3D sound interactive environments for blind children problem solving skills

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Audio-based virtual environments have been increasingly used to foster cognitive and learning skills. A number of studies have also highlighted that the use of technology can help learners to develop effective skills such as motivation and self-esteem. This study presents the design and usability of 3D interactive environments for children with visual disabilities to help them solve problems in Chilean geography and culture. We introduce AudioChile, a virtual environment that can be navigated through 3D sound to enhance spatiality and immersion throughout the environment. 3D sound is used to orientate, avoid obstacles, and identify the positions of various characters and objects within the environment. We have found during the usability evaluation that sound can be fundamental for attention and motivation purposes during interaction. Learners identified and clearly discriminated environmental sounds to solve everyday problems, spatial orientation, and laterality.

Keywords: Hyperstories; 3D sound; Virtual world; Problem solving; Role-playing game

1. Introduction

People with visual disabilities perceive the surrounding world differently to sighted people. In order to orient and mobilize in the real world they have to learn to exploit other senses such as touch and hearing. To orient spatially within a surrounding environment is a complex process that requires learning to explore smells and textures as points of reference to search for objects in the environment.

Children with visual disabilities need to learn how to use their sense of hearing to interpret the surrounding world, localize sounds that serve as cues to orient and mobilize autonomously. Spatial sound stimuli can provide a stimulating atmosphere for developing thinking skills to cope with everyday situations and solve current problems and issues with independence.

Blind children are increasingly having more contact with virtual environments (Mereu and Kazman 1996, Cooper and Taylor 1998, Sánchez 1999, 2001, Lahav and Mioduser 2000, McCrindle and Symons 2000, Westin 2004, Sánchez and Aguayo 2005, Sánchez and Baloian 2005, Sánchez and Sáenz 2005). Computer games have been used for entertaining purposes by using accessibility interfaces.

However, few initiatives have focused on the design of games to develop and rehearse cognitive skills in children with visual disabilities (Sánchez 2003, Kurniawan *et al.* 2004).

Applications conceived for users with visual disabilities have been developed using auditory information as the main output channel and haptic devices for input (Mereu and Kazman 1996, McCrindle and Symons 2000, Baldis 2001, Sánchez 2001, Sánchez *et al.* 2004a,b). These systems have been principally developed to help blind people overcome their difficulties with standard interfaces such as the Web page 'reader' Jaws®. Other focus is the development of 3D audio interfaces used to develop skills to recognize spatial environments through sound. However, we have no record of research work on virtual environments for problem solving by children with visual disabilities.

Sound has also been used as input and output to help develop learning and cognitive skills in blind children. Most applications use spatial sound to help children develop

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abstract and short-term memory, haptic perception, collaborative skills, spatial abstraction, mathematics skills, and algorithmic thinking skills (Sánchez 1999, 2001, Sánchez *et al.* 2004a,b, Sánchez and Aguayo 2005, Sánchez and Baloian 2005).

An experiment with audio stimuli to simulate visual cues for blind learners (Mereu and Kazman 1996) have found that 3D audio interfaces help them localize specific points in a 3D space concluding that navigating virtual environments through sound can be a precise task for blind people. Other studies describe positive effects of 3D audio-based virtual environments (Cooper and Taylor 1998).

Authors have used sensory virtual environments through force feedback joysticks simulating real-world places such as the school, concluding that by providing appropriate spatial information through compensatory channels the performance of blind people can be improved (Lahav and Mioduser 2000).

A research work replicated the traditional computer game Space Invaders by using 3D sound. Authors used force feedback joysticks as the input device to allow blind and sighted children to share the same experience (McCrindle and Symons 2000).

Authors evaluated the skill of bearing in mind a specific localization without concurrent perceptual information or spatial update through the use of audio stimuli to trace specific places through sound (Loomis *et al.* 2002).

A study to design and evaluate a spatial audio system that models the acoustic response of a closed environment with varying sizes and textures for a blind user was implemented, concluding that there was almost no difference in user perception of room sizes between sounds in real and simulated scenes (Kurniawan *et al.* 2004).

Finally, a real-time 3D graphic game for low-vision gamers was developed to propose general methods of making real-time 3D games accessible. These methods can be used in virtual reality applications, e-commerce, and distance learning (Westin 2004).

Studies to enhance problem-solving skills through 3D sound in blind children are scarce. This research study presents the design, development, and usability testing of AudioChile, a 3D sound interactive environment for children with visual disabilities. The system was designed to assist learners to solve everyday problems and thus explore the life, culture, and idiosyncrasy of different geographical regions of Chile.

AudioChile is a role-playing game. Children have to travel through main Chilean regions where different hyperstories occur. The interaction is through sound and music. Within a region the child takes on a character and navigates through virtual environments looking for cues and information to perform actions and make decisions. At the end the child can understand the whole picture and information about the adventure.

2. Purpose of the study

The main purpose of this study is to design 3D virtual environments based on hyperstories and assisted by stereo and spatial sound to develop problem-solving skills in children with visual disabilities. This includes searching, mobilization, localization, designing strategies, and orientation skills.

