SPATIALIZED AUDIO IN A VISION REHABILITATION GAME FOR TRAINING ORIENTATION AND MOBILITY SKILLS

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ABSTRACT

Here we propose a serious game for training orientation and mobility skills of visually impaired children and youngsters. The game was designed for touch screen mobile devices and has an audio virtual environment created with 3D spatialized audio obtained with head-related transfer functions. The game helps the players to train sound localization skills and distinguish concepts usually covered at orientation and mobility classes, such as front/back, left/right, close/far. In addition, the game helps the players to train simple body rotation mobility skills.

1. INTRODUCTION

Due to the entertaining factor, well designed (serious) computer games can be a very useful tool to teach school curriculum or skills. The past few years have witnessed an increasing interest for serious games and it has been shown that serious (educational) games can be effectively used to study school curriculum [1]. While playing, students feel more motivated and engaged in the studying and learning process. With games, school material can be presented in a fun way to help the students in the learning and studying process. In addition, if the games include a reward system that is a function of the learned school material, students can actually end up putting a bigger effort on learning the material in order to receive the reward. Additionally, games can be used for training skills like problem resolution strategies, data interpretation, problem analysis, ability to create mental representations of abstract concepts, among others [2, 3].

Though most games have a strong visual component and have been designed for sighted users, visually impaired children can also benefit from playing such games to study the school material or for vision rehabilitation purposes, including for orientation and mobility training. Orientation and mobility can be defined as the ability to move independently, safely and efficiently from one place to another. This often translates into the ability to independently cross streets, to use public transportation systems, to travel from home to work, etc. During their school time, visually impaired students need to develop the concepts and skills which make the aforementioned goals attainable in later life, thus making it possible to have an active and independent life.

Here we propose a serious game, the Audio Space Station game, which was designed for visually impaired children and youngsters and that aims at training orientations and simple mobility skills (figure 1). The game uses 3D spatialized audio to create a virtual environment that the player can enjoy while training these skills. The 3D sound is implemented with head-related transfer functions (HRTF). The game has three challenges that focus on training different skills. The goal of the first challenge is to train sound localization in the azimuth, while the second challenge also includes elevation. In the third challenge distance to the sound sources is also included. In order to maintain the child's motivated in playing, the difficulty of the challenges adapts to the player's performance and the game includes a reward system. Apart from training sound localization (orientation) skills, the game can also be used for training body rotation skills and to help blind youngsters to be more confident on moving without assistance (from parents, teacher, friends, etc.).

Figure 1: A blind youngster playing Audio Space Station.

In section 2 we discuss educational and vision rehabilitation games designed for visually impaired children. Section 3 describes the game and its three challenges. It also describes the technical details and how 3D spatialized sound is obtained. The tests are discussed in section 4 and the conclusions in section 5.

2. RELATED WORK

Serious games can be an excellent tool to transmit knowledge and provide extra motivation, including training orientation skills. Nonetheless, only a few games have been proposed that are accessible to blind children. In order to be accessible to visually impaired children, games must use non-visual modalities, such as audio. In this section we discuss a few serious games developed for developing cognitive or mobility skills of visually impaired children, that illustrate how audio can be used to substitute the images and convey information to the users.

Sánchez and colleagues have developed a few educational games for blind children that use audio for accessibility purposes. These include the AudioDoom, Audiobattleship and AudioMUD games [4, 5, 6]. AudioDoom uses 3D spatialized audio in an highly interactive acoustic environment to test the hypothesis that this type of environment can be used to stimulate and reinforce some abilities of blind children, such as spatial representation. Audiobattleship is a version of the classic battleship game that was adapted to blind children. The game uses spatialized sound to substitute the visual cues of the classic version of the game. This game was developed to stimulate the cognitive development of blind children using interaction with machine as well as with other children. AudioMUD is a 3D virtual environment that instead of using spatialized sound, it uses speech to give the user all information about the environment and navigation instructions.

There are also educational games designed for specific school subjects. The *Código Pitágoras* is a math game that aims at motivating blind students to learn and enjoy mathematics [7]. All the features in the game are complemented with audio and the game uses 2D audio to guide blind players while traveling in the game's maps. The game can be played individually by blind students but sighted students can also play: While designed for blind students, this game also has graphics so as to be more interesting to sighted students. This characteristic can be an incentive for the collaboration of blind and sighted students and serve as a means to help blind children to integrate better in their inclusive classrooms and society.

