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Dedicated to the memory of Academician Andrei Țugulea

SOUND OF VISION 3D VIRTUAL TRAINING ENVIRONMENTS – A GAMIFICATION APPROACH FOR VISUAL TO AUDIO-HAPTIC SENSORY SUBSTITUTION

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The purpose of this paper is to introduce our training strategy, based on gamified 3D virtual environments, for improving sound localization and navigational skills of visually impaired people (VIP). During training, the VIPs will use an advanced sensory substitution device (SSD) which conveys information about the environment. An example of such device is the Sound of Vision device (Sound of Vision website) which performs a visual to audio-haptic encoding of the environment. In this paper we explain how a virtual environment can provide, in such cases, the same scenarios and outputs as real life situations, within full safety and control. Most serious games are specifically designed for training or educating users, rather than entertaining them, and in most cases, users play them out of necessity to gain a practical skill set - which is also the case for our visually impaired users. However, in this paper, we argue that a serious game success is highly dependent upon creating game specific entertainment and even fun, immersion and motivation for the user. Serious games' effectiveness comes from many related factors, such as sense of presence, mental and emotional involvement, motivation, sense and flow achievement, player's feeling of uniqueness and individualization in the environment. In this paper we explain our efforts in designing a "serious-but-entertaining" game with hierarchical levels of difficulty that would provide auditory and haptic stimuli and tune in unique ways general game design and learning principles, such as learning by doing or experimenting, reflection and meta-reflection for transferring the learning outcomes from virtual to live contexts. Particular attention is given to level design and interaction (which, unlike in almost all other cases, is based only on audio-haptic outputs) to maximize immersion and motivation through all available means and taking into account the specificity of our users group.

1. INTRODUCTION

Worldwide, more than 285 million people are estimated to suffer from a certain degree of visual impairment, of which 39 million are blind and 246 million have low vision [1]. In Europe, there are approximately 3 million blind individuals and 24 million low vision people [2]. The purpose of the Sound of Vision project [3] is to design, implement and validate a non-invasive device for the visually impaired people that would provide a continuous, real-time multisensory (auditory and haptic) representation of the environment. The acquisition system scans the environment and creates a 3D model of it that encodes the elements of interest (objects, people) into auditory and haptic cues delivered via the hardware devices. This representation enables the users to perceive and navigate the environment, without blocking any relevant auditory information. In addition, the device is meant to detect and alert the user concerning any significant events, both of positive nature (e.g., encountering friends) or negative (e.g., obstacles hitting, dangerous situations, etc.). Thus, the system can improve users' perception, mobility and interaction with the environment. This is considered to lead to a more active and healthier lifestyle and improved personal wellbeing. We consider that the visually impaired subjects can learn to adapt to the haptic and auditory representation provided by the device and achieve efficiency in usage through well-defined training procedures based on simulations in virtual environments.

This paper presents the Sound of Vision training strategy for improving sound localization and navigational skills of visually impaired people in a gamified 3D virtual environment. The subjects will use the Sound of Vision's device for navigating the 3D virtual environment – using the same audio and haptic encoding and rendering methods available in the modes related to real operational usage. The complexity and the difficulty of the serious game gradually increase with increasing competency. Furthermore, in order to provide a highly immersive, motivating and entertaining experience to the players the principles of serious game development are applied. The current version of the game contains realistic scenes simulating a Virtual Training Environment and a series of mini-games that will be further described in Section 5.

Our work has a two-fold impact, materialized in enhancing the blind subjects' proficiency in using advanced assistive devices (adaptation to the perception of auditory and haptic cues, sound localization, navigation and orientation & mobility skills improvement), and focusing on providing new and detailed perspectives on how gamification can be integrated into training strategies for people with impairments or disabilities.

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2. SERIOUS GAMES FOR VISUALLY IMPAIRED PEOPLE

Serious games are games used for training and improving various skills, with purposes other than mere entertainment. Serious games have more than a story, graphical design and challenges – they add pedagogical objectives and instructional activities that are included in the narrative. In addition, they allow the players to experience situations and events that would seem difficult or impossible in the real-world environment. In the case of the visually impaired, serious games are used for educational purposes and for improving navigational skills. Various experiments demonstrated the positive effects of blind-accessible audio games on the development of learning, navigation, problem-solving and social skills [4] as well as on enhancing motivation and user confidence [5].

