as legally blind and most of them also had learning disabilities, such as varying degrees of intellectual development. Special education teachers and usability experts also participated in each study as facilitators. Usability experts were software engineers with human-computer interaction research and practice experience that fully evaluated the interfaces to map and tailor correctly the game use to blind children.

As displayed in Table 1, 37 of the 67 students evaluated the usability of the games, and 30 participated in the cognitive evaluation. The usability evaluation involved children who did not participated in the cognitive evaluation. The idea was that the children who interacted with the game for the cognitive evaluation did not have any previous experience with the software that could contaminate the studies. The usability evaluation did not consider a control group; all 37 children interacted with and used the games.

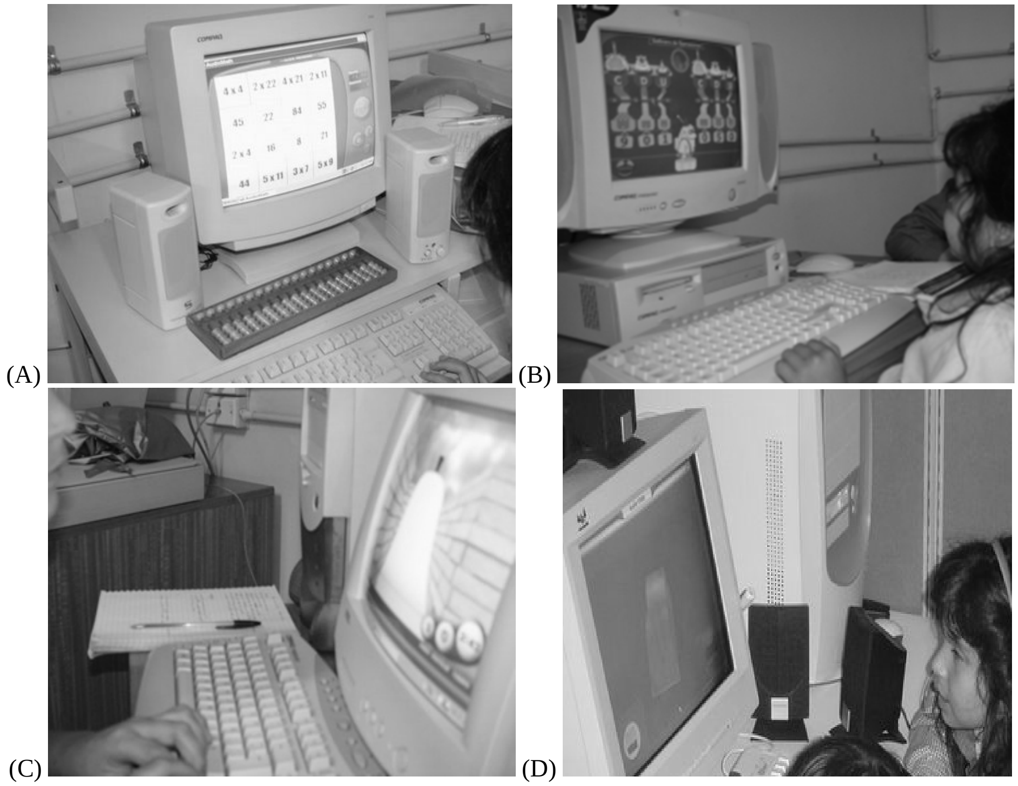

Figure 1. A user interacting with different software: (A) *AudioMath*, (B) *The Farm of Theo & Seth*, (C) *AudioVida* and (D) *AudioChile*. For the games shown in A, B and C, the setting is stereo sound. In the case of *AudioChile*, the actual setting for 3D sound interaction is also shown in D.

Table 1. Participants in the Usability and Cognitive Evaluations of the Four Games.

	Participants				
	AudioMath	***The Farm of Theo & Seth***	***AudioVida***	***AudioChile***	**TOTAL**
Usability Evaluation	19	9	3	6	**37**
Cognitive Evaluation	10	6	9	5	**30**
	29	**15**	**12**	**11**	**67**

It is important to note that all of the studies were conducted in Spanish with native speakers of Spanish using Spanish-language programs. The information has been translated for the purpose of this paper.

Usability Evaluation

For the usability of *AudioMath*, the sample consisted of 19 children, 9 boys and 10 girls, aged 6–15 years. Children had diverse intellectual development, such as normal, slow normal, borderline, below normal, and mentally deficient.

The usability evaluation of *The Farm of Theo & Seth* was implemented with a sample consisting of 9 children aged 8 years old. Four of them were blind (2 girls and 2 boys) and five had residual vision (4 girls and 1 boy).

For the usability evaluation of the game *AudioVida*, researchers selected a sample of three blind children, aged 10–15 years. One of them was blind from birth and the other two acquired blindness during childhood.

The sample for the usability evaluation of *AudioChile* consisted of 6 children with visual disabilities, 4 boys and 2 girls, aged 10–15 years. Three children had low vision and the other three had total blindness. Two of them were blind from birth, one child acquired blindness during childhood, two had good residual vision, and one had poor functional residual vision.

Cognitive Evaluation

The cognitive evaluation of *AudioMath* was implemented with 10 children, aged 8–15 years, 5 girls and 5 boys. The evaluation of *The Farm of Theo & Seth* was implemented with 6 children, aged 7–8 years, 3 girls and 3 boys. The sample for the evaluation of *AudioVida* consisted of 9 children with visual disabilities, 7 boys and 2 girls, aged 10–15 years. Five children had low vision (three had good residual vision, and two had poor functional residual vision) and four were totally blind (two of them were blind from birth, two acquired blindness during childhood). The sample for the evaluation of *AudioChile* sample consisted of 5 children with visual disabilities, 3 girls and 2 boys, aged 8–12 years. Four of them had total blindness and one had low vision.

Research Stages

Special care has been put into the software design for blind children because an effective outcome cannot be created from the mindset of a designer who simply closes his/her eyes: The designer must understand the blind children's behavior and way of thinking and reasoning. Therefore, the methodology used for these studies was user-centered design for blind children, meaning that we started from the needs and interests of blind children and then designed audio-based software accordingly. Blind children participated in the studies, interacting with and evaluating the usability and cognitive impact of *AudioMath*, *The Farm of Theo & Seth*, *AudioVida*, and *AudioChile* as they were being developed. The intervention is explained here, specifying the major stages in the methodology, followed by the games used, the system requirements, the evaluation instruments, the cognitive tasks employed, and experimentation procedure.

The following methodological stages were established in order to evaluate the usability and cognitive impact of game-based virtual environments for blind children (see also Figure 2).

1. *Analysis*. In this stage, the cognitive skills to be improved were considered as a baseline component of the software, and were defined through software features and interaction modes. In addition, the corresponding technologies were defined following an analysis of the current technologies and the solutions they provide. Evaluation instruments were also analyzed and selected. The usability and cognitive effectiveness of current research was evaluated by using already validated instruments. Cognitive tests varied according to the cognitive skill studied.