Our study also includes a usability evaluation of the virtual environment. We have studied: (1) 2D and 3D graphic interfaces for children with residual vision, (2) stereo and spatial sound interfaces, and (3) problem-solving strategies developed when using AudioChile.

3. Model

AudioChile is based on a model for implementing educational software for children with visual disabilities (Sánchez *et al.* 2004a, Sánchez and Baloian 2005). It is centered on providing facilities for evaluation purposes and giving prompt feedback to the user. It also clarifies, for implementation purposes, similarities and differences between software for people with and without visual disabilities. The resulting architecture model after applying the developing model is depicted in figure 1.

AudioChile has a *model* (metaphor) that represents three major Chilean cities. The user navigates through these cities searching for cues and information to solve a posed problem.

Editors consist of a virtual world and the definition of its properties, objects, and characters.

The *knowledge representation model* is based on the mapping of real-world behaviors in a virtual world, state variables (physics, kinetics, and luminous), and actions.

The *strategy* (AI) is in charge of following up the actions performed by the user. It provides a compass that perceives the user's orientation within the virtual world, helping him to navigate and take actions.

The *learner model* is such that as the user goes through the adventure he can learn and process more information to solve a problem in order to reach the end of the story.

Evaluation is that of the compass to provide information to the user to find various objects and characters within the virtual world.

Projection consists of 3D images and virtual sound worlds. It explores diverse fine representation qualities to achieve a high standard of use as well as to solve the problem posed.

4. Software description

AudioChile is composed of diverse hyperstories (Lumbreras and Sánchez 1997). Once immersed in the 3D

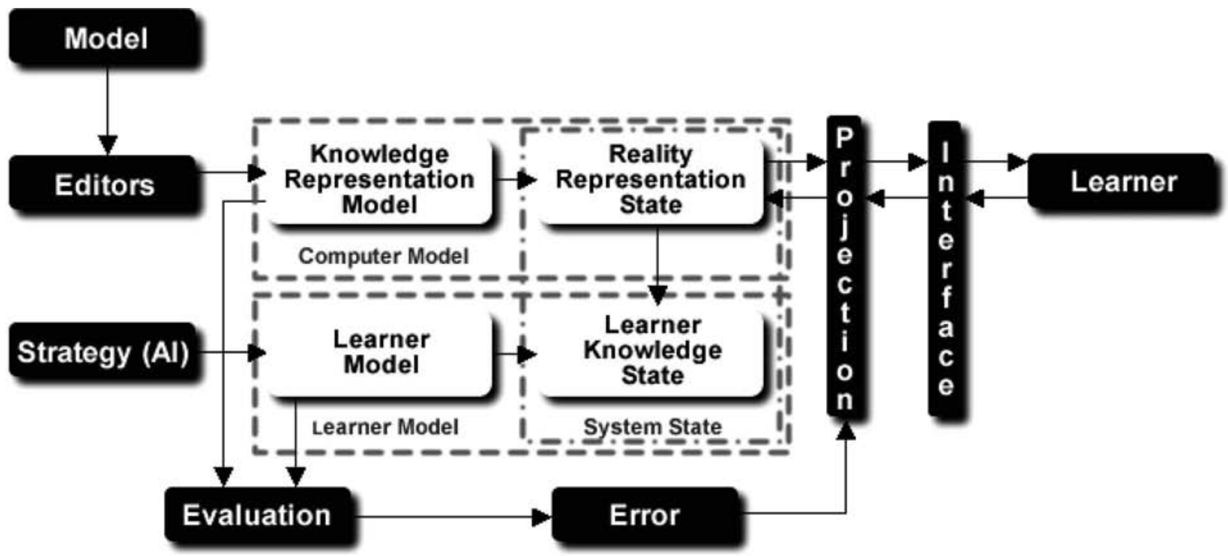

Figure 1. Architecture of the resulting software (Sánchez and Baloian 2005).

world the user can adopt a character that can be a girl or boy. Each story consists of an adventure that occurs in one of three geographical regions of Chile. The learner navigates, interacts, and solves tasks and problems. The overall story is that the child must find a copper ingot in the region of Chiloé (south) and return it to the region of Chuquicamata (north). To do this the child needs to follow directions and cues given by some characters throughout the story. They constitute a subset of the major problem concerned with returning the ingot to Chuquicamata (see figure 3).

Virtual people and objects have been designed for the 3D virtual world. All are designed according to real characters of the geographical zone in the story.

Interaction occurs through actions such as to take, give, open, push, pull, look, speak, use, travel, check the backpack, movements, and turns (90 and 180 degrees). These actions can be done by using the force feedback joystick and keyboard.

Diverse interactive components have associated actions defined by a matrix that crosses the user's behavior and there are different elements to represent the viability of the operation.

Through the 'take' action the character can load elements during the adventure that can serve in future actions. To do this there is a virtual backpack to save these elements. The backpack is an interactive element that can be accessed and the content saved inside it can be checked to be used in conjunction with the surrounding environment.

All actions performed in the software such as accessing the menu and actions during the story itself have audio feedback, e.g. stereo sounds, so the user can understand what is happening in the story. To navigate through the virtual world AudioChile uses 3D sound to provide a better sense of spatiality and immersion in the game. Orientation is provided by spatial sound emerging from obstacles such as the boundaries of the labyrinth as well as the position of characters and objects within the virtual environment. If the user performs an illegal action for a certain element an error feedback is provided. Thus, interaction with the software can occur both generally and specifically.