Though not educational, AudioPuzzle and Terraformers are games accessible to blind children that are worth mentioning [8, 9]. AudioPuzzle consists of a musical puzzle in which the players use the Android's haptic screen to sort music pieces. Terraformers uses speech and 3D spatialized audio in several different features, such as in verbal hierarchical menus, and to simulate an acoustic compass and a sonar, among other features. This game shows that audio can effectively be used in many different forms to give information to blind users in alternative ways.

As for orientation and mobility games, also only a few games have been proposed in the literature. *Blindfarm* is an iOS game that uses both GPS and the compass sensor [10]. The purpose of this game is to help visually impaired children to learn paths they use in their daily life routines. For that, the game includes a feature that adults can use to mark a path by placing virtual animals in specific locations. Then the players have to follow the real path by listening to the vocalizations of the virtual animals in stereo sound. These sounds signal the direction towards which the child shall walk.

Other serious games and tools for orientation and mobility have been developed by Sánchez and colleagues. These include an outdoor navigation tool that uses the GPS of the Pocket PC to estimate the user's position and sound to communicate with the user [11], an audio-haptic game in which the players have to navigate a virtual space while collecting objects as game goals [12]. The goal of this game is to analyze the usability of an audio-haptic game and its influence in orientation and mobility skills. Although the virtual world is three-dimensional, the sound is not, which certainly limits localizability of the game sounds.

These orientation and mobility games lack the immersion needed to train certain orientation and mobility skills. None of them use three-dimensional sound, which is of great importance given the special condition of the target users. On the other hand the proposed game, Audio Space Station, uses 3D spatialized sound to train audio localization and body rotation skills.

Another game developed for blind users that uses 3D spatialized sound and that can be used for orientation and mobility training is Demor [13]. This game requires the players to localize the target sounds, and while the game was primarily designed for entertainment, it can be used to train localization skills. Nonetheless, we feel that the theme is not appropriate for children as it is a shooting game. On the contrary, the Audio Space Station game has a theme that is appropriate for all ages, and we were careful not to use any kind of violence in the game. As it will be seen below, users have to localize target sounds (sounds of alien insects or a robot) and catch, photograph or follow them (there is no firearm shooting in the game).

3. THE 3D AUDIO SPACE STATION GAME

The game proposed here was designed to train orientation and simple mobility skills of visually impaired children and youngsters. More specifically, the game aims at helping players to perform accurate sound localization and training other orientation concepts that are taught and trained at orientation and mobility classes, such as the use of landmarks and sound cues for navigation. In addition, the game can also be used to train simple body rotation skills and to help the players to surpass their fear of moving in unknown environments.

The game's theme, which is science in a space shift, was chosen with the purpose of having a theme adequate for a wide age range. The game is about a scientist working in a space station, who has to capture or photograph alive alien insects for posteriori analysis, or follow a robot in a laboratory while avoiding some (sonified) obstacles that lay in the room. The game includes three challenges in which the player uses sound localization skills and simple body rotation motion to control the game's main character. The challenges can be chosen in any order and can be played more than once.

3.1. Technical details

Since one of the goals of this game is to train simple body rotation movements, we needed a mobile platform that can easily be used while standing and moving. We also needed to be able to estimate the orientation of the player and detect his/her movements, therefore we needed a platform with sensors that allow us to estimate this information. In addition, we wanted the game to be accessible to the general public and in particular to visually impaired users. After consulting a blind person who regularly uses modern technology, we realized that tablets and iPads can be harder to use by visually impaired people due to their large screen size and the used layouts. For those reasons, we decided to develop the game for Android smartphones.

We used the free version of Unity3D[1] for developing the game. While this is an audio game, which should be played without access to the graphics, we opted to maintain a simple visual interface, to allow the teachers or parents to monitor the player's progress.

[1] http://unity3d.com/

The only specific requirements of the game are that the smartphone must have a gyroscope, and users should wear a set of headphones. To correctly play the game, the players should always position the smartphone facing their faces (figure 1). Also, the users should stand while playing the game because they will need to freely rotate over themselves.

The gyroscope is used to input information about the player's rotation and spatial orientation into the game. This information is used to control the main character, whose orientation depends on the player's orientation. More specifically, the player controls the main character by rotating and moving the smartphone.

The headphones are required to give three-dimensional audio feedback to the player, which can only be achieved with the reproduction of sounds through two channels, directly to the player's hears. We used OpenAL[2] to produce 3D sounds with HRTFs (more details will be given below).

