Videogaming Interaction for Mental Model Construction in Learners Who Are Blind

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Abstract. The purpose of this work is to present the design, development and evaluation of a videogame that allows users who are blind to gradually build up a mental model based on references between different points on a Cartesian plane, in a way that is both didactic and entertaining. Two prototypes were iteratively created, and were subjected to usability evaluations by the end users, who used the videogame in the context of a set of defined tasks. This allowed researchers to adjust, improve and validate various aspects of the interfaces that had been designed and implemented. In addition, the cognitive impact of the game on blind learners was evaluated, based on the use of the final version of the videogame, and leading to revealing results regarding the proposed objectives.

Keywords: People who are blind, Videogame, Reference system, Mental model, Audio and haptic based interfaces, Wiimote.

1 Introduction

For people who are blind, the adoption of a mental model that allows them to orient themselves through the use of reference points does not occur naturally as it does with sighted people. This is because the latter have associated and familiarized themselves visually with the environment since the day they were born. In this way, it is interesting to research the mechanisms that are able to foment the construction of a mental model in people who are blind, through a structure of reference points that allows them to develop an improved approach to problems, such as orientation and mobility when navigating [8][14][15][16], or interpreting graphics and relationships between points on a Cartesian plane [1][5].

One method for the reproduction of haptic and audio trajectories in order to teach and transfer information on shapes, gestures and trajectories to people who are blind (and those with visually impairment) has been reviewed [3]. The combination of audio and haptic-based information significantly improved the performance of blind and visually impaired users, for tasks based on recreating shapes [3].

Sonic Grid is a system of audio representation in two-dimensional space that provides visually impaired users with a spatial context while navigating graphic user interfaces (GUIs) [6]. A multimodal, interactive system based on audio, haptics and visualization was designed, in order for users to create, edit and explore graphic structures through direct manipulation operations [2]. The MaskGen system was developed in order to transfer the illustrations from schoolbooks into tactile graphics in an interactive manner [11]. The results showed that the tactile graphics allowed visually impaired users to explore the illustrations and to answer questions regarding their content [11].

The various problems for visually impaired users regarding different kinds of graphics supported by Excel (lines, bars, circles, scatter plots) were studied [1]. In order to approach this problem, a system was proposed with the objective of supporting a multimodal presentation of two-dimensional graphics through haptic (using the Novint Falcon device) and audio (both spoken and iconic) feedback [1].

A tangible interface called Tangible Graph Builder was designed, which allows visually impaired users to access the information displayed in graphs [10]. Through the use of this tool, visually impaired users were able to adequately create graphs and perform navigation-based tasks [10].

The use of audio feedback techniques in order to recognize shapes and gestures based on spatial sound relations was reviewed [13]. The interaction is based on the use of common pointers such as the mouse, pen or finger on touch screens. When navigating a curve, the intensity of the sound reproduced is inversely proportional to the distance between the pointer controlled by the user and the curve itself [13].

GraVVITAS is an audio and haptic-based tool that serves to provide accessibility to graphs, allowing users who are blind to understand a series of graphs, tables and planes that model a particular place [5]. The transfer of information from statistical graphs to visually impaired people was also studied [7]. TeslaTouch is a technology that provides tactile sensation when moving one's fingers over a touch screen surface, through which the device represents the information in 2D [17]. TeslaTouch helps to show people with visual impairment certain kinds of complex information, such as mathematical expressions, illustrations, diagrams and maps [17].

A multimodal system of interactive cubes for the orientation of objects that can be manipulated by people with visual impairment was developed [9]. Through this system, users can create, modify and interact naturally with diagrams and graphs on a Cartesian plane, using a multi-touch screen [9].

Finally, the use of audio graphics for blind high school learners was also studied [4]. The proposal considers audio graphics to be an acceptable alternative to visual and tactile graphics, in terms of curriculum compatibility, learner performance and teacher satisfaction [4].

In this context, the purpose of this work is to present the design, development and evaluation of a videogame that allows users who are blind to gradually build up a mental model based on references between different points on a Cartesian plane, in a way that is both didactic and entertaining. The research considered the use of a Wiimote as an entry device in order to record the user's interactions. In addition, a cognitive

analysis was made of the adoption of this structure of coordinates as a theoretical basis for moving through real environments.