A more detailed perspective on the navigational audio games, from the point of view of the type of virtual environment, game scenario, user interface, user interaction, sonification approach and experiments on evaluating the potential for transferring the learning skills into real-world environments can be found in [6].

3. OUR SOLUTION OF A SERIOUS GAME FOR VISUALLY IMPAIRED PEOPLE

The sound of vision training strategy can provide a fun experience to our visually impaired users. We consider that the psychological and motivational aspects are fundamental for ensuring effective training through gameplay. Thus, our approach is based on the principles of "training by motivation" and "motivation by fun". The game is based on the concept of "meaningful play" which is defined as "what occurs when the relationships between actions and outcomes in a game are both discernable and integrated into the larger context of the game" [7]. The focus is on achieving the learning outcomes – effective navigation in unknown environments, improvement of the orientation and mobility skills, sound localization enhancement, while providing a playful, immersive and entertaining experience to the visually impaired users. Thus, in our game, we simulate situations and events that are significant and meaningful for the visually impaired players – real-world contexts, navigation tasks, object recognition, obstacles detection and avoidance, various aspects from day-to-day activities, routines and other frequently encountered situations.

The following objectives [8] are pursued:

A. Prioritize the most important skills and divide them into atomic skills – navigation in various indoor and outdoor settings (inside a room, an office, hallway, on the street, crossing the street, inside a supermarket etc.), object recognition (including people), obstacles detection.

B. Engaging interface, significant to the domain of the simulation – both real-world situations and events that are relevant to the visually impaired people and engaging, immersive fantasy realms.

C. An alternation between the moments of tension or challenge with peaceful phases, before the start of a task or when an activity is completed, a goal is achieved or a level is finished.

D. Rewards (points, badges) given when a task or a level is completed and "measurement achievements" that are given depending on the progress of the player, as a method of increasing intrinsic motivation. As we have vibration and sound as output mechanisms, it is important that we leverage these two inputs to their maximum ability. Firstly, it is important to use motion as emotion – and create an emotional connection through the vest vibrations. This can be done by using the motors for rewarding the player – spiraling/swirling to create a "feel good" experience – as the swirls around Cinderella when she transforms into a princess for the ball. Sound is the second element to create a sense of feeling and reward. Narrative is a third tier to emotional engagement – building up a picture of the space from the storyteller and the other characters.

E. Entertaining virtual worlds (various storylines and characters), non-playing characters (NPCs) with sense of humor. NPCs act as characters to inform the story or as side quests themselves. Specific characters can be suitable for certain missions/challenges based on their skill set and level of ability.

The NPCs could have specific skills (classes) such as agility, stealth, negotiation skills, etc. (based on the game genre selected) which the player can develop. We propose to link the development of these characteristics to training modules which are designed around specific system competencies. Therefore, the more the player develops the characters, the more they are learning about the system. The player will begin with a limited environment and limited options. The environment and the options may be expanded as the player progresses, both as a reward and to broaden the possible activities to train the player with the equipment in different ways. The player is able to progress either the main narrative or perform side quests (mini-games) at a time. The mini games have good possibilities for leveling and increasing difficulty but may lack long term immersion. They can easily be linked to competencies players need to achieve to be classed as an expert in using the system.

The game experience starts in a hub. The hub is a place that links the other levels and "serves as a main area that the player will use to progress through the game" [9]. Pursuing the main narrative will expand the hub, whereas side quests are additional challenges and activities. The extras can be used to influence some of the characters and story outcomes in the main narrative, incentivizing their use and adding additional layers of complexity to the experience.

Two alternative, widespread, mature, industry adopted technologies were considered by the project partners to support the low-level implementation of the 3D virtual training environments: Unity3D and Unreal Engine 4. These two technologies were carefully evaluated in order to determine which one should be used for the Sound of Vision training environment. For this, the speed of development, required expertise and the learning curve were considered. Furthermore, several technical aspects had to be validated before a final decision was made. These aspects were mainly related to efficient implementation of stereo and time-of-flight (ToF) virtual cameras. Taking into account the technologies learning curves (easier for Unity3D) and the preliminary intention to make the Sound of vision virtual training environments an open source project to stimulate further development from 3rd parties, Unity3D was, upfront, the favored solution.