They ranged from general domain skills (problem solving) to specific domain skills (mathematics). The instruments used are fully explained in the Instruments subsection below.

2. *Design*. In this stage, storyboards, scripts, frameworks and other aspects of the software were defined, along with key interface usability issues. Usability evaluation involved the evaluation of software interfaces. The cognitive evaluation involved cognitive tasks implemented during interaction with the game and comprised concrete, hands-on activities that students performed and which involved solving problems similar to those encountered when playing the virtual game. There were fixed goals and procedures for these tasks in order to be able to later replicate the experience several times with different learners.

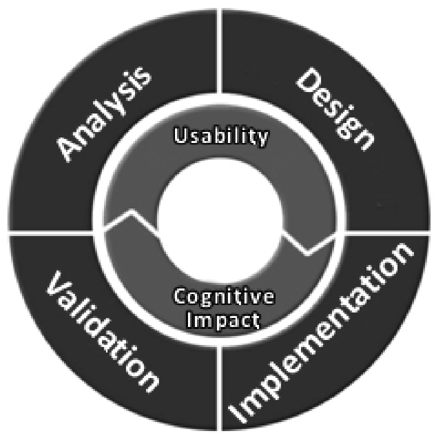

Figure 2. Research processes model. The research process starts with the analysis stage, then continues with design, implementation, and validation. The usability and cognitive aspects are considered in all research.

The idea was to combine gaming with cognitive tasks—completed by using concrete work materials—in order to form an integrated whole in the learning process of the blind children. This process helped to improve the perception and abstract representation of software elements, story personages, places, and scenarios. Blind children can understand more easily and thoroughly when working and learning with concrete materials first, and then interacting with the software (Roth, Petrucci, & Pun, 2000).

3. *Implementation*. During this stage, the software development was based on user-centered design, which makes the users and their opinions, interests, needs, thoughts, emotions, and behaviors key factors in the software's success. The same children that participated in Stage 2 also evaluated each iteration of the same program. The rapid prototyping model (Boehm, 1988) for software engineering was used.

4. *Validation*. The end users' usability evaluation was crucial in evaluating the blind user's understanding, affordances[6], visibility[7], mapping, and mental modeling of the software. The results obtained in the usability experience were later used for redesigning the software by tailoring it to the specific needs and mental models of blind children.

Based on the work of Shneiderman (1992), the researchers followed seven phases in each session of usability evaluation with end users:

a. *Introduction to the virtual environment*. The purpose of the testing and how to use input devices to interact with the applications were explained to the user. Facilitators (experienced special education teachers who specialize in working with visually impaired children) mediated the orientation process when the children were using the input devices;

b. *Software interaction*. Children navigated throughout the virtual environment and, according to their needs, they were encouraged to ask the facilitators for help in order to improve their orientation within the software.

c. *Anecdotal record*. Relevant data and observations of the child's interaction with the software were registered onto observation sheets by facilitators;

d. *Usability evaluation*. The facilitators asked the user questions from prepared questionnaires regarding issues such as icon usability and understandability during the software interaction, as well as an end-user questionnaire. These questionnaires are fully explained in the Instruments subsection below. On certain occasions, the children had to solve concrete tasks;

e. *Session record*. Each session was photographed and videotaped to register the child's behavior during the interaction;

f. *Protocol reports of the session*. All data from the child's interaction were archived for later analysis and revision. From these data we obtained comments, feedback, and suggestions in order to improve software navigation and interaction;

g. *Software design and redesign*. Each usability test ended with suggestions and comments from the children for redesign, change, and improvement. According to the comments and observations received from the session, the software was redesigned and new functions were added.

Following usability testing, a separate group of the blind users fully interacted with the software and solved problems using concrete cognitive tasks, thus learning cognitive skills as a consequence of interacting and using the software. They used real-world tasks and the virtual environment to assist in their learning and cognition. Cognitive evaluation is important in order to determine the impact that the use of the software has on learning and the development of cognitive skills, as demonstrated through cognitive tasks. The evaluation is based on the application of both qualitative and quantitative evaluation measures. These data, collected by different instruments, are described in the Instruments subsection below.

Game-Based Virtual Environments

AudioMath

This game (Sánchez & Flores, 2005; Sánchez et al., 2005) was modeled with mathematical content, and allows for the practice of audio memory by legally blind children, and for the practice of visual memory by children with residual vision. The tasks embedded in the game include the exercise of audio/oral, visual/oral, audio/image, and visual/image memory. By opening pairs of tokens on a board with several levels of difficulty, the child has to find the corresponding pair of tokens that agree with the current mathematical content presented. The game emphasizes the establishment of correspondence and equivalence relationships, the development of memory, and the distinguishing of tempo-spatial notions (see Figure 3).

AudioMath was designed to go beyond merely enhancing general domain skills, such as memory and tempo-spatial notions, by integrating mathematical content. The researchers embedded the game with mathematical concepts like position value, sequences, additive decomposition, multiplication, and division.

The Farm of Theo & Seth

This farm-themed game (Sánchez & Sáenz, 2005) presents the objective of learning mathematical concepts, such as position value, sequences, additive decomposition, addition, subtraction, and cardinality. This game includes motivating and engaging activities for learning through different levels of complexity, and stimulates the relationship between entertainment and learning, thus motivating children to interact with the game (see Figure 4).

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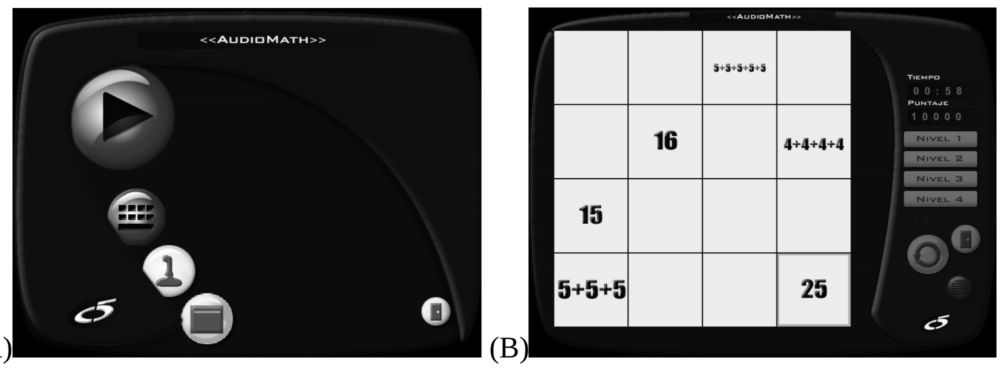


Figure 3. Screenshots of the graphic user interface (GUI) of *AudioMath*. GUIs are used by users with residual vision. (A) The user starts a new game by selecting the entrance interface: keyboard, joystick or tablet. (B) The game interface: On the left side there is a grid with paired cards and corresponding mathematics exercises; on the right side is the control menu.