2 Videogame

The Tower Defense game metaphor was adopted, as this implicitly allows learners to be able to interpret and associate points on a Cartesian plane. The videogame was designed, redesigned and adapted in order to fulfill the requirements proposed for the project. To achieve this, the trajectories of the game's enemy units were controlled, in order for the user to gradually generate a mental model of their paths, directionalities, and the association of their coordinates in order to attack them.

The videogame is presented on a limited two-dimensional plane, in which the unit values for the X and Y-axes are in the range of $[-10, 10]$. In this way, it is important to point out that the solution can be scaled to more extensive planes. The different trajectories of enemy movement determine the various levels that the game offers. These trajectories are determined by points on the Cartesian plane. The enemies start off at point $(0,0)$, which is referred to as the starting point, and they eventually arrive at an ending point. In order to pass a level, the player must arrive to the ending point of the enemy's trajectory first, and install the tower that will be used to attack them.

In order to develop the videogame, C# language was utilized, as well as the videogame development framework Microsoft XNA Framework 4.0. This was used together with the Visual Studio 2010 Ultimate and Microsoft XNA Game Studio 4.0 tools.

2.1 Design

The videogame contains the following main elements: map, player pointer, enemies, towers and levels. The videogame map is displayed on a Cartesian plane made up of whole numbers, along which the enemies travel. The player moves and can locate the towers that will attack the enemies. This map identifies the points on the Cartesian plane that the player can navigate and those that he cannot, in addition to the points where the towers are located. The map also identifies the start and end points of the enemies' trajectories. In addition, the characteristics named on the map vary according to the different levels of the game. The map uses a graphic representation in order to identify the areas that can be navigated and those that cannot.

The enemies, the player pointer and the towers all have specific positions on the Cartesian plane, and are represented graphically and also have corresponding sound effects in order to provide feedback regarding their location and actions. The enemies also have an associated direction and speed regarding their movement through the map, as well as an energy value (which must be higher than zero for them to be alive). On the other hand, the towers have a damage value (corresponding to the diminished value of the enemies' energy when they are shot), a reach value (which is the maximum distance to which a tower can attack the enemies), and shot direction towards the closest enemy.

Fig. 1. Modes of navigation (A) Free Navigation, (B) X Axis Priority Navigation, (C) Y Axis Priority Navigation

The levels of the game are determined based on the points on the Cartesian plane, excluding the $(0, 0)$ point. Based on these points, various significant aspects of the level are determined, such as: the characteristics of the map, the points of the enemies' trajectories, the points that can be navigated and those that cannot be navigated by the player, and the points where the player can install towers. This point (where the player installs the tower) determines the end point of the enemies' trajectory, as well as the end point for the player's navigation. The end point is defined as (X_f, Y_f) . It is important to point out that both the enemies and the player begin their navigation at the starting point $(0, 0)$. In addition, a further characteristic was added, establishing a mode of navigation for the player through the map, restricting his or her navigation through space. The following options are available to the player (Figure 1):

- Free Navigation. Here the player can move freely through the area determined by $(0, 0)$ and (X_f, Y_f) .
- X Axis Priority Navigation. The player can move down a restricted path. Initially, the player can navigate the path determined by the $(0, 0)$ and $(X_f, 0)$ points. Later, the navigation can continue down the path determined by the $(X_f, 0)$ and (X_f, Y_f) points.
- Y Axis Priority Navigation. The player can move down a restricted path. Initially, the player can navigate the path determined by the $(0, 0)$ and $(0, Y_f)$ points. Later, the navigation can continue down the path determined by the $(0, Y_f)$ and (X_f, Y_f) points.

An additional characteristic was added, which can be configured in both the X and Y Axis Priority Navigation modes. This characteristic consists of blocking the return to the previous point, once the player has advanced. This makes the path uni-directional.

2.2 Interfaces

In order to play, the learner uses a Wiimote control, which allows him to execute actions such as: move about, obtain clues, and install towers within the game. The

videogame includes 3 interfaces: (i) an audio interface, which provides all of the information related to carrying out actions and the status of the game; (ii) a haptic interface, which provides feedback associated with movements that are blocked within the game through the vibration of the Wiimote; and (iii) a graphic interface, which is presented in high contrast (black and white) on the screen, so that users with low levels of vision can visualize the map and the various elements of the game.