3.2. 3D Spatialized Audio

The game uses verbal and non-verbal audio. The verbal audio is used to give information to the player, such as instructions and menu options. Non-speech audio is used to indicate the existence and position of objects, insects, etc. All non-speech sounds consist of 3D spatialized sounds.

In order to produce spatialized audio we can change the right and left channel signals to simulate what happens in the real world. The signals that reach our right and left ears are not exactly the same and the brain uses their differences to determine the location of the sound source.

These differences can be for instance temporal or in intensity (interaural differences). Yet, when using only interaural differences, our brain cannot unambiguously determine the exact direction of a sound source. There are other cues that the brain uses. In particular, sound is modified by the head, torso and pinnae, and our brain uses this direction-dependent acoustic filtering of the sound waves to unambiguously determine sounds' direction.

HRTFs can be used to reproduce this direction-dependent acoustic filtering. By changing the left and right channel signal with HRTFs, we obtain a pair of signals that when heard simultaneously (at the left and right ear) produce the perception of 3D spatialized sound.

The Audio Space Station game uses HRTFs to produce 3D spatialized audio. We opted to use HRTFs instead of other simpler cues such as interaural differences, because we wanted that the 3D direction of the sounds could be unambiguously determined.

In a preliminary test with visually impaired students from an inclusive school, we compared the sounds obtained with Unity3D's audio engine with sounds produced with HRTFs. In this test we used two sounds: one obtained with Unity3D's audio engine and the other with OpenAL's HRTFs. Then we asked the subjects to localize the sounds. The goal of this simple test was to determine if Unity3D's sounds are good enough for 3D localization or if we required a more complex technique, like using HRTFs, to process the sounds.

The results clearly demonstrated that the techniques used by Unity3D's sound engine are not capable of conveying proper localization cues, which is due to the fact that Unity3D simply uses sound intensity panning. Unlike HRTFs, sound panning does not allow our brain to distinguish sounds coming from opposite sides (front versus back, etc.), which leads to confusion and very poor performance on a game such as this.

[2] http://openal.org/

3.3. The Orientation Audio Challenges

Being a virtual reality audio game, the player controls the main character in a first-person perspective, similarly to what happens in Terraformers or any first-person shooter [9, 14]. The players listen and move just like the character would, which contributes to the game's immersive and engaging qualities. Since the game aims at training body rotation movements, the players do not have to walk but they need to rotate over themselves holding the device with the screen facing their faces or chest. This way, they are able to move in the game's virtual environment.

Since the game is designed for visually impaired users, it consists of an audio game and it is supposed be played without seeing the graphics. All information is output as audio (speech and 3D spatialized audio) and vibrations of the device. The players can interact with the game and control the main character by touching the screen and moving the device. In order to keep track of the users orientation, the game uses information from the device's gyroscope.

In each of the three challenges, the players have to heavily use their hearing. The first challenge, called *Cockroach Hunt*, takes place in one of the spaceship's rooms. Here, the players have to capture some alien roaches that escaped from the science laboratory. In this challenge, the main character is standing in the middle of the room and hears the alien insects around him/her. The sounds of the roaches are static 3D spatialized sounds, that is, the insects are standing somewhere in the lab. Also the roaches appear in turn in the virtual environment, that is, at a time the players hear only one roach.

The players must locate the roaches, that is, they must estimate their 3D direction, and then they must capture them. To achieve this, the players should turn around themselves (holding the smartphone in front of them) until they hear the roach right in front of them. Once they are facing a roach, they can capture it by touching the device's screen. This action is followed by a sound representing a capturing gadget in action, and a sound suggesting that the insect was caught, in case of success. If the player takes too long to capture the roach, the insect escapes. To indicate this, the device vibrates and the players hear the roach running out of the room. Since this is an audio game, we need all these sounds (like the sound from the capturing gadget, the sound of the roach being captured, etc.) to give feedback to the player about what is happening in the game.

The second challenge, which we called *Space Bees*, is very similar to the first challenge. Again, the player has to locate and turn towards alien insects, which here are alien bees, but in this challenge the creatures are not static. Instead, they are flying around the character, while describing a sinusoidal motion (flying up and down). In this challenge the players have to photograph the bees as fast as they can, for documentation purposes. Once the insects are photographed they disappear. Also, after a short period the insects that were not photographed disappear. Again the main character is standing in the middle of the room and there is only one insect present in the lab at each moment. Like before, the players have to use their hearing sense to localize the sound sources (the bees) and rotate over themselves to face the insects in order to photograph them (by touching the device's screen).