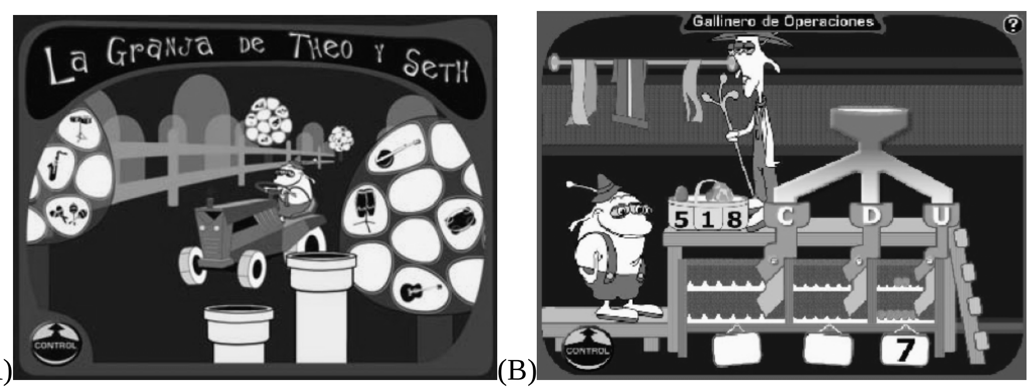
(A) (B)


Figure 4. Screenshots of the graphic interface of *The Farm of Theo & Seth*. (A) The main game interface puts the user into the context. (B) The Operations Henhouse requires the user to complete addition and subtraction exercises.

The game is separated into various learning areas in which the child can learn numbers and solve basic operations and problems. This spatial farm metaphor provides two major virtual environments: the numbers kitchen and the operations henhouse. The kitchen has two subenvironments: serving the food and interaction with kitchen utensils. Serving the food covers ordinal numbers (through the creation of a "numbers soup") and the kitchen utensils involves cardinal numbers (the position of utensils in numerical order, and information about preceding and succeeding numbers). The operations henhouse is a virtual space where children learn how to add and subtract. It also includes a help option to familiarize children with the keyboard.

AudioVida

This game, introduced in Sánchez & Sáenz (2006c), is targeted toward assisting with the development of problem solving skills. *AudioVida* emphasizes the implementation of different routes for displacement in a complex virtual environment, based on audio stimulation to facilitate reaching a specific destination and locating a particular object. To achieve this goal, the learner must analyze and interpret the virtual space by applying notions of spatiality and temporality. This favors the child's ability to recognize different possibilities for displacement, to exercise audio discrimination through the navigation of the virtual environment, to make a mental representation of the virtual space while moving, and to elaborate strategies used to navigate the environment through shortcuts (see Figure 5).

The user navigates the labyrinth assisted by audio orientation. The learner's immersion in the virtual environment is induced through spatial sound effects that indicate their position and provide references about walls, doors, elements with which they can interact, and intersections within the labyrinth. Children are informed about contextual changes through volume and the positional variations of the sound sources. When contexts are changing, learners receive an audio signal that defines the direction and closeness of the various game components, motivating learners to "walk through" the virtual labyrinth as they would do it physically.

AudioChile

This game attempts to analyze the development of problem-solving strategies (Sánchez & Sáenz, 2006a). The goal is for children to develop strategies for problem identification and planning, to execute those strategies for subsequent verification, and to develop a capacity for verification, reflection, and the generalization of their strategies for use in solving other problems in a given virtual hyperstory (see Figure 6).

Once immersed in the game's 3D world, the user can adopt a main character that could be a girl or boy. *AudioChile* takes place in three different regions of Chile: Chiloé, Valparaíso, and Chuquicamata. Information relevant to each zone is provided by searchable clues that allow children to visit and learn about aspects of Chilean geography and cultural traditions. The clues are specified by the different personages within the game, so if the user does not talk with these personages, he/she will never find the clues. To be able to virtually travel between the different zones, children must attain certain objectives that will help them in future tasks. Navigation in the virtual world is delimited by labyrinths that allow for

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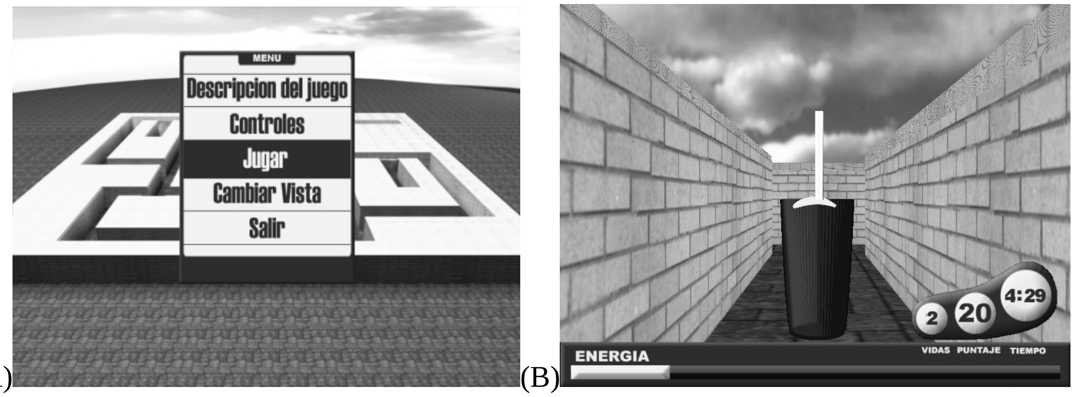


Figure 5. Screenshots of the graphic interface of *AudioVida*. (A) The main menu of the game shows that a new game will start. (B) The user navigates game labyrinths and encounters different elements that result in winning or losing a game, depending on the decisions made.

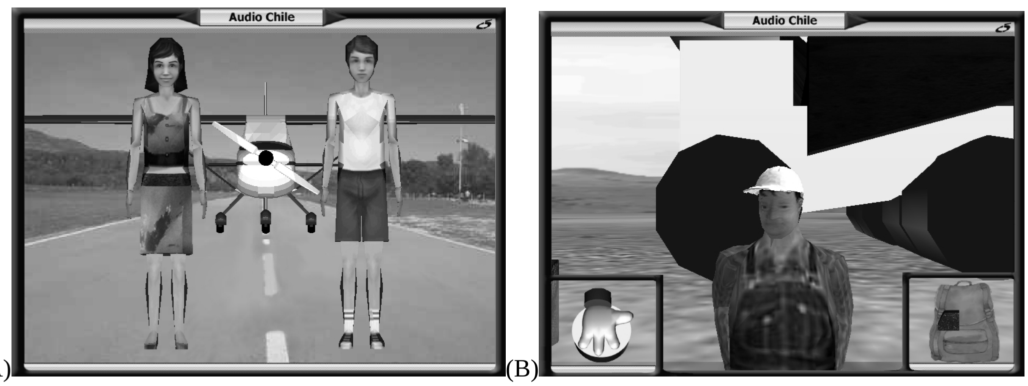
(A) (B)


Figure 6. Screenshots of the graphic interface of *AudioChile.* (A) Once the user has chosen to start a new game, an avatar from the virtual world is selected. (B) The user interacts with virtual persons in the game.

the character's mobility and freedom within certain parameters. Interaction occurs through avatar behaviors, such as taking, giving, opening, pushing, pulling, looking, speaking, using, traveling, and checking the backpack, as well as movements and turns. These actions are performed via the force feedback joystick and the keyboard.