The videogame provides the user with feedback related to the various actions that are taken as a result of the interaction. This feedback is provided through audio cues that can be either spoken, stereo iconic sound, or spatialized iconic sounds. Haptic feedback is also provided through the vibration of the Wiimote. In sum, feedback related to the following events in the videogame was incorporated:

- When the player moves from cell to cell along a navigable path (stereo iconic sound).
- When the videogame blocks a player's movement towards a non-navigable area (stereo iconic sound and Wiimote vibration).
- When the player installs a tower (stereo iconic sound).
- When the towers shoot at the enemies (spatial iconic sound).
- When the enemies move (spatial iconic sound).
- When the videogame automatically provides instructions or relevant information, or when the player requests information (sound with spoken texts).

3 Usability Evaluation

Two prototypes (initial and final prototype) were iteratively created, and were subjected to usability evaluations by the end users, who used the videogame in the context of a set of defined tasks. The objective of the usability evaluation was to adjust, improve and validate the interfaces proposed for the videogame. The methodology utilized is presented in the following.

3.1 Sample

The sample of end users consisted of 7 learners who are blind (3 female and 4 male) between 9 and 13 years of age, from the Hellen Keller School in Santiago, Chile. The sample was divided up into two groups, in which group 1 consisted of an 11-year-old girl and a 9-year-old boy, and group 2 included two girls and three boys, between 9 and 13 years of age. Having had prior experience using similar products was not a prerequisite to make up part of the sample.

The learners included in the sample correspond to videogame end users. For this reason their participation in the usability evaluation represents a direct contribution for improving the design of the application, further adjusting its needs, and validating the videogame interfaces.

3.2 Instruments

An adaptation of the end-user and facilitator questionnaire for software usability [12] was used. The original questionnaire consisted of 18 statements that the user has to evaluate on a scale between 1 and 10, in which 1 is ‘a little’ and 10 is ‘a lot’. The adaptations were made by changing the word “software” to “videogame” in the statements included in the questionnaire. The statements were classified into the following dimensions, according to the user’s perception regarding the interface: “Satisfaction”, “Learning”, “Control and Use”, and “Sounds”. In addition, the questionnaire included a section with 5 open questions (just as in the original questionnaire), and as in the case of the sentences, the only change was to include the word ‘videogame’ instead of the word ‘software’. However, 5 additional questions were added. The first added question was: “Did you like the joystick? Why or why not?”. This question sought to obtain the level of the user’s satisfaction with the use of the Wiimote. The following 4 added questions were: “Did you understand the videogame’s instructions?”, “Did the videogame help you to move around?”, “How did you use the instructions in order to move around?”, and “Did the joystick’s vibration help you to move around?”. These questions aimed to measure the learner’s perception and satisfaction regarding the mechanisms of interaction, and the transfer of information needed to be able to play the game.

3.3 Tasks

Two sets of tasks were established. The first set of tasks consisted of three different levels [(5, 5), (5, 6), and (5, -6)], all of which included the ability to return to the previous cell, and with an X-axis Priority over the Y-axis. This is a minimal set of tasks that allowed researchers to observe the learner’s behavior when playing the videogame. The second set of tasks consisted of 3 sets with 4 levels: (5, 4), (5, -4), (-5, 4), and (-5, -4). The first subset of tasks included navigation without being able to go backwards, and with priority of the X-axis over the Y-axis. The second subset included navigation without being able to go backwards, and with priority given to the Y-axis over the X-axis. The third subset included free navigation.

3.4 Procedure

First, researchers worked individually with each learner in Group 1 of the sample, explaining the basic premise of the game. The various devices that were to be utilized were presented: headphones, the Wiimote control and the Nunchuk. The actions that can be taken in the game were summarized, as well as the buttons that can be used on the Wiimote control. It is worth highlighting that the learners were asked to explore the entry interface, and not every single button was explained to them. They were instructed to discover the various actions that they could take with the buttons themselves. The first set of tasks was configured on the initial videogame prototype, and the players began to play the videogame. Once the tasks had been completed, the end user usability questionnaire was applied.