In the third challenge, the *Sound Path* challenge, the sounds

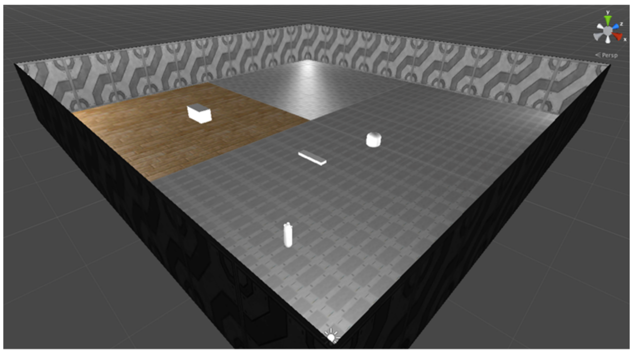


Figure 2: A scene from the third challenge

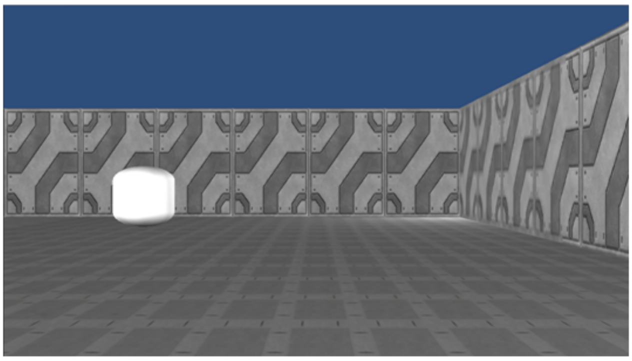


Figure 3: A scene from the third challenge in the user's perspective.

have still another dimension: distance. In this challenge, the player navigates in a virtual room to follow a robot. When the challenge starts, the player will hear the sound of the robot, which is standing in a random initial position in the room. The player must navigate towards the robot. Once the player gets there, the robot will navigate to another position. The process is then repeated: the player hears the robot's sound and has to follow it again. the challenge ends when the player reaches the robot three times. (While this number is fixed, it can easily be configured.)

In order to navigate and reach the robot in the virtual room, the main character can walk. As before, the player can rotate the device to make the main character turn around, but here the player can also make the main character walk by touching the screen (the player does not need to walk in the real world).

In order to increase the difficulty of the challenge, there may also be some obstacles in the room that the main character must avoid. All obstacles produce sound, so that it is possible to locate and identify them in the audio virtual environment. More specifically, in this challenge the player can choose to enter one of two labs: In the first lab there are no obstacles and the player only needs to follow the robot. In contrast, the second lab has some obstacles: a dog, which is barking and therefore can be identified and localized, and a bee from the Space Bees challenge. The player must localize them and make the main character avoid them while he/she is following the robot. While these obstacles do not move, their positions are random.

As an example, figure 2 shows a scene from the third challenge. (Note that the graphics are not used to play the game, these can be used by the teachers or parents just to help the child if needed.) Here the player (the thin cylinder) has to follow a robot (the large cylinder) while avoiding obstacles in the room (the two parallelepipeds). Figure 3 shows the user's perspective for the same scene. In this scene the user will hear the sound of the robot, which is represented by the fat cylinder in the figure, coming from the front-left.

To give players feedback on when the main character is walking, the sound of footsteps is reproduced whenever the main character is in walking mode. Note that there are three types of floor in the Sound Path challenge room (figure 2). The sound of the footsteps varies according to the flooring so that the player can better identify in which region of the room he/she is.

3.4. The reward system

The reward system was implemented to motivate the players to play often. The targeted orientation and mobility skills can improve better with repetitive training. Therefore we wanted the players to feel motivated to play frequently. In order to increase their motivation to play, we added a reward system to the game. This reward system consists of a score that increases when the player manages to capture or photograph insects (in the Cockroach Hunt and Space Bees challenges, respectively).

Before the proposed version of this game was ready, we run a preliminary test with blind and low vision students in an inclusive school to ascertain if blind and low vision students enjoyed the game and if it had any compromising faults. In order to catch/photograph as many insects as possible, one of the students who participated in that study adopted a technique that consisted of touching the screen repeatedly and quickly (even before he could hear the insect) while moving the phone around. The student was so concerned about catching/photographing the insects quickly that he did not pay the necessary attention to the sounds.