AudioChile is performed in three Chilean regions: Chiloé, Valparaíso, and Chuquicamata. Relevant zone information is provided by hidden cues that allow users to visit and learn aspects of the geography and traditions of Chile. To travel between different zones users must attain certain objectives that can help them in futures tasks.

Virtual world navigation is delimited by labyrinths that allow mobility and freedom to the character within certain parameters (turns of 90 and 180 degrees, and move forward). In any moment the user can save the story or load it from the same leaving point when quitting the game. Each time the user interacts with different characters in the game a log file is created to register the results of the session. This information is used to create a story at the end of the adventure that summarizes the actions performed throughout the game and how they solved the posed problem (see figure 2).

AudioChile has a compass to orient the user when interacting with different objects and characters in order to solve the problem posed.

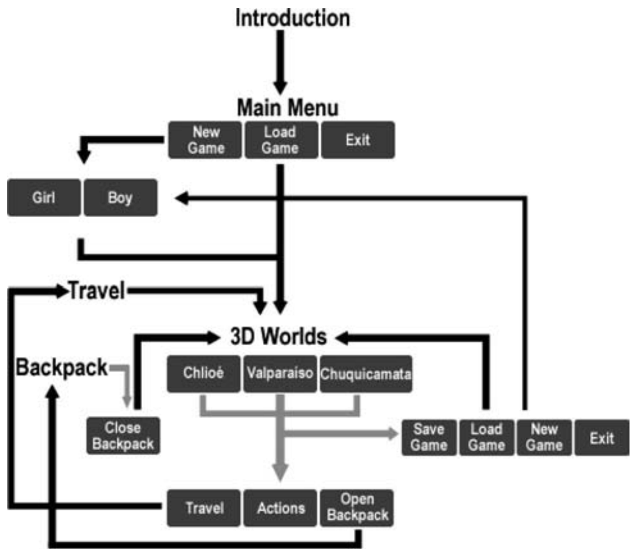

Figure 2. The navigation map.

The interface allows easy access and navigation in the software. Users with residual vision can identify elements on the screen through the use of contrasting colors and well-defined images.

4.1 *Mazes and interfaces*

AudioChile has defined virtual environments of some Chilean cities. They consist of three different labyrinths that the user has to navigate through the selected character. There are also objects and characters with defined positions within the virtual world (see figure 3).

Three virtual environments represent three Chilean cities. Each virtual world can be navigated by interacting with textures and special sounds. Each city consists of a spoken introduction with a typical music of the zone. Within the travel environment there are some representative places of different cities in order to trace the travel through Chile (see figure 4).

5. Usability testing

5.1 *Participants*

The sample consisted of 6 Chilean children with visual disabilities, 4 boys and 2 girls aged 10 to 15 years that attend the school 'Santa Lucía' for blind children in Santiago, Chile. Three children have low vision and three children have total blindness. Two of them are blind from birth, one child acquired blindness during childhood, two with good residual vision, and one with poor functional residual vision. Two special education teachers and one usability expert also participated in the study.

Children participated in four testing sessions each over four months. Each session was especially dedicated to one child in order to allow him to 'walk' through the software thoroughly.

5.2 *Methodology*

Each usability testing consisted of the following steps.

- *Introduction to the software*. The user receives explanations about the purpose of the testing and how to use the keyboard to interact with AudioChile. Teachers mediated by helping children to orient when using the keyboard.
- *Software interaction*. Users have to navigate throughout the virtual environment and according to their needs they can ask teachers for a better orientation.
- *Anecdotal record*. Key data and observations of the child's interaction with the software are registered.
- *Application of usability questionnaires*. The user answers questions asked by special education teachers.
- *Session recording through photography*. Each session was photographed to register the child's behavior during interaction.
- *Protocol reports of the session*. All the data from the child's interaction is registered to get comments and suggestions to improve the software navigation.
- *Design and redesign*. According to the comments and observations received the software is redesigned and some new functions are added.

5.3 *Instruments*

Three usability questionnaires were used: (1) end-user questionnaire, (2) prototype interface evaluation questionnaire, and (3) problem-solving understandability questionnaire. The end-user questionnaire was applied at the end of the usability sessions. It is basically a software acceptance test and consists of 18 closed statements with an answer scale of 1 to 10. It also contains five open questions. The prototype interface evaluation questionnaire was applied during the usability sessions. It is intended to evaluate images and audio feedback by including an observation instrument that has two parts: (1) a set of questions to identify images of characters and objects in the software, as well as to record observations during interaction, and (2) a set of questions to identify input/output sounds and related associations made by blind children. It also contains observations recorded during interaction. The problem-solving understandability questionnaire was applied during interaction and consists of a questionnaire with 10 open questions to evaluate the understandability of the problems and tasks posed and