During a second stage, researchers worked individually with all of the learners from group 2 of the sample. First, the game was explained to them. The devices that would be used were also presented: headphones and the Wiimote control. The various actions that could be taken in the game were explained, but the corresponding buttons were not explained. The second set of tasks was configured sequentially for the final prototype of the game. In this way, the learners were able to start up and play the videogame. Once the tasks had been completed, the end user questionnaire was applied.

3.5 Results

In quantitative terms, increments between the initial prototype and the final prototype were observed regarding the means of all of the dimensions of the end user evaluation: Satisfaction (Initial prototype mean = 7.42; Final prototype mean = 9.77), Learning (Initial prototype mean = 5.00; Final prototype mean = 6.90), Control and Use (Initial prototype mean = 4.38; Final prototype mean = 9.00), and Sounds (Initial prototype mean = 5.50; Final prototype mean = 8.67).

Researchers went into more depth regarding the statistical significance of the differences observed between the two means. First, a T-test for independent samples was run with the values obtained for the different dimensions, based on the users' evaluations of the second prototype and the final prototype. From this test, it was observed that the increase in the mean scores for the "Sounds" dimension ($t = -2.942$, $p < 0.05$) was statistically significant. The increases in the means for the other dimensions were not observed to be statistically significant.

Qualitatively, the users' appreciation improved notoriously for the final prototype. The learners expressed a clear level of acceptance regarding how fun the game is, its elements, the use of the controls, and the mechanisms for providing information. All of these were aspects that were criticized for the initial prototype, and were then improved and validated for the final prototype. One aspect worth pointing out regarding the results obtained from the open-ended questions is the unanimous acceptance of the Wiimote control. All of the users liked this control, as it is easy to use and helped them to move around in the game.

4 Cognitive Impact Evaluation

Once the final videogame prototype had been created, following the redesigns based on the results of the previous usability evaluations, a cognitive impact evaluation of the videogame was performed. The methodology utilized and the results obtained from this process are described below.

4.1 Sample

The sample was made up of 4 visually impaired learners from the Hellen Keller School of Ñuñoa, in Santiago de Chile (2 boys and 2 girls), between 9 and 13 years of age. The learners from this sample had previously participated in the final prototype usability evaluation.

Fig. 2. Learners playing the game

4.2 Instruments

The instrument of evaluation was integrated as part of the videogame, through the log files that recorded the actions performed by the users. In processing the videogame log files for each level that the player had completed, records were obtained regarding the number of steps taken (Ne), and the number of optimal steps needed to pass the level (No). From these records, the efficiency indicator (E) was defined as:

$$E = No / Ne$$

With this indicator, a quantitative mean for the progressive construction of the learners' mental maps was obtained. The paths in the game lead to a final destination, and the learner was free to choose the best strategy for reaching that destination. These decisions are reflected in the efficiency indicator.

4.3 Tasks

Twenty levels were considered for the tasks: (3, 3), (3, -3), (-3, 3), (-3, -3), (4, 4), (4, -4), (-4, 4), (-4, -4), (5, 3), (5, -3), (-5, 3), (-5, -3), (5, 4), (5, -4), (-5, 4), (-5, -4), (5, 5), (5, -5), (-5, 5), y (-5, -5). Afterwards, 3 sets of tasks were determined. First, for the pretest tasks, the free navigation modality was configured for all the levels considered. Following the development tasks, the X-Axis Priority navigation mode without being able to go backwards was configured for all of the levels considered. Finally, for the post-test tasks, the free navigation mode was configured for all of the levels considered.

4.4 Procedure

Researchers worked individually with all of the learners in the sample. The main premise of the game was explained, and they were given instructions on how to use the devices for interacting with the game (headphones and Wiimote). The actions

available within the game and the associated buttons were also explained. The sets of tasks for the videogame were configured sequentially, as each learner completed the tasks required by the videogame.

Each learner completed each of the 3 sets of tasks in successive work sessions. Each of these sessions lasted for approximately 15 minutes. For each set of tasks, the learner played individually with the videogame, until he was able to pass the levels involved in each game. Once the sets of tasks had been completed by all of the users, the records obtained in the log files were analyzed.