That type of behavior is not desirable (it would be preferable that the student would have played more attention tho the sounds to make more correct localization estimations, even when that means taking a bit longer to do it). In response to this behavior, we adapted the scoring system and added the adaptive difficulty mechanism described in section 3.5, which do not favor the type of behavior shown by this subject. In more detail, the score can decrease when the player is not able to capture/photograph an insect; if the player touches the screen to catch/photograph an insect and misses the target, the score will decrease.

3.5. Adaptive difficulty

The two first challenges, that is, the Cockroach Hunt and the Space Bees, have background noises to increase their difficulty. The intensity of these noises depends on the difficulty level of the challenges: the higher the difficulty, the louder these noises become. Another parameter that depends on the difficulty level of these two challenges is the time the scientist has to capture each insect, that is, the time the insects remain in the room before they disappear: the higher the difficulty level, the less time the insects remain in the room. Finally, as the difficulty increases, the intensity of the sounds decreases, as if the insects were further away from the player, which makes the localization of the insects a little harder. All these three parameters (background sound level, the time to catch the insects and sound intensity) have minimum and maximum values, so as to prevent that the game becomes impossible to play.

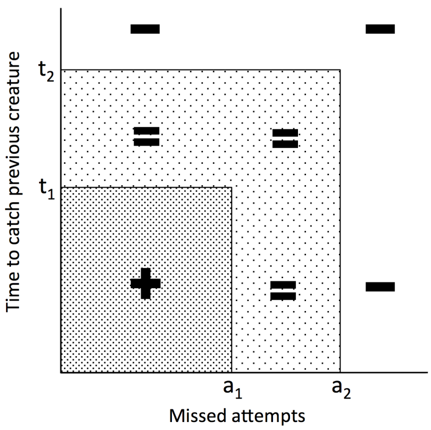


Figure 4: Adaptive difficulty rules for the training mode.

The two first challenges have two distinct game modes. One for competition and one for training. In the competition mode, the challenges contain a fixed number of insects, n_c and n_b, for the Cockroach Hunt and Space Bees respectively. The difficulty level, d, of the challenges increases as a linear function on the number of creatures that have appeared so far: $d(n) = d(n-1) + 1$, where n is the number of creatures that have appeared, $d(1) = 1$ and $1 < n \leq n_c$ or $1 < n \leq n_b$ for the Cockroach Hunt and Space Bees respectively. In this game mode the player never really loses, but the final score reflects the player's degree of success.

As opposed to the competition mode, the training mode does not have a maximum number of creatures. The number of insects that appear in the room depends on the player's performance. Basically, the player is allowed to let escape up to three creatures. When the third one escapes the challenge stops running.

In this mode the player's performance also defines the difficulty level. This mode uses adaptive difficulty, that is, the difficulty increases or decreases depending on the player's performance. If the player has a very good performance, the difficulty increases. On the other hand, if the player is struggling to succeed, the difficulty will decrease. By adapting the difficulty to the player's performance, the game allows the player to learn and improve at his/her own pace and according to his/her abilities.

The adaptive difficulty function is illustrated in figure 4 and follows the same difficulty-adaptation scheme suggested in [15]. The figure shows that the difficulty increases when the player's performance falls in the left lower square, that is when the child takes less than t_1 seconds to catch or photograph the insects, and misses less than a_1 insects (in other words, the child shows good performance, she is fast and precise on localizing the sounds). The difficulty does not change (region with = in the figure) when (a) the player is fast but not very precise (that is, the time, t, to localize the sound is less than t_1 seconds but the number of missed insects, a, is between a_1 and a_2), (b) when the player is precise in localizing the sounds but takes a bit longer to do it (that is, $a \leq a_1$ and $t_1 < t \leq t_2$ seconds), or (c) when the performance is not great but also not too weak ($t_1 < t \leq t_2$ and $a_1 < a \leq a_2$). Finally, the difficulty decreases when the player takes to long to localize the sounds ($t_2 < t$) or misses many of them ($a_2 < a$).

The parameters t_1, t_2, a_1 and a_2 can be easily reconfigured and have different values for the two challenges:
$t_1 = 3, t_2 = 6, a_1 = 2$ and $a_2 = 4$, for the Cockroach Hunt challenge, and
$t_1 = 4, t_2 = 7, a_1 = 3$ and $a_2 = 5$, for the Space Bees challenge.

3.6. Game menus

One of our major concerns when designing this game was to make it fully accessible to visually impaired children. It is important that blind players can use the game independently and without great effort or frustrating moments. For this end, the game uses sound, text-to-speech technologies and menus that allow players to navigate between game modes and levels according to their own preference. The user interaction techniques and the mechanics of the game menus were carefully designed so that these are suited to blind users.