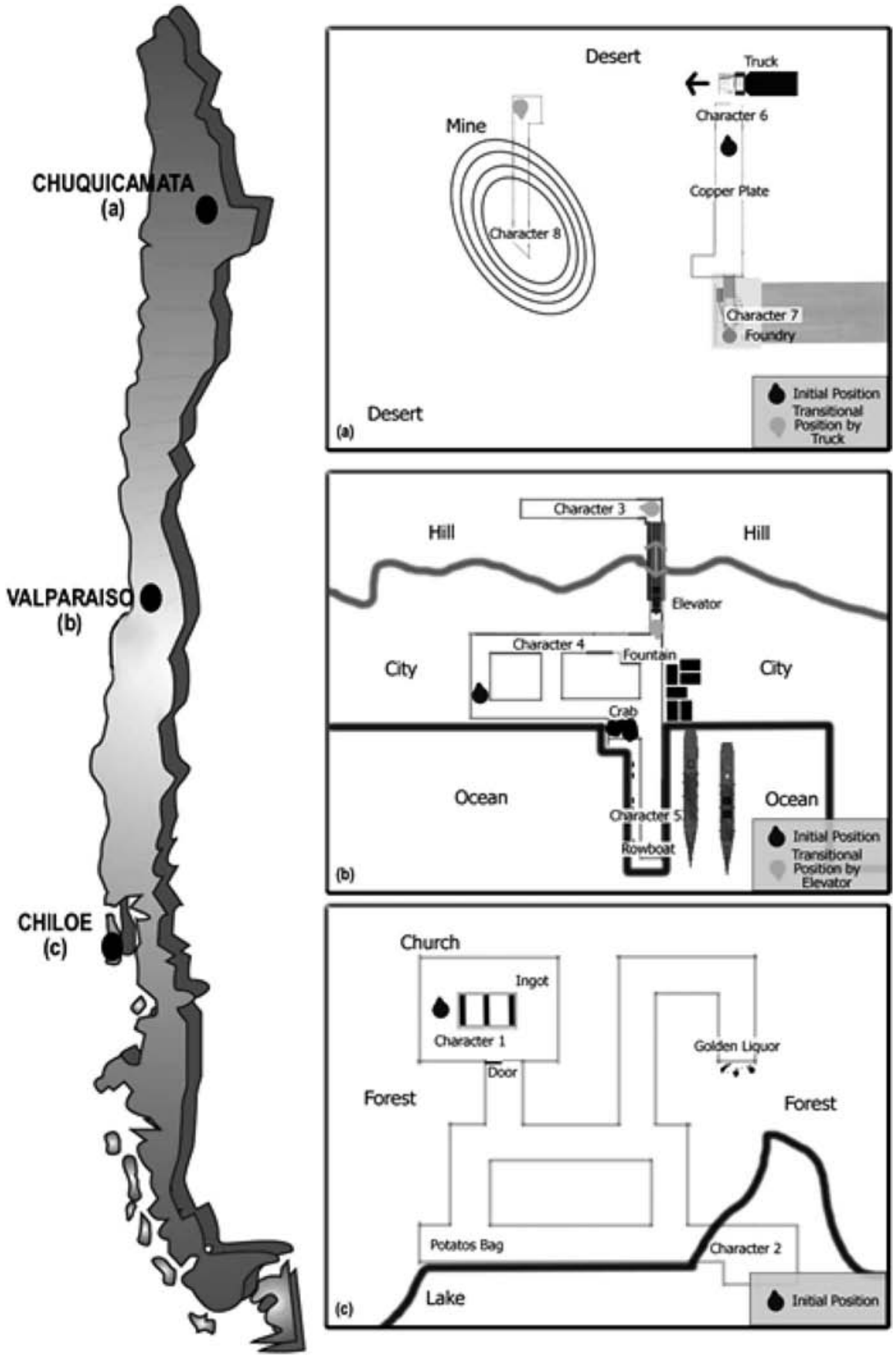

Figure 3. Labyrinth of three Chilean cities: (a) Chiloé, (b) Valparaíso, and (c) Chuquicamata. (Golden liquor is a typical liquor of the Chiloé zone.)

related interface elements such as instructions, sounds, visual and sound cues, voice, navigation issues, and strategies to find hidden cues.

5.4 *Procedure*

The usability testing was first implemented in March 2004. Children pre-tested early prototypes of AudioChile during interaction (see figure 5). The objective was to have an initial feedback about the sounds and images of the software in order to have information early in the implementation phase to orient the final design of interfaces. To get more detailed information we used the interface evaluation questionnaire.

The second stage of the usability testing was implemented in April 2004 after we processed the data from the first