All activities performed in the game, such as accessing the menu and actions taken during the story itself, have audio feedback (e.g., stereo sounds) so that the user can understand what is happening within the story. In navigating the virtual world, *AudioChile* uses 3D sound to provide a better sense of spatiality and immersion in the game.

System Requirements

All of these games were developed for a PC platform with the following system requirements: PC with the equivalent of a 1 GHz processor or higher, Microsoft Windows XP SP2, 128MB of RAM (256MB recommended), 32 MB DirectX 8 compatible video card required, sound card, 4 speakers or headphones required for audio (depending on the game) and keyboard.

AudioMath, *The Farm of Theo & Seth*, and *AudioChile* were developed using a Macromedia Director 8.5 framework, with Lingo language. In particular, *AudioMath* and *AudioChile* were developed with a library of routines for external joystick control, Xtra RavJoystick. *AudioVida* was developed with C++ language and an OpenGL library.

Instruments

Table 2 shows the use of the different evaluation instruments in the various methodology stages of each game's production.

Table 2. Evaluation Instruments Used for Each Methodological Stage.

Methodology Stage	Instruments	
	Usability	**Cognition**
Design	▪ Icon usability questionnaire ▪ Heuristic evaluation questionnaire ▪ Understandability questionnaire	
Implementation	End-user questionnaire	
Validation	End-user questionnaire	Cognitive Tests

Usability Evaluation

The main instruments used for the usability evaluation were icon usability, heuristic usability, understandability, and end-user questionnaires.

1. *Icon Usability Questionnaire*. This instrument was used for early evaluations of the interface. An icon evaluation questionnaire was taken during the usability sessions to evaluate the images and audio feedback by including an observation instrument with two parts: (a) a set of questions to identify the images of persons and objects in the game (for children with residual vision), as well as a section to record observations during the interaction, and (b) a set of questions to identify input/output sounds and any related associations made by the blind children. It also contained observations recorded during the interaction.

2. *Heuristic Evaluation Questionnaire*. The heuristic evaluation was based on systematic inspections of the interface made by two usability experts per each game. Researchers used heuristic evaluation questionnaires (Sánchez, 2000), designed using Shneiderman's (1992) "golden rules" and Nielsen's (1993, 1994) usability heuristics. The resulting test consisted of 12 heuristics, embracing a total of 25 items. These items were presented as a series of statements about which usability engineer experts had to indicate their appreciation using a 5-point Likert-type scale, ranging from *strongly agree* to *strongly disagree*. The 12 heuristics considered were: visibility of system status; the match between the system and the real world; user control and freedom; consistency and standards; error prevention; recognition rather than recall; flexibility and efficiency of use; aesthetic and minimalist design; assistance for children to recognize, diagnose, and recover from errors; help and documentation; content design; and media use.

3. *Understandability Questionnaire*. The problem-solving understandability questionnaire was applied during the interaction and consisted of 10 open-ended questions. The instrument was used to evaluate the understandability of the problems and tasks posed to the children, and of the related interface elements, such as instructions, sounds, visual and audio cues, voice, navigation issues, and strategies to find hidden cues.

4. *End-user questionnaire*. This instrument (Sánchez, 2003) was applied at the end of the usability sessions. It was basically a game acceptance test and consisted of 18 closed-ended questions based on a 5-point Likert-type scale, ranging from *strongly agree* to *strongly disagree*. Each of the answers was matched to a scoring scale from 5 to 1 respectively. The results can be grouped within five categories: (a) game satisfaction, (b) game control, (c) game usage, (d) quality of the game sound effects, and (e) game image and color quality.

Cognitive Evaluation

To evaluate the impact of virtual environments on blind children's cognition, researchers used a set of cognitive tests validated and adapted to the children's cognitive level and to the degree of their blindness. The Precalculus Test (Milicic & Schmidt, 2003) and Mathematics Knowledge Test of Benton & Luria, adapted for children with special needs by Chadwick & Fuentes (1980), were used to evaluate the impact of *AudioMath* and *The Farm of Theo & Seth* on the learning and practice of mathematical concepts. The purpose of the Precalculus Test is to measure the development of the mathematical skills of first-grade learners. The Mathematics Knowledge Test measures the capacity to understand oral and written numbers; the skills to make oral and written calculations; the skills to count numeric series and graphic elements; and mathematical reasoning skills. In the case of *AudioVida* and *AudioChile*, a part of the WISC-R (Wechsler Intelligence Scale for Children-Revised) test (Wechsler, 1981) was used. This test contains a subtest in two scales: manual and verbal. In particular, the verbal scale of comprehension was used because it did not need to be adapted for blind children. This scale determines the child's capacity to use practical judgments in the social situations of real life, referring to the child's common sense in real situations, and provides questions that can be asked in such situations. This is especially linked to the capacity of problem solving because the user has to be able to detect when and how to use his/her judgment and to ask questions to find a solution.

Cognitive Tasks

Once all the usability tests were completed, we evaluated the cognitive impact of each game. To do that, children who were not involved in the iterative usability interaction with the software were exposed to cognitive tasks during their interaction with the games. These tasks were designed and presented with concrete materials that represent structural and functional aspects of the virtual navigation, in order to develop and enhance different cognitive processes. Children understand some processes more fully when modeling and solving tasks with concrete materials during interaction with a virtual environment (Roth et al., 2000; Sánchez & Flores, 2004). Therefore, this methodology helps to improve the perception and abstract representation of interface elements. Audio-based virtual environments with accompanied cognitive tasks are crucial user-centered technologies for blind children.

For the cognitive tasks, researchers used concrete materials, and macro-type writing (traditionally in black ink for children with residual vision) and Braille (for children without vision) for the text portions. The idea was that children would transfer the tasks solved during virtual gaming to real-world tasks. For the games designed for mathematics learning, the researchers used the follow tasks (see Figure 7).