First of all, as the players are visually limited, the game menu entries are spoken. The menu entries were recorded and the sound was modified to fit the game theme. As the players navigates between options, the corresponding sound of the menu option is played. The navigation (switching menu options) is achieved by simply sliding a finger on the device's screen, either to the left or to the right. The menu can be mentally visualized as a cylinder with the multiple options written on its surface. The sliding action would make the cylinder rotate on its vertical axis.

4. TESTS WITH BLIND AND LOW VISION USERS

We have run a usability test with visually impaired students in an inclusive school[3]. The goal of the test was to determine how the students reacted to the game and to observe the impact it had on their localization and mobility skills. Only the first and second challenges were tested.

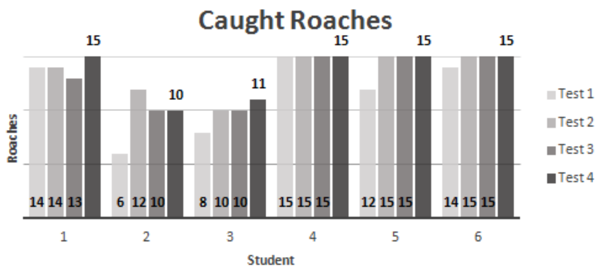
Six blind and low vision students, one girl and five boys with ages between 11 and 14 years old, participated in the test. All students had severe visual impairments: four were blind and two had low vision. The two students with low vision (students number 1 and 4), played the game without seeing any graphics. Other identified problems of the students were: Bardet-Biedl syndrome (student number 1), cerebral palsy (student number 2) and hyperactivity (student number 6). Four of the students had independent mobility (that is, they walked independently), while two of them were dependent on the help of a friend or teacher (students number 2 and 3), that is, they held someone's arm while walking.

4.1. Protocol

During this test, the students played the Cockroach Hunt and Space Bees challenges in a mobile phone and wearing headphones (figure 1). The test was done indoors, in a spacious school office where the students had space to move around without constantly bumping into objects (this indoor space is shown in figure 1). Since the tests were performed during the school breaks, there was background noise from children playing in the school playground that could be heard in the office.

In order to understand if there was any improvement on the results, each student played the game on four different days during two or three weeks. On each day, they played each challenge once in the competition mode (there were 15 insects for each trial). There was an exception of one student who played the game four times on three days because he missed school several days during

[3] Inclusive schools are schools where special needs children are integrated in the same classrooms as regular children



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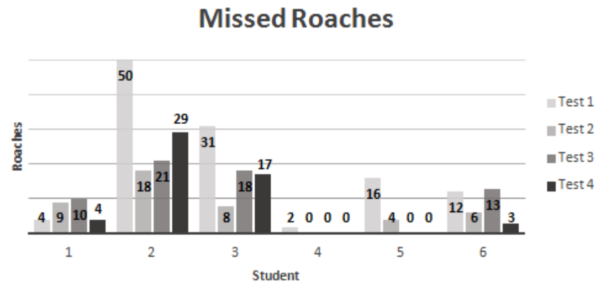
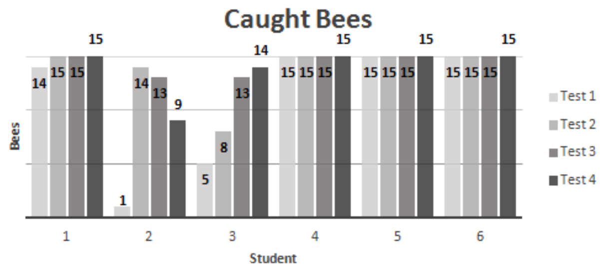


(b)

Figure 5: CockRoach Hunt challenge. Results from the four trials of all students: (a) total number of caught static roaches and (b) total number of missed attempts.



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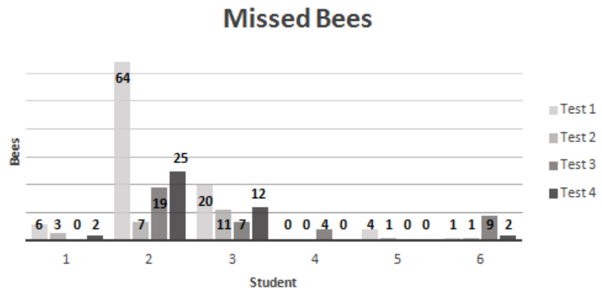


(b)

Figure 6: Space Bees challenge. Results from the four trials of all students: (a) total number of photographed flying bees and (c) total number of missed attempts.

the trials. On the last day of the test, this student played the game once in the morning school break and another time at lunch break.