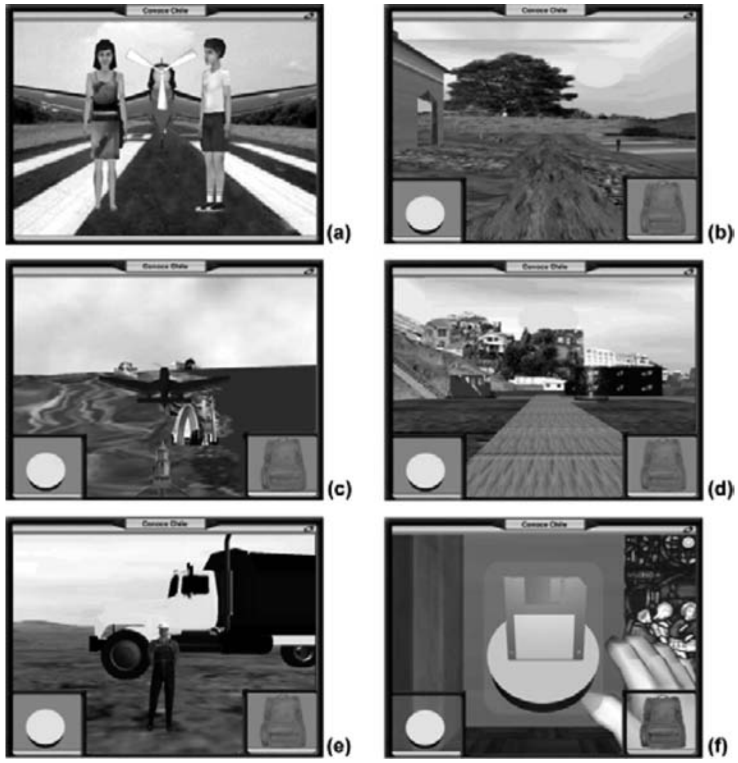

Figure 4. Screenshot of the graphic interface of AudioChile: (a) character menu; (b) Chiloé; (c) travel; (d) Valparaíso; (e) Chuquicamata; and (f) option menu (save game).

Figure 5. A blind user interacting with AudioChile.

testing and redesigned and improved the prototype. Therefore at this stage we had a more advanced prototype. We used the prototype interface evaluation questionnaire.

The third stage of the usability testing was applied in two parts. We applied the end-user questionnaire to the same sample at two different times: May and July. We analyzed data from open and closed questions after each application and made decisions about interface design and redesign. Both applications served to improve the usability of AudioChile.

5.5 *Results*

The application of the prototype interface evaluation questionnaire provided us with information about the presentation and use of graphics and sound interfaces. The interfaces for the action menu of the character were first planned in 2D format. These initial icons easily understood by sighted users were not appropriated in their representation for users with residual vision. For this reason we replaced them with more representative images of associated actions to have a better effect on the user. This representation was made in a 3D format.

We also realized that there was a need for sound feedback to allow certain logic of actions so we associated a characteristic sound to each action. For opposite actions we also provide the same feedback but inverted. In the same line, we used the keystrokes with some relief (F, J) and those that surround them to orient easily around the keyboard.

The design of AudioChile was specially developed for blind children. Thus we emphasized the presentation of menus with one feature available at a time based on the concept of a circular menu. This idea came out after realizing that when designing software for sighted children the pointer of the mouse is crucial in the interface as well as always maintaining visibility by highlighting relevant controls and functions. Children with visual disabilities do not need to have a total visibility of the menu. Actually they currently select one option and then go through all the functions of the menu by using the keyboard. This gives more screen space to improve the design.

The idea of mapping objects through sound according to the four cardinal points (north, south, east, and west) worked very well for the users, allowing them to identify behaviors such as reaching a wall, a border of the forest, and a beach avoiding colliding with some elements of the virtual world.

The sounds associated to the steps of the character on different types of roads were modified many times to find the adequate sound for the steps and the type of terrain where the user walked.

From the application of the problem-solving understandability questionnaire we obtained relevant information about the use of the software, the understanding of the main instructions, the idea of finding a lost object, and thus understanding the whole problem. Children used the keyboard adequately and understood that the character can take objects from the virtual world and save them in a backpack. They also identified, received, and understood the information provided by the software and applied it during the game.

Only one learner needed some mediation to navigate through the software, perhaps due to the fact that the introduction to the software was too long. He may have lost the main objective and key directions on how to use the software. This needs to be improved to get a better response from users.

The application of the end-user questionnaire provided us with very important information. We present this data by contrasting the software acceptability of children with residual vision and those who are totally blind. Later we present data comparing the results of the pre- and post-testing.

5.5.1 Contrasting users. The motivation to interact with AudioChile was evaluated. To do this we posed 6 statements in the end-user questionnaire: (1) I like the software, (2) AudioChile is pleasant, (3) The software is challenging, (4) AudioChile makes me be active, (5) I would like to play the software again, and (12) The software is motivating. The possible scores spanned from 1 (very low) to 10 (very high).

Children with residual vision showed a great motivation to interact with the software, obtaining average scores between 9 and 10. Blind children mentioned a little lower motivation, with scores between 7 and 9 points (see figure 6). This is a very interesting result because in general children with visual disabilities of our sample were motivated to interact and walk through AudioChile.

A second relevant aspect was the software utilization. The statements considered were: (9) I felt in control of the software, (11) The software is easy to use, and (13) AudioChile adapts to my pace. Users with residual vision did not have difficulties when using the software (scores 8–10). Blind users had more difficulties in interacting with AudioChile (scores 5–7). Controlling the software and the ease of use was more complex to blind children. Most children with visual disabilities mentioned that AudioChile adapts to their pace (scores 7–10) (see figure 7).

To evaluate the sounds used in the software we considered the following statements: (15) I like the sounds of the software, (16) The sound is clearly identified, and (17) The sounds of AudioChile convey information.