(A) (B)

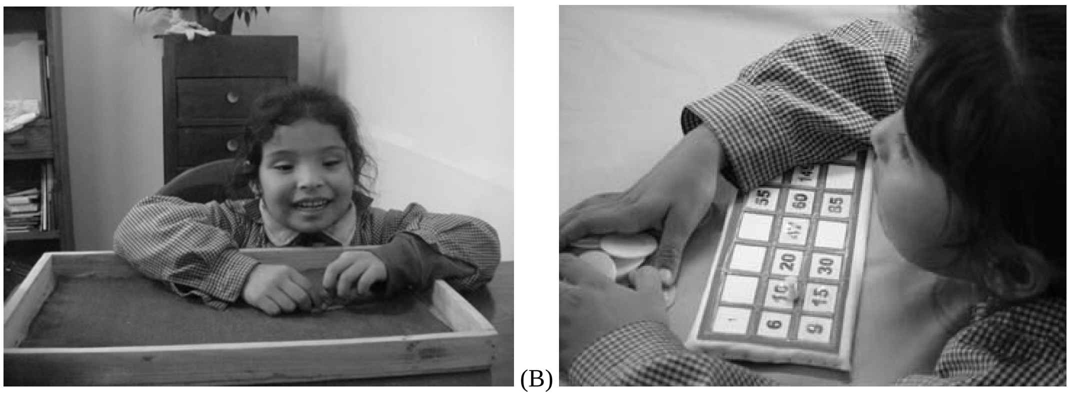


Figure 7. A blind user solves cognitive tasks related to mathematical concepts. (A) The user solves tasks of *AudioMath* by playing a *Game of Slug.* (B) The user solves the tasks of *The Farm of Theo & Seth* by playing the *Lottery*.

1. *Roulette*. Learners spun the roulette to obtain a number and indicated the numbers coming before and after that number. Then the students exchanged questions with their peers about the numbers prior to and following other specific numbers. The idea was to motivate students to ask related questions and to prepare answers to correct their peers, if necessary.

2. *Game of Slugs*. Children participated in a race against time with four stops, each one with a mathematical exercise. Each child had to go through the four stops by solving the exercises. Once a child solved the four exercises, another student started the game

3. *The Lottery*. Learners played the lottery in which the teacher randomly chose a number from the raffle box that indicated a mathematical exercise (addition or subtraction) for all the children to answer simultaneously. Once the exercise was solved, it was written on the player's card. The winner was the child who first solved an entire line of exercises across his or her card or filled the whole card with solved exercises, depending on the version of the game. The game continued until all children had at least a chance to successfully fill a line of correct answers.

4. *The Store*. The classroom was transformed into a small supermarket where learners could spend a certain amount of money. Each student entered individually and was assisted by a teacher. Learners had to plan and choose what to buy, and made as many subtractions and additions as was necessary to make their shopping needs fit the monetary limitations.

In regard to assisting the users with analytic and problem-solving skills, the children had several problem-solving games to conduct. They developed their own activities to solve three cognitive tasks associated with the virtual games (see Figure 8):

Task 1. To identify and comprehend the use of skills to solve problems posed by the virtual environment;

Task 2. To plan and design a strategy to fulfill the goal of the game;

Task 3. To recognize the spaces navigated in the virtual environment through concrete mock-ups.

The children then had to apply the same strategy they used virtually to meet the final goal in the physical world. All of these cognitive tasks were considered in analyzing the strategies used to solve problems when children with visual disabilities interacted with *AudioVida* and *AudioChile.*

(A) (B)

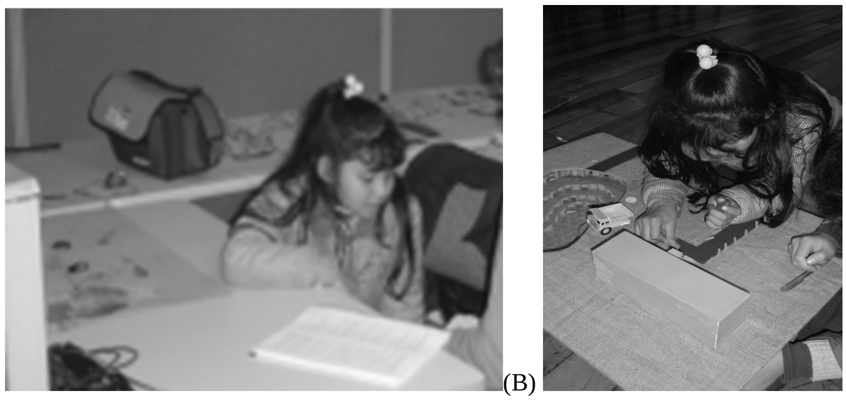


Figure 8. A Blind user solving cognitive tasks related to problem solving. (A) The user undertakes a spatiality and temporality task after she interacted with *AudioVida*. (B) The child solves a problem in which she must represent in the concrete mock-up the spaces that she navigated in the virtual environment *AudioChile*.

Procedure

The four games used for the research are sound-based virtual environments that support the learning and cognition of legally blind children. *AudioMath* and *The Farm of Theo & Seth* are games that assist in the learning of basic mathematics concepts through the use of different metaphors and dissimilar learning methodologies. *AudioMath* uses stereo sound and the user has to move through a grid. *The Farm of Theo & Seth* uses stereo sound too, but the child can navigate freely and autonomously by interacting with different interfaces. *AudioVida* and *AudioChile* are virtual environments to support the development of problem-solving skills. They differ in the way of representing the contexts. *AudioVida* uses stereo sound and the movement is made through a rigid labyrinth, while *AudioChile* uses 3D sound and the child can move more freely. These four games were implemented and evaluated concurrently.

The usability testing was implemented in three stages during 5 months at the Santa Lucía School. The first stage, during the initial development of the games, consisted of pretesting the various modules and prototypes with the participants, assisted by the facilitators. The objective was to obtain initial feedback about the sounds and images of the games, with the information used to form the design of the interfaces in the beginning of the implementation phase. To obtain more detailed information, researchers used the icon evaluation questionnaire.

The second stage was implemented after researchers processed the data from the initial testing and redesigned and improved the prototypes. Researchers used the heuristic evaluation and problem-solving understandability questionnaires to evaluate these more advanced prototypes.

In the third stage the researchers applied the end-user questionnaire to the same children at two different times following their interaction with each game. After each questionnaire was administered, researchers analyzed the data from both the open- and closed-ended questions and made decisions concerning the interface design/redesign. Both tests served to improve the usability of the game.

Interacting with the games and solving the cognitive tasks were the main emphasis of the overall studies. During these steps, the children were observed and assisted by two special education teachers, who filled in check lists and recorded the behaviors that they observed. The teachers also administered the usability evaluation tests and observed the children. Also the children were video recorded and photographed for a later evaluation.