Exploratory prototyping validated the possibility to integrate with Unity3D through plug-ins, in order to efficiently acquire in-game stereo and ToF frames and

efficiently stream them to external applications through memory transfer. Based on these aspects, the final decision was made to use Unity3D as development platform for the sound of vision virtual training environments.

3.1. INPUT AND OUTPUT MODALITIES

The system's specifications consist of a haptic vest with vibrating motors (10 × 10 or 10 × 15 actuators with several types of vibration patterns, controllable intensity and duration, placed either on the user's back or abdomen) and 3D sound (3–5 sound sources, with an estimated precision for object localization of 10–30° in the horizontal plane and 20–30° in the vertical plane). Control is ensured by a remote that includes physical buttons dedicated to operating the device and 6 buttons dedicated to navigation and actions in the serious game: 4 directional buttons (arrows), pause / resume or save – on long press and 1 action button – for in-game custom actions (for example, pick an object). A headset is wired to the vest with inertial motion unit (gyro and accelerometer), so that the game receives the player's head rotation. We include a calibration option which is available at any time as motion-based devices tend to lose proper alignment.

We anticipate that the user can benefit from a good sense of control through the feedback provided by the game. In what concerns game practice scenarios, we envision that the users will be able to play the game:

A. At home – by themselves (estimated at 80–100 % of training time). The total training time is of about 2 months.

B. In a specially design training center, under the guidance of trainers or with additional hardware (multidirectional treadmill or body tracking)

C. Mixed reality in a physical training environment:

- Also within a dedicated training center, under the guidance of trainers;
- In a room (e.g. 10m × 10m) or outdoor space, empty or decorated with real objects, upon which the serious game can overlay virtual elements (e.g. virtual obstacles, virtual pick-ups);
- This option has the distinct advantage that it can support a multitude of training scenarios while allowing the player to move naturally and also use the white cane for the real elements.

3.2. TRAINING SKILLS

The tasks presented to the player in the sound of vision game are all designed to build up the skills defined by the learning outcomes. Those skills are essential to the visually impaired people - navigation, orientation & mobility, object recognition, obstacles detection. The ultimate goal is to provide a good degree of autonomy and understanding of the surrounding environment (in other words, to be able to perceive their environment).

The following are examples of a few skills at different levels to be developed in the sound of vision training Environment:

Basic skills

- Using the device controls (volumes for audio and haptics, changing operating modes);
- Identifying position (direction + distance) and size of objects;
- Being aware of moving objects and being able to track those objects;
- Identifying several types of specific objects such as: doors, stairs, poles, holes (in the ground), texts etc.;
- Walking on streets, side-walks, identifying and using cross-walks;
- Locating and reading texts.

Composed scenarios involving several basic skills

Players use a few basic skills to explore a space or series of spaces such as single room, house, building, office, supermarket etc. During the exploration, the player is given a task, for example:

- Moving in a room without hitting obstacles;
- Navigating all the rooms of an apartment to reach specific targets;
- Exiting a room / building;
- Entering a building and finding your way to reach a specific room;
- Finding a specific shop / building on a street;
- Navigating in a shopping mall and finding a specific area;
- Navigating in a park from the entrance, walking around to some targets and then finding the way back to the entrance;
- Find and pick-up / drop (deliver) objects;
- Multiplayer environment with obstacles where targets are generated randomly and continuously; division of players in teams; competitive gameplay - which team collects most targets, with penalties for hitting obstacles.

Mental skills:

- Ability to focus (selective attention);
- Distributed attention;
- Planning, mental mapping, deductive thought and reasoning.

3.3. DIVISION OF REALMS – REALISTIC & FANTASY SCENARIOS

From the start of the experience, the player can select between the two realms and proceed from there. There is no cross-over between the two distinct modes. In the sound of vision's game virtual 3D environment, the players can improve their navigational and orientation & mobility skills through exploration, object manipulation and collaboration with other characters. They can also benefit from guidance, especially for the first levels of the game. The tutorial contains a collection of mini games, either standalone or within a narrative structure that build up the basic interactions.