As depicted in figure 8, children with residual vision highly accepted the sounds (score 10). Blind children also accepted the sound of AudioChile (scores 9–10). This was a very sensitive aspect of this study because the software relies heavily on diverse sounds and voices.

5.5.2 Pre- and post-testing. We also analyzed the users' final acceptance of the software before and after we redesigned and improved the software based on the results and requirements detected with the prototype interface evaluation questionnaire and the problem-solving understandability questionnaire.

The contrasting results are displayed in figures 9 and 10. We can observe that motivation increased after redesigning the software, especially in software acceptability aspects such as likeability and pleasantness of the software as well as the activity of the user. The acceptation of sounds increased after software redesign.

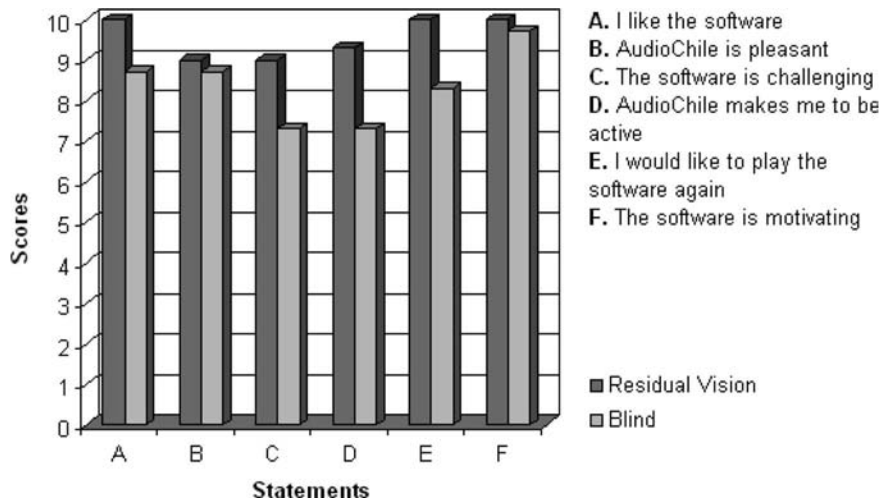

Figure 6. Motivation when interacting with AudioChile.

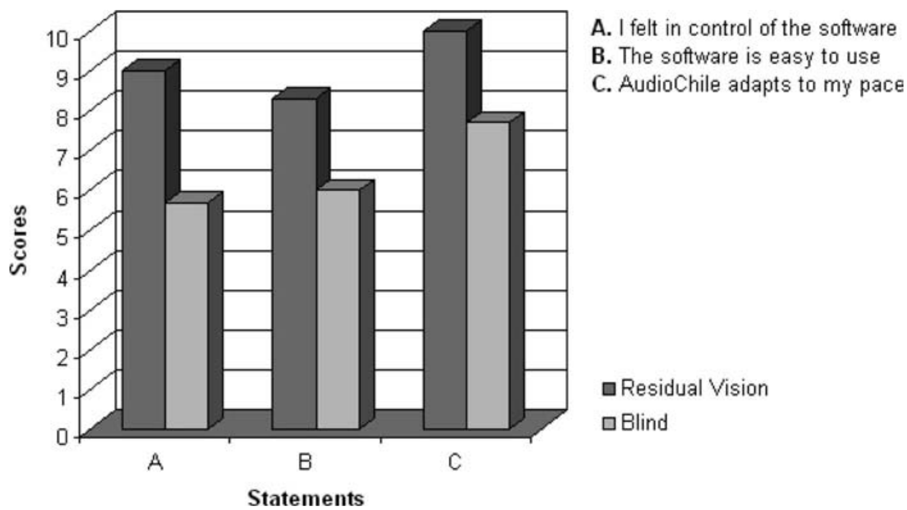

Figure 7. The use of AudioChile.

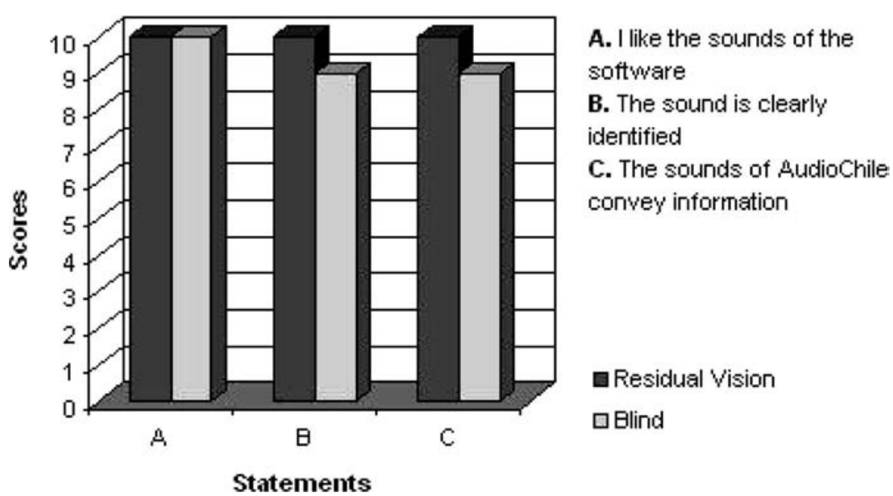

Figure 8. Perception of sounds of AudioChile.