Finally, upon completion the usability studies, the second group of children were administered cognitive tests during two 1-hour sessions per week, over a 3-month period. They followed the steps of the pretest by taking the cognitive test and then interacting with the virtual games. The cognitive tasks of the Roulette, Game of Slugs, Lottery and Store were then applied of *AudioMath* and *The Farm of Theo & Seth*, and separate problem-solving cognitive tasks were applied to *AudioVida* and *AudioChile*, where the children solved real-world tasks. Finally, the children were posttested by taking the cognitive test.

RESULTS

Usability

The development process of the four games for blind children resulted in relevant data that has implications beyond this paper. The implications of these results should be considered and used when other learning games are created, designed, and developed for blind end users.

From the understandability questionnaire, applied to all games, researchers primarily learned that sounds must always convey information to the blind user. The audio elements should not be used as simple interface ornaments, as they are in some software for sighted people. Further, it is important to maintain normalized sounds. They must be coherent with what is being represented.

The icon usability tests provided researchers with essential knowledge about the design of the graphical interface for children with residual vision. From the *AudioChile* evaluation, we found that a simplistic set of icon buttons is not adequate for these children; rather the design should be clear and direct, representing the associated functionality more exactly by considering the appropriate affordances. Moreover, to keep confusion to a minimum, it is important to provide clear instructions to children before and during the game interaction and that a guide should be present to facilitate complete understanding of the required task. As the user gains experience with the game, these instructions may be reduced. The visually impaired and, most importantly, totally blind children need a diversity of cues and instructions to make for a better orientation because their navigation through the virtual environment should be as much like their real environment as possible.

From the end-user questionnaire of the four games, researchers found that the motivation of both residual vision and totally blind children for using audio-based virtual environments was triggered by their acceptance of sounds and acoustics. Interacting with some of the virtual environments described above allowed the learners to differentiate and identify environmental sounds that helped them to navigate and orient themselves spatially in the virtual world. In the case of *AudioChile*, this interaction also contributed to improving their laterality and spatial concepts of up, down, left and right. When children recognized and accepted the sounds that were embedded in the virtual environments, they attained better control and navigability of the game. Moreover, the audio communication was fundamental for blind children to feel motivated to use and interact with sound-based game environments. Blind children needed clear and significant sound stimuli.

From *AudioChile*, the visibility[7] of the menus used in software applications for blind children was directly associated with their ability to navigate the games infinitely, thus creating a circular style of navigation. While sighted children expect to see all of the functions of the menu on their screens, the graphical interfaces for children with residual vision do not necessary need to provide all of the audio functions of the menu. Instead, it is enough to present the current item and allow the user to rotate through the other options, when necessary.

Furthermore, although many graphical interface elements are recognizable and used frequently by sighted children, there is no guarantee that the same results would apply to children with residual vision. The same applies to audio cues: Different sounds were tested and accepted by children throughout the series of studies summarized in this paper, generating a library of recognizable cues for blind children. Moreover, the classic ways of representing and performing actions in software is through the menus, which are organized in a certain hierarchy that allows for the visibility of the menu and direct access with a pointer, resulting in a multisensory interaction. However, when a blind user interacts with the menus through the keyboard (with or without the total visibility of the actions) he or she accesses only one action at a time. Therefore, the priority should not be the visibility but rather the ease of the user's navigation through the different options in the menu. For this reason the menus must be circular, allowing the blind user to select better the way he or she wishes to navigate.

The use of high contrast colors in the visuals of the four games was fundamental for children with residual vision, who will always try to use their vision for aiding the interaction within game-based virtual environments. The use of graphical screens allows for a higher degree of integration when sharing their experiences with sighted children. The majority of the characters and objects created in these games were identified by the children with residual vision, in some cases without the exact details but with enough clarity to recognize the context.

Figure 9 shows the results of the first and last usability tests. These are the average results obtained from all four of the games. For each of the statements the score goes from 1 point (*very low*) to 10 points (*very high*). Findings indicate that the interfaces developed are highly usable, especially in their acceptance, design, and use of audio and associated actions. The average score in the analyzed dimensions of the four games was 5.8 points in the first usability test and was improved to 7.4 points in the second usability test.

From the usability evaluation of *AudioMath* and *AudioChile*, the researchers found that the use of force feedback joysticks was an excellent aid for interaction. These devices allowed for information to be provided in conjunction with the audio, avoiding the excessive presence of sounds that could saturate and even confuse the user.

When a keyboard is used as an input interface in games, the keys that are easily recognizable for blind children, such as Enter, Space, Tab, and the directional arrows, should be utilized. Further, all QWERTY keyboards should have marks on the F and J keys that can be used as a reference for identifying and using the keys around them.

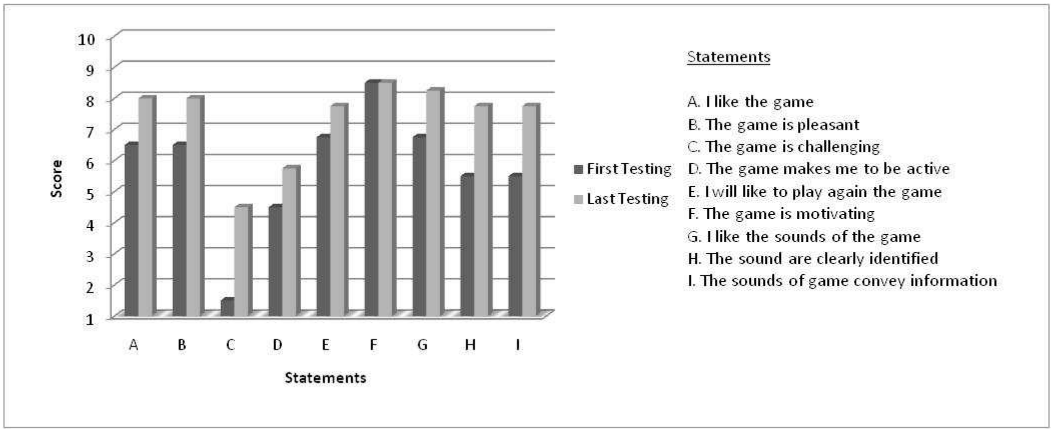


Figure 9. Combined mean scores of usability testing results for the four games for blind children: *AudioMath*, *The Farm of Theo & Seth*, *AudioVida* and *AudioChile.*

Cognition

From the application of the cognitive tests and tasks, researchers gathered data concerning the actual support that each game provided for the specifically targeted cognitive skills. From the analysis of *AudioMath* and *The Farm of Theo & Seth*, learners demonstrated that they can become quite agile in mental calculation when performing basic operations such as addition, subtraction, multiplication, and division. There also have been substantial gains in the learning of the abstract mathematical concepts involved in such operations (Sánchez & Flores, 2005; Sánchez et al., 2005). The children who worked with the mathematical games and associated cognitive tasks increased their knowledge of basic concepts remarkably. They also increased their ability to solve basic mathematics operations.