4.5 Results

The total efficiency was determined for each user, considering the total numbers of steps taken. The total efficiency indicator increased between the pretest and post-test for all learners in the sample (pretest mean = 75.74%, post-test mean = 85.75%). In order to further research these results, a T test for related samples was performed. The results showed that the difference in the total efficiency means (meaning the increase in the total efficiency mean between the pretest and the post-test) was statistically significant ($t = -3.198$, $p < 0.05$).

5 Discussion

As a result of this study a videogame was designed and developed for visually impaired learners, allowing them to learn as well as interpret points on a two-dimensional plane, and to apply their knowledge directly within a system of references. The final videogame operates within a limited 2D plane, with X and Y values ranging in whole numbers between $[-10, 10]$. In this way, it is important to point out that the solution can be scaled up to more extensive planes.

The iterative cycle of design, implementation and usability evaluation led to the generation of the final videogame prototype, for which all of the designed and implemented characteristics were validated by the end users. The final prototype was clearly well-accepted by the end users, which is reflected in the quantitative data corresponding to the “Satisfaction”, “Control and Use” and “Sounds” dimensions, as well as from the answers to the open-ended questions, which were generally very positive.

One interesting result obtained regarding usability pertains to the modest level of satisfaction obtained for the “Learning” dimension, which can be interpreted as the user not perceiving that he or she is actually learning anything. This result is complemented by the opinions of the learners that they had fun playing the videogame. Taken together, these two aspects are quite positive when it comes to motivating the learners to work with the game.

Regarding the cognitive impact evaluation, the increase in the total efficiency of blind learners when performing the cognitive tasks, points to the fact that the videogame allows users to gradually construct a mental map. This occurs through the

interpretation and use of the information that the game provides, which is used at first to locate oneself on the Cartesian plane, after which users were able to utilize their own strategies to complete the levels by reaching the destination points. Although the number of users in the sample was low, and the extension of the two-dimensional planes was limited, the results showed that using the established working modality, positive changes were produced regarding the desired skills.

6 Conclusions

The purpose of this work was to present the design, development and evaluation of a videogame that allows users who are blind to gradually build up a mental model based on references between different points on a Cartesian plane, in a way that is both didactic and entertaining. The objective of the research was fulfilled. A tool was designed and developed for blind users, allowing them to gradually construct a mental reference model based on an association between points on a two-dimensional plane. The videogame implicitly integrated the interpretation of points on a Cartesian plane. In addition, as part of the tasks, learners applied their knowledge towards orientation within the integrated system of references built into the videogame.

The usability evaluations allowed researchers to detect problems and generate new requirements for redesigning the videogame. This allowed researchers to adjust and improve the interfaces in the following prototype, in addition to validating aspects of the interfaces that had been designed and implemented. All of these changes were made by taking the perspective of the end user into account.

Regarding the cognitive impact evaluation, the desired skills to be developed by the learners were those related to the interpretation of points on a Cartesian plane, and to knowledge applied within the system of references established by the videogame.

For future work, it is proposed to work with a larger sample and to apply further and more complete cognitive impact evaluations. It is also proposed to increase the scope of the tasks that users perform, and to explore other ways of evaluating cognition. Such measurements could be through the application of the knowledge gained in a real life context, or through their application to daily activities performed by the blind users.

Acknowledgments. This report was funded by the Chilean National Fund of Science and Technology, Fondecyt #1120330, and Project CIE-05 Program Center Education PBCT-Conicyt. It was also supported by the Program STIC-AmSud-CAPES/CONICYT/MAEE, Project KIGB-Knowing and Interacting while Gaming for the Blind, 2014.