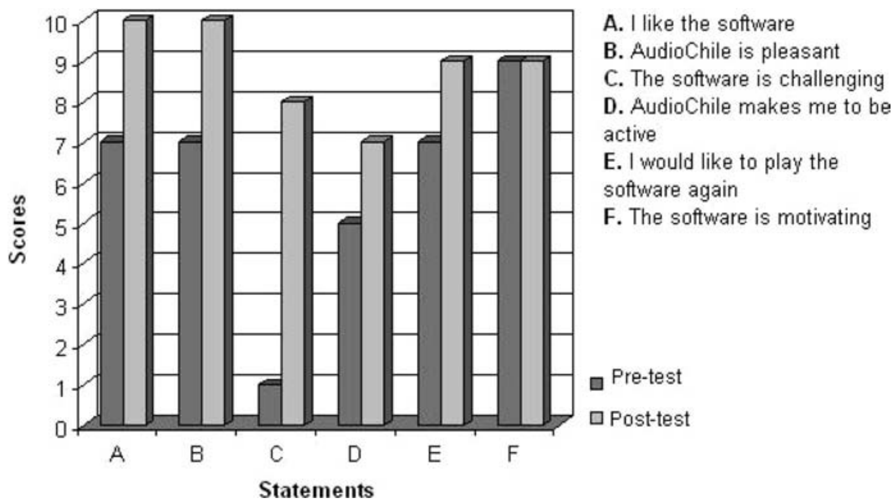

Figure 9. Motivation when interacting.

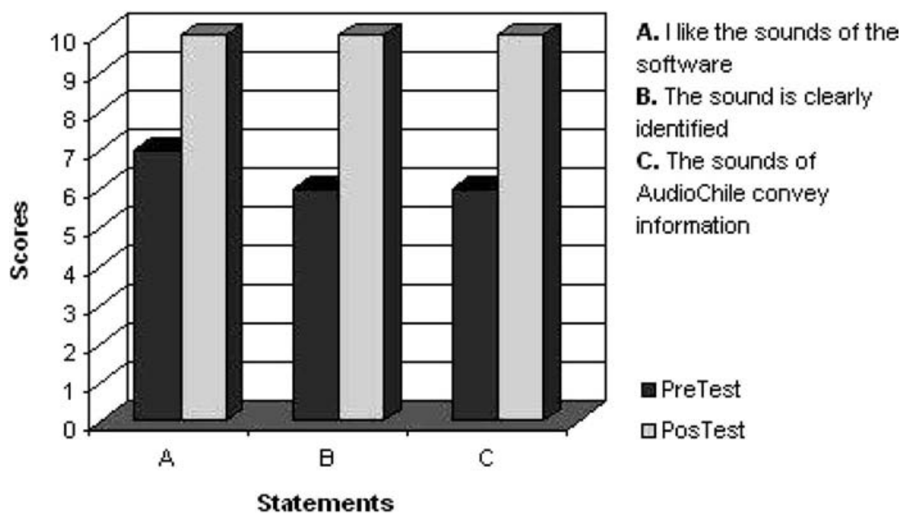

Figure 10. Perception of sounds of AudioChile.

These results confirm our beliefs and experience concerning the importance of testing and retesting the software during implementation in order to design and redesign as much as possible when designing software for children with visual disabilities.

6. Impact on problem solving

We also pilot tested the cognitive impact of AudioChile. We were interested in knowing what type of problem-solving strategies can be developed by using this virtual environment, the paths followed and how sound helps these children to develop cognitive strategies to solve everyday problems outside the virtual software.

6.1 *Design*

This sample consisted of 5 Chilean children with visual disabilities, 3 girls and 2 boys aged 8 to 12 that attend the school 'Santa Lucía' for blind children in Santiago, Chile. Four of them have total blindness and one has low vision.

Testing consisted of three stages followed over three months. First, we pre-tested children by applying the WISC-R test. Second, children interacted with AudioChile and solved cognitive tasks. Third, we post-tested children by applying the WISC-R test.

The WISC-R test contains subtests in two scales: manual and verbal. We used the verbal scale of comprehension for blind children. This helped to determine the child's ability to use practical judgments in social situations of everyday life in terms of his common sense in real situations and self-questioning during these situations. This is linked to the ability to solve problems because the child has to detect when and how to use his judgment and self-questioning in order to find a solution.

In the second stage, children worked to solve three cognitive tasks. Task 1 was to identify and comprehend the use of skills to solve problems posed by the virtual environment. Task 2 consisted of designing and planning a strategy to attain the goal of the game. Task 3 asked children to recognize the spaces navigated in the virtual environment through concrete mock-ups. Children also had to apply concretely the same strategy used virtually to meet the final goal. All of these cognitive tasks were thought to analyze the strategies used to solve problems when children with visual disabilities interacted with AudioChile (see figure 11).

Figure 11. Blind children interacting with cognitive tasks.