The mean score obtained in the pretest for *AudioMath* was 40.5 points and, after interacting with the game, the children demonstrated important gains, obtaining a posttest mean score of 74.3 points (see Table 3 and Figure 10). For *The Farm of Theo & Seth*, there was also an important pretest/posttest gain. In the pretest, children obtained 74 points; in the posttest children obtained 90.2 points.

Table 3. Pretest/Posttest Mean Scores in Mathematics Achievement after Playing *AudioMath* and *The Farm of Theo and Seth*.

SOFTWARE		PRETEST	POSTTEST
Audiomath	Mean	40.4900	74.2800
	N	10	10
	Std. Deviation	13.7259	12.2848
Theo and Seth	Mean	74.000	90.1667
	N	6	6
	Std. Deviation	23.5966	24.2439
Total	Mean	53.0563	80.2375
	N	16	16
	Std. Deviation	24.0701	18.6968

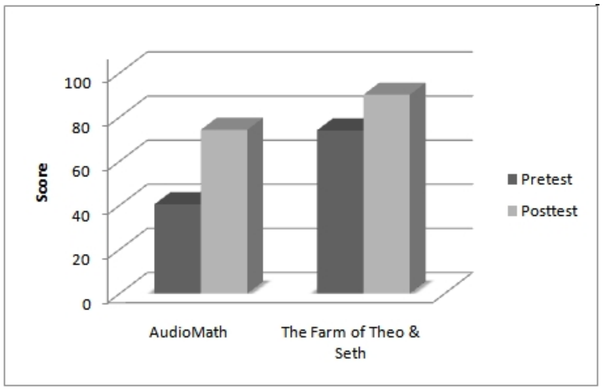


Figure 10. Children's achievement in mathematical skills following interaction with the virtual games *AudioMath* and *The Farm of Theo & Seth*.

By comparing *AudioMath* and *The Farm of Theo & Seth*, it can be seen in Table 3 that *AudioMath* children obtained lower pretest scores, but showed a higher pretest/posttest gains than *The Farm of Theo & Seth* children (34 points). *The Farm of Theo and Seth* children obtained a higher pretest and posttest performance scores than *AudioMath* children but a lower pretest/postest gains (16 points). It is important to notice that the games were applied to different aged user groups. The ages of the *AudioMath* children were from 8 to 15 years, while those for *The Farm of Theo and Seth* were between 7 and 8 years.

To analyze the statistical significance of pretest–posttest gains in *AudioMath*, the paired samples *t*-test was used. Significant pretest–posttest differences (t = -5.6; $p < 0.05$) were found between the groups, so it is possible to think that the game is the key factor for the increase in the scores (see Table 4).

For the game *The Farm of Theo and Seth*, pretest–posttest differences (t = -3.5; $p < 0.05$) were also significant. In this case we can also consider that the game was the main factor in explaining the differences in the scores (Table 5).

The analysis of *AudioVida* focused on verifying the children's skills in identifying the shortest paths from a fixed starting point to a certain goal. For this, a task was developed that consisted of locating one object inside the maze through several routes, and then indicating which one was the shortest path. Graphs, such as the one in Figure 11, were constructed using the information analyzed in these tests, showing that the more frequently the children utilized the game, the better they were able to accomplish the goal of identifying the most efficient route, thus decreasing radically the distance employed to attain the same objective.

In this case, the virtual environment and issues that the children faced in the problem-solving game allowed for the generation of adequate experiences for them to identify successfully the problematic situations, resolve them, and evaluate their actions. This was supported by the application of standardized tests to evaluate these types of skills. The results obtained from the evaluation of the impact of *AudioVida* on blind children have shown that these children can anticipate problems, plan, and apply different problem-solving strategies, explain the strategy proposed in the game and used to solve the problems, and transfer strategies to other contexts.

From the same analysis, researchers found that, once children explored the virtual environments, they were able to represent these environments through the use of concrete

Table 4. Paired Samples Test of *AudioMath*.

	Paired Differences					*t*	*df*	Sig. (2-tailed)
	Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1 PRETEST-POSTTEST	-33.7900	19.0141	6.1280	-47.919	-20.1881	-5.620	9	.000

Table 5. Paired Samples Test of *The Farm of Theo & Seth*.

	Paired Differences					*t*	*df*	Sig. (2-tailed)
	Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1 PRETEST-POSTTEST	-16.1667	11.4266	4.6649	-28.1581	-4.1752	-3.466	5	.018

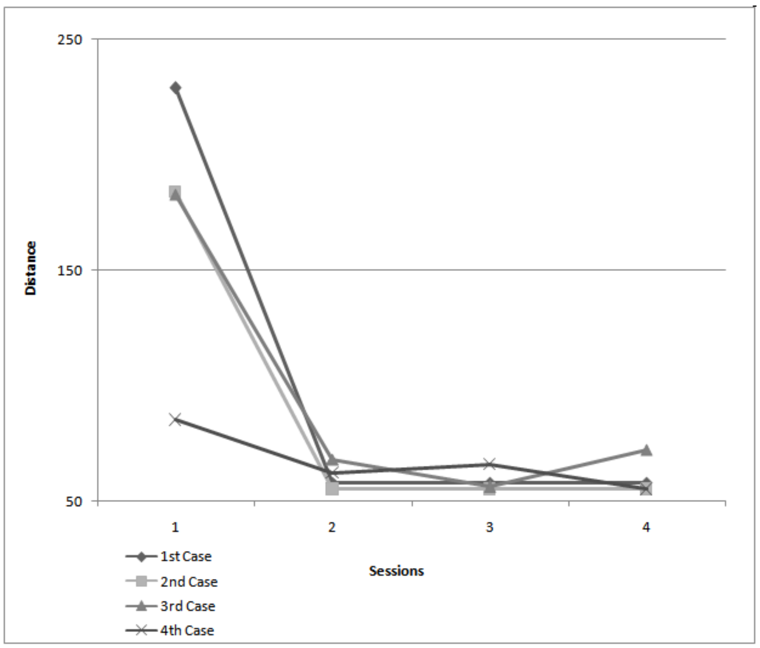


Figure 11. Learners' performances during interaction with *AudioVida*.

materials, showing exceptional skills for spatial and abstract memory. Due to the fact that they memorized the number of turns and the sequences necessary to obtain a representation of the explored route, the real-world reconstruction of the virtual map was directly related to the number of turns the user had to make, as well as to the number of times it took him or her to explore the labyrinth. When the user explored more than four times a certain route with no more than four turns, the resulting reconstruction was very faithful to the virtual environment. It is important to understand the degree of complexity of a space that a user can explore without getting lost.

The analysis of the impact of interacting with *AudioChile* on problem-solving data shows a different scene. As displayed in Table 6 and Figure 12, prestest/posttest mean scores show slight gains (from 6.2 points to 7.6 points). This was a small gain and a statistically nonsignificant difference between scores (t = -1.9; p = 0.13) was found between the groups. The game was not key factor in increasing significantly the scores even though there was a slight difference in the pretest/posttest mean scores (see Table 7).