Before starting the test on the first day, we explained the students how to interact with the game. They were also told that they had to hold the phone in front of them and that to capture the insects they had to turn themselves along with the phone. As suggested by a blind adult, in order to avoid having unexpected reactions to the sounds, the students also heard all the sounds before starting the actual test.

In order to overcome any initial difficulties and to verify that the students held the phone properly and could interact with the game in the expected manner, there was a training period before the first two trials (two days). The training consisted on playing the challenges until the students were able to capture five insects. After that, most of the students adapted quite quickly to the game and needed little or no further instructions. There was an exception of a student who needed extra help and further training: this was the blind student with cerebral palsy.

After the last trial, the students answered a small set of questions about their personal opinion on the game, difficulties felt, etc. While the test was run by the authors, there was a special education teacher present in the office during all the trials. After the test, she also gave us very valuable feedback.

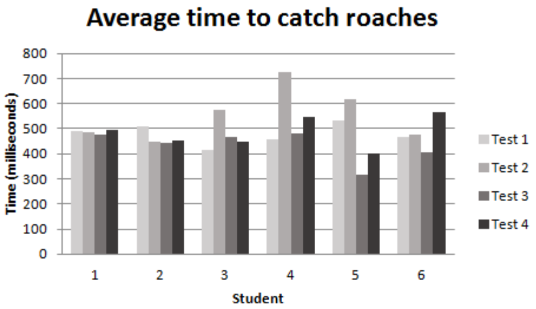
4.2. Results

We observed that there was a learning pattern in the two challenges. Some students showed very good results, that is, a high number of caught insects, on all four trials. Figures 5.a and 6.a show the number of caught/photographed insects for each student on all four trials. Note that since there are 15 insects in each trial (and for each challenge), if the student is able to catch x insects, it means that $15 - x$ insects are able to escape, which happens when the student takes too long to catch the insects. As it can be observed, the students who did not catch many insects on the first day showed improvements on the remaining three trials. More precisely, students 2 and 3 can only catch 6 and 8 roaches in the first trial, but those numbers increase to 10 and 11 in the last trial. The same observation can be made for the bees challenge: students 2 and 3 had the poorest results on the first trial but were able to improve in subsequent trials.

Interestingly, students 2 and 3 are the two students with dependent mobility, which suggests that since they were used to depend on a friend to move, either at the beginning of the test they were not so confident on turning around by themselves to catch the insects or they were also used to rely on a friend or adult to do the localization for them. Either way, the results show that the game can help the children with dependent mobility to gain more confidence on moving by themselves without the need to hold a friend's arm.

Another observation is that the students improved their localization estimation and/or their confidence on their estimations. Figures 5.b and 6.b show the missing attempts to catch/photograph the insects. When an insect appears, the players can make several attempts to catch it before they actually manage to catch it or before the insect disappears. As it can be observed, in average, the number of missed trials decreased from the first day to subsequent days (especially in the roaches challenge). This shows that the localization estimations improved.

Although one could expect that the time to catch or photograph the insects would decrease with adaptation to the game, that



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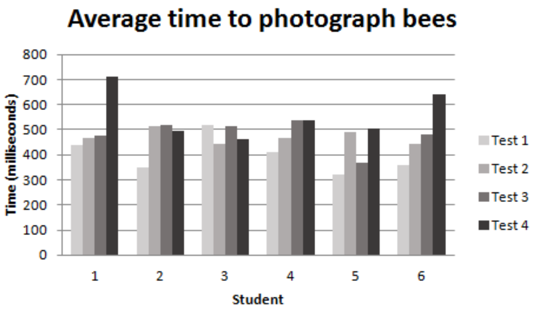

(b)

Figure 7: Average time spent to catch or photograph the insects. Each bar indicates the average time spent by one student (a) to catch all roaches or (b) to photograph all bees in one trial.

was not observed. As shown in figures 7.a and b, while for some students that time decreases, for others that time can even increase.

We observed that as students learned how to play with confidence, they tried to obtain higher scores. The time to catch or photograph the insects has no effect on the score, provided the insects do not escape (i.e., disappear from the room). On the contrary, if the students miss the insects, that is if they try to target them by touching the screen and fail the target, the score decreases. Therefore, in order to obtain higher scores, the students paid more attention to the sounds and risked less often, even if that means taking a bit longer to catch the insects. They attempted to catch/photograph the insect only when they were sure they would not miss the target, that is, when they had a high degree of confidence on their estimation of the insects' location.