References

1. Abu Doush, I., Pontelli, E., Son, T., Simon, D., Ma, O.: Multimodal Presentation of Two-Dimensional Charts: An Investigation Using Open Office XML and Microsoft Excel. *ACM Trans. Access. Comput.* 3(2), Article 8, 50 pages (2010)
2. Bernareggi, C., Comaschi, C., Marcante, A., Mussio, P., Provenza, L., Vanzi, S.: A multimodal interactive system to create and explore graph structures. In: *CHI 2008 Extended Abstracts on Human Factors in Computing Systems (CHI EA 2008)*, pp. 2697–2702. ACM, New York (2008)
3. Crossan, A., Brewster, S.: Multimodal Trajectory Playback for Teaching Shape Information and Trajectories to Visually Impaired Computer Users. *ACM Trans. Access. Comput.* 1(2), Article 12, 34 pages (2008)
4. Davison, B.: Evaluating auditory graphs with blind students in a classroom. *SIGACCESS Access. Comput.* 102, 4–7 (2012)
5. Goncu, C., Marriott, K.: GraVVITAS: Generic multi-touch presentation of accessible graphics. In: Campos, P., Graham, N., Jorge, J., Nunes, N., Palanque, P., Winckler, M. (eds.) *INTERACT 2011, Part I. LNCS*, vol. 6946, pp. 30–48. Springer, Heidelberg (2011)
6. Jagdish, D., Sawhney, R., Gupta, M., Nangia, S.: Sonic Grid: an auditory interface for the visually impaired to navigate GUI-based environments. In: *Proceedings of the 13th International Conference on Intelligent User Interfaces (IUI 2008)*, pp. 337–340. ACM, New York (2008)
7. Kim, D., Lim, Y.: Handscope: enabling blind people to experience statistical graphics on websites through haptics. In: *Proceedings of the 2011 Annual Conference on Human Factors in Computing Systems (CHI 2011)*, pp. 2039–2042. ACM, New York (2011)
8. Lahav, O., Mioduser, D.: Haptic-feedback support for cognitive mapping of unknown spaces by people who are blind. *International Journal Human-Computer Studies* 66(1), 23–35 (2008)
9. Manshad, M., Pontelli, E., Manshad, S.: MICOO (multimodal interactive cubes for object orientation): a tangible user interface for the blind and visually impaired. In: *Proc. of the 13th International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS 2011)*, pp. 261–262. ACM, New York (2011)
10. McGookin, D., Robertson, E., Brewster, S.: Clutching at straws: using tangible interaction to provide non-visual access to graphs. In: *Proc. of the 28th International Conference on Human Factors in Computing Systems (CHI 2010)*, pp. 1715–1724. ACM, New York (2010)
11. Petit, G., Dufresne, A., Levesque, V., Hayward, V., Trudeau, N.: Refreshable tactile graphics applied to schoolbook illustrations for students with visual impairment. In: *Proc. of the 10th International ACM SIGACCESS Conference on Computers and Accessibility (Assets 2008)*, pp. 89–96. ACM, New York (2008)
12. Sánchez, J.: End-user and facilitator questionnaire for Software Usability. Usability evaluation test. University of Chile, Santiago, Chile (2003)
13. Sanchez, J.: Recognizing shapes and gestures using sound as feedback. In: *Proceedings of the 28th of the International Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA 2010)*, pp. 3063–3068. ACM, New York (2010)
14. Sánchez, J.: Development of navigation skills through audio haptic videogaming in learners who are blind. In: *Proc. 4th Intl. Conf. on Software Development for Enhancing Accessibility and Fighting Info-Exclusion (DSAI 2012)*. *Procedia Computer Science*, vol. 14, pp. 102–110 (2012)

15. Sánchez, J., Mascaró, J.: Audiopolis, navigation through a virtual city using audio and haptic interfaces for people who are blind. In: Stephanidis, C. (ed.) *Universal Access in HCI, Part II, HCII 2011*. LNCS, vol. 6766, pp. 362–371. Springer, Heidelberg (2011)
16. Sánchez, J., Espinoza, M., Garrido, J.: Videogaming for wayfinding skills in children who are blind. In: Sharkey, P.M., Klinger, E. (eds.) *Proc. 9th Intl Conf. on Disability, Virtual Reality and Assoc. Technologies*, Laval, France, September 10–12, pp. 131–140 (2012)
17. Xu, C., Israr, A., Poupyrev, I., Bau, O., Harrison, C.: Tactile display for the visually impaired using TeslaTouch. In: *Proc. of the 2011 Annual Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA 2011)*, pp. 317–322. ACM, New York (2011)