A mentor is a continual and familiar guide through the narrative/activities. The mentor can give the player an indication of the environment and objectives – similar to old text adventures, the mentor becomes the story teller. The story teller can use the 3D sound and vibrations as introductions as the story progresses, such as approaching from a distance, from different positions, and walking around the player so he gets used to the new sensations in a safe, pressure-free environment.

4. THE SOUND OF VISION GAME STRUCTURE

The game will contain multiple scenarios to train competencies. It will include a main narrative flow with additional side quests, distributed on levels (we envision more than 10 levels) - both concrete, realistic and meaningful levels and fun/fantasy tasks (having a fun or intriguing

cover story and storyline, placed within fantasy environments). The levels will be of gradually increasing complexity (in terms of 3D content complexity, dynamics and tasks complexity). They will attempt to emulate real life environments and situations, starting with static worlds populated by very few entities and ending with complex and dynamic virtual worlds.

Here are some examples of levels with various complexities:

Very simple levels that contain simple static scenes requiring the player to detect or count objects, navigate without colliding etc.

- A world containing a single 3D object (initially a static object and next a moving one);
- Worlds containing 2, 3, 4 static objects;

Medium complexity levels:

- Worlds with 5-20 objects of various types;
- A world with objects simulating stairs, doors, walls, ceilings;
- A world with objects containing text.

Complex, very complex and highly complex levels:

- Walk in a crowded city, containing a large number of people, moving cars, obstacles (like a hole in the asphalt or a puddle), street crossings, parks etc.;
- A hypermarket, with people, products containing text, cash registers, booths and shops etc.;
- An office building, with multiple floors, elevators, stairs, doors, walls, people etc.

All these tasks will require the user's selective attention. Moreover, as suggested in, focused attention is an important factor that facilitates the flow experience [10]. Each level includes a degree of randomness or newness (variations in the core structure or the 3D space and randomized placement of obstacles and pick-ups) so that the user will not learn the levels structure by mind. The degree of randomness will be very low (close to zero) for new users and then it will increase, based on the user's progress.

The different scenarios will randomly draw from a large variety of created environments in accordance with the premise. Game challenges and experiences should never be impossible or even extremely difficult and soft failures can be possible if they serve learning. There will be 3 difficulty levels: beginner, advanced and expert, with different sublevels. These basically control the evaluation by the system of how the user performs the given tasks, in terms of accuracy, speed, number of accepted errors etc. Soft failure should be possible if it serves the learning – this means that the player can be asked to retry a level or a task if they have not achieved sufficient performance after completing the activity. In addition, gentle guiding language will be used to encourage replay and the feedback will focus on results rather than errors.

The general rule of thumb for dealing with failure is to always "forgive error". This can be done in the following ways:

- Focus on user's results rather than on their errors
- No strong penalty after failure – simply give the player an opportunity to correct their error by trying again without penalty (for a better result or purely for player's personal gratification)
- Passive feedback – explain how to do something better / encourage them to do better (via dialogue)
- Withhold or temporarily block progression (items, progression etc.) from player or completely block progress until a task is complete [7,8].

Nevertheless, in order to improve communication and social interaction, some levels will be designed as multiplayer. Multiplayer parties will range in size from 2 to a maximum of 10 players.

The following types of interactions will be implemented:

A. Exploration of space together:

- A user can invite other users to visit his virtual house or neighborhood; besides socialization, this has the advantage to provide diversity of content (as each house/neighborhood will be unique, through randomized procedural generation).
- Users can form parties to visit together special environments designed for such purposes (e.g. large realistic city models, large realistic parks, large fantasy environments).

B. Collaborative gameplay: some quests may be accomplished through collaborative gameplay, where players have to cooperate to solve some tasks.

C. Competitive gameplay: in this case, players are perceived as competitors, trying to win some mini-games based on best scores or best time criteria.

D. Teams play: competitive gameplay where players are divided into 2 or 3 teams and the scores are counted at team level.