6.2 *Results*

Figure 12 displays pre-test and post-test results in problem-solving skills of children with visual disabilities before and after interacting with AudioChile and solving cognitive tasks. Three children improved their testing scores and two children maintained their pre- and post-test scores in problem-solving skills.

From the qualitative results of task 1 we observed that most of the children verbalized the problems posed, defined and applied a strategy to solve them. During task 2 we observed that children applied problem-solving skills and could anticipate problems after interacting with AudioChile. By considering the results obtained they redesigned their strategies. They planned and applied different problem-solving strategies to solve the mission of the game. In task 3 children explained the strategy used to solve problems embedded in the virtual environment and transferred strategies for solving problems in other contexts beyond the software. They could also contrast the results obtained when applying different strategies, self-evaluate their work, and redesign the used strategies.

7. Conclusion

We have presented the design, implementation, and usability testing of AudioChile, a 3D sound virtual environment to assist the learning of problem solving in children with visual disabilities.

Children liked, accepted, used, and were very motivated with the software. After designing and redesigning 3D sound interfaces they mapped and navigated throughout the virtual environment.

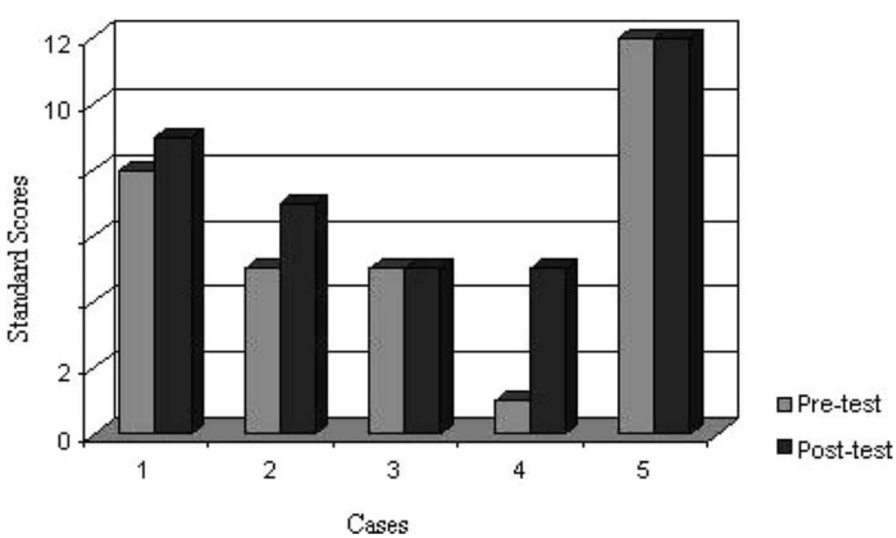

Figure 12. Problem-solving skills gains.

Usability testing was crucial for meeting the end-user requirements and understandability of the software. Children with visual disability played a key role in the design and redesign of AudioChile by making suggestions, comments, and answering questionnaires to elicit information about how a 3D sound environment can meet their needs and way of thinking.

Before the usability testing was planned we thought the main idea was that the learner could discover events in the game without including as many cues. However, after the first testing we had to add more instructions because learners needed many clues and instructions to orient themselves in the software to make it similar to their real environment.

When designing graphic interfaces for children with residual vision we found a clear issue of mental modeling. For a sighted person it is natural to see icons and associate them to certain actions. However, children with residual vision have difficulties recognizing certain icons and did not associate them with the designed actions. After the first usability testing we changed icons to a 3D format to obtain more fidelity in their representation. We also used stereo sounds that were the opposite in their related actions. For instance, sounds for opening were the opposite of closing sounds.

The use of AudioChile has allowed children to differentiate and identify surrounding sounds that helped them to orient spatially. It has also assisted them in improving the laterality and spatial concepts of up and down in relation to the north and south coordinates within a map. Sounds helped to catch the attention and motivation of children. The contrasting colors of the interfaces were also important for users with residual vision.

The visibility of graphic elements in the interface is also relevant. While sighted users prefer the visibility of possible actions and rapid access, for a user with visual disabilities the main interaction device was the keyboard and the use of circular menus. This prompted us to design menus with more emphasis on functionality rather than appearance, by using representative icons of a larger size for easier interaction for users with residual vision. This also saved screen space to adjust the representation of the interface by these users.

Our pilot testing of the cognitive impact of AudioChile combined with cognitive tasks showed that children can plan, design, apply, and redesign strategies to solve problems. They identified the purpose of the game and got involved in different strategies to solve a problem. The software provides flexible environments with multiple ways to attain a goal. Different virtual environments with diverse problems to be solved allowed multiple experiences for children to identify, solve problems, and evaluate their course of action.

AudioChile is ready to be used by children with visual disabilities. Software design and redesign has been possible with the participation of children with visual disabilities from a Chilean school for blind children. We envision a long-term application of this software to evaluate more fully the impact on the development of problem-solving skills and thus helping these children to solve real-life problems through sound.

8. Future work

We are now working on the cognitive testing of AudioChile. We are interested in knowing what type of problem-solving strategies can be developed by using this virtual environment as well as the paths followed, and how sound can help these children to develop cognitive strategies to solve everyday problems outside the virtual environment.

Acknowledgements

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