Another relevant conclusion concerned the motor coordination of the subjects. The game compelled them to rotate in their standing position, in order to rotate in the virtual environment. We observed that on the first day of the trials, the blind participants tended to rotate the upper body, or moved only their arms and phone, keeping the feet static on the ground. Low vision participants did not show this behavior as pronounced as blind participants. On subsequent days, this behavior was less pronounced or disappeared. In discussion the special education teacher who attended the tests, we concluded that this behavior was probably caused by the student's lack of security regarding the surrounding environment. It was then acknowledged that the game could have a positive impact in such motor coordination details, which contributes to the students' orientation and mobility skills.

All of the students who participated in the test enjoyed the game, were interested in playing it further and acquiring it to their mobile phones. Even subject number 2, who was the student with more difficulties had fun playing the game.

Some of the students (including student number 2) were so immerse in the game that even gave a few steps in the room trying to get closer to the insects (even though this type of movement was not necessary). While some of these students were dependent on other students to support them while walking, the game made them to forget about their limitations and compelled them to move freely in the room. The special education teacher who watched the test commented that she noticed many improvements on the mobility of the players while they were playing but that once they returned to their normal routines, the mobility inhibition returned. This suggests that playing the game further may have benefits on the students' independent mobility.

While most trials were done with only one student present in the room, there were a few trials in which students 5 and 6 were both in the room. We noticed a high competitiveness between the two, as both wanted to obtain the higher scores. For these two students, competitiveness was an important factor in the test, as the higher scores were obtained in the trials in which both students were together in the room.

The three-dimensional sonification of the game was also implicitly tested and approved by all subjects. The results from the Cockroach Hunt challenge showed that the sounds are easily located in the horizontal plane. On the other hand, the results from the Space Bees challenge show that the movements of the sound source on both horizontal and vertical plane are also easily noticeable.

5. CONCLUSION

Here we proposed a vision rehabilitation game that uses 3D spatialized sound to create a virtual environment to train orientation and mobility skills of visually impaired children and youngsters. The game was especially designed for visually impaired children and teenagers, and therefore it can (and should) be played without seeing the graphics. Blind and low vision users can play the game without any help from sighted people, nonetheless, for convenience of the teacher or other sighted person who might be accompanying the user, the game has very simple graphics.

The goal of the audio Space Station game is to help visually impaired children and teenagers to improve their orientation and mobility skills, while having fun with something usually inaccessible to them. The game aims at training audio localization skills, simple body rotation motion, and helping the users with concepts such as front/back, left/right, close /far (which are usualy covered at orientation and mobility classes). Besides the main educational goals, the game's entertaining characteristics, help users to surpass self-confidence problems commonly felt by children with this type of disability.

The audio virtual environment was created using 3D spatialized sound. We used HRTFs for this end. Using the HRTFs we were able to create a realistic virtual 3D sound environment, with which the user can interact by localizing sounds. The game is played on a common smartphone and is characterized by its immersiveness and ease of use. To interact with the game, the user has only to rotate him/herself along with the phone, and touch the screen.

Some important characteristics of the game are the adaptive difficulty and reward system. The objective of these two characteristics is to maintain the players interested in the game without getting frustrated (when the difficulty is too high for them) or finding the game tedious (when the difficulty is too low).

In a usability test with visually impaired students, we observed that the students enjoyed the game and understood how to play it quite quickly. We also observed the immediate impact of the game in the motor coordination of the participants and their self confidence on moving freely in the room: Some participants had a very noticeable evolution on the movements they made, starting by turning around while keeping their feet static on the ground, to moving freely in the room without fear of the unknown surroundings. This shows that access to these activities can have a positive impact in this type of motor coordination abilities and self confidence of the users, especially for blind users without independent mobility.

We also observed an improvement on the localization skills of the participants. While on average, they made several missed attempts to catch the insects on the first trial of the game, on subsequent trials, they were able to catch the insects on the first attempt much more often.

As future work, we plan on having another challenge that requires the players to actually walk a few steps. According to the opinion of teachers of special needs children, this type of challenge would be very useful to help the children loose the fear of moving in unknown spaces and also to help those who do not like to use the cane on feeling more motivated to use it (as it would allow them to more easily walk those few steps needed in the challenge.)

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