Even though there was no statistically significant difference between the scores, learners were observed to have developed problem-solving skills after interacting with *AudioVida* and *AudioChile* (see Figure 12; see also Sánchez & Sáenz, 2006a,c). The different virtual environments and issues that the children had to face in the problem-solving games allowed for the generation of adequate experiences for them to identify successfully the problematic situations, resolve them, and evaluate their actions.

Table 6. Pretest/Postest Problem-Solving Mean Scores of *AudioChile.*

		Mean	Sample	Standard Deviation	Standard Error Mean
Pair	PRETEST	6.2000	5	4.0866	1.8276
1	POSTTEST	7.6000	5	2.9665	1.3266

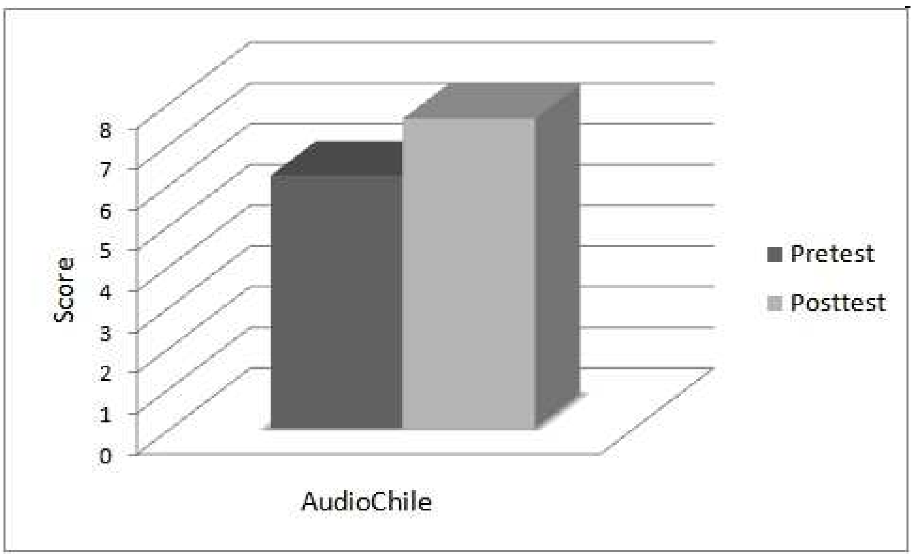


Figure 12. Pretest/postest problem-solving mean scores of *AudioChile.*

Table 7. Paired Samples Test for Problem-Solving Results of *AudioChile.*

	Paired Differences							
				95% Confidence Interval of the Difference				
	Mean	Std. Dev.	Std. Error Mean	Lower	Upper	*t*	*df*	Sig. (2-tailed)
Pair 1 PRETEST-POSTTEST	-1.4000	1.6733	.7483	-3.4777	.6777	-1.871	4	.135

DISCUSSION

The purpose of this report was to review, summarize, and illustrate the work of four audio-based games created through a user-centered design methodology of successive usability tasks and evaluations. Frequent usability testing was crucial to be able to map the end users and their understanding of the game-based applications. Learners liked, accepted, used, and were very motivated by the games. After designing and redesigning the 3D sound interfaces, the children were able to map and navigate comfortably throughout the virtual environments.

The main axis of the researchers' line of research was the development of audio-based interfaces to increase blind children's learning and cognition, in which audio was used to convey information and knowledge. The research studies' analyses identified key interface issues necessary to map blind children's mental models, needs, and ways of interacting. It is very important to be aware of such matters when designing games for blind children because these considerations can determine the success or failure of a software project.

These findings confirm the idea that it is not enough to simply add audio to an existing application or to use screen reader tools to assist blind children in their interactions with technology. The mental model of blind users is unlike that of sighted people in that their styles of interaction to perceive and process stimuli and information are quite different. The challenge then is to create custom-made games for these children, such as the ones presented in this paper.

These studies demonstrate that the sense of hearing is a capable substitute for vision in its capacity for perceiving information and in the quantity and nature of the information that can be perceived. This reality should be considered for software design purposes when the children are sight-impaired. In the development of these interfaces, it is relevant to implement numerous usability evaluation methods to identify the interfaces' proximity to the blind children's needs, interactive modes, and mapping of mental models. It is also necessary to consider the methodology, instruments for evaluation, and the cognitive tasks used to design and implement usable interfaces for blind children.

Generally, the tools introduced in this report have allowed blind children to differentiate and identify ambient sounds that help them to orient themselves in various spaces, and to navigate and interact with objects and entities in virtual worlds. They have also contributed to improving cognitive laterality and spatial concepts, such as up, down, left, and right. Spatial sound has always been an important interface component in the research on game-based virtual environments. However, it is a critical aspect in the blind children's cognition that widens the scope for the use of other senses for learning and cognition. Thus through an ample variety of audio stimuli, children can stay alert and be motivated during their interaction with the game. Perhaps most importantly, audio can help them to actively construct knowledge. Spatial sound is especially required for newly blind children, who urgently need to minimize the deficiencies in accessibility that separates them from the cognitive experiences of sighted children.

Cognitive tasks accompanying the audio-based games were very helpful for children with visual disabilities who participated in the cognitive evaluation because the tasks improved the children's active tactile experience. Researchers observed that when children enjoyed using the concrete materials, and when the experiences were based on real life, the interest in learning and exploring increased. This is fundamental for children with visual disabilities because, with the total or partial loss of vision, the ability to understand through tactility allows them to construct meaningful learning experiences. For this reason, software designed for the sight impaired should be accompanied by related cognitive tasks so that the learning achieved virtually can be constructed tangibly and effectively. Such a process permits the knowledge to be transferred to different settings and experiences. Finally, these studies have demonstrated that sight-impaired children can learn with a decrease in verbalism, which is the typical teaching behavior for children with visual disabilities.

As a result, significant improvements were achieved in learning and cognition by using audio-based games that were specially tailored as a medium for interaction through user-centered technology for blind children. These findings indicate that user-centered software for blind children can help to support and develop their intellectual capabilities, thus helping to close the gap between sighted and blind children.

ENDNOTES

1. Mental model: Users' individual thinking and reasoning about themselves, others, the surrounding world, and the interacting objects.
2. Digital native: A user who has been surrounded by technologies since birth, and thus is capable of using them naturally and transparently.
3. Digital immigrant: A user who has learned to use and adapt to technology.
4. Three-dimensional (3D) Sound: Sound that comes from all directions surrounding the user, allowing the person to determine the distance and location of the sound.
5. Mapping: The natural relation between the control of an interface and its functions.
6. Affordances: Properties that determine how objects should be used.
7. Visibility: Major parts of an interface should be easily identifiable.

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