Some examples of basic and complex mini games, together with the skills they promote, description and game mechanics are presented hereby:

Frogger

Skills: Avoiding moving objects or people;

Description: The player must choose when to progress forward, avoiding obstacles that intersect their path;

Factors: Timing. Distance. Proximity Signals. Single/ Multiple moving objects, at varying distances;

*Multiplaye*r: Competitive. Players race to the other end;

Input: Controller. Gyro commands are possible ('nodding' to proceed).

Crowd surfing

Skills: Stationary crowds. Navigating densely inhabited areas;

Description: The player must navigate densely clustered areas of stationary obstacles. There are gaps between obstacles but may not be a viable path. The player must find the path of least resistance forward, with some obstacles moving to accommodate the player;

Factors: Distance. High obstacle density. Social maneuvering. Proximity signals.;

Multiplayer: Competitive. Players race to the other end. In the same space, movement choices may influence the path of others;

Input: Controller.

Dodging / catching

Skills: Avoiding approaching obstacles. Interpreting simultaneous signals.

Description: The player must either dodge or collide with oncoming objects.

Factors: Distance. Multiple, moving objects. Proximity-strength signals.

Multiplayer: Competitive. Players challenge one another to see who can last the longest against increasing difficulty. Conversely, an alternate mode of 'pong' with each player acting as their respective bat.

Input: Controller. A 'three lane' system could be

controlled with gyro.

Maze

Skills: Navigating tightly enclosed or confusing spaces. *Description*: The player must navigate an enclosed, static environment.

Factors: Distance. Orientation. Simultaneous signals. Proximity signals.

*Multiplaye*r: Competitive. Players challenge one another to navigate the maze faster.

Input: Controller.

Hot'n'Cold

Skills: Interpreting proximity signals. Find the central point between multiple sound nodes, they do this by listening for the tones or sounds at the same volume.

Description: The player must use proximity signals to find/locate the position of goals.

Factors: Distance. Orientation. Proximity signals. Free movement.

Multiplayer: Competitive. Players challenge one another to acquire the most, faster.

Input: Controller. Input includes a button to signal for an update on proximity

Simon Says

Skills: Recognizing the orientation of signals. Remembering previous input.

Description: The player must recognize, remember and repeat multi-directional signals in sequence, to increasing amounts of accuracy.

Factors: Orientation. Accuracy.

Multiplayer: Competitive. Players can challenge each other to last out the longest or take turns creating inputs for one another to repeat.

Input: Gyro control, orientation of body. Controller is possible, but would require sensitivity of a control stick over buttons.

Sound Target

Skills: Interpreting differing strength signals.

Description: The player must rotate and scan the vicinity for proximity signals of differing strength, to identify when they should stop.

Factors: Orientation. Multiple signals. Proximity signals.

Multiplayer: Competitive. Players challenge one another to 'unlock' a vault first.

Input: Gyro control, orientation of body. Controller is possible, but would dampen the potential for improving the player's connection with the equipment.

5. IMPLEMENTATION

The current version of the virtual training environments includes a series of 3D scenes, simulating a realistic realm, as well as various mini-games, having the purpose of training the visually impaired users for a sensory substitution device. A scenario for a fantasy realm has also been written and will be implemented in the near future. In the following subchapters, we will describe the basic functionalities of the application, the technical approach, as well as the validation process in the experimental setup [11].

5.1. FUNCTIONALITIES

After establishing the purpose and the requirements of the virtual training environments, various modules have been implemented, in order to train and develop some required skills of the user. From the main menu, the user can choose several options:

- The realistic realm option which can start a new game or resume the previous session;
- The mini-games option to choose a game for training a specific skill;
- The playback option, which has the goal of recording and replaying a part of the previous training sessions (a mini-game for instance) in order to analyze the performance and the difficulties encountered by the user.

The realistic realm scenario contains a series of scenes simulating real life day-to-day activities, taking place in different contexts: the interior of a house, a small town (Figure 1), two universities, an office building or a mall. The scenes are created as realistic as possible, with 3D sounds, animations and real-sized scaled objects. For the exterior scenes, the time of the day (day/night cycle) or the weather conditions (sunny or rainy weather) are customizable. The sequence of scenes evolves as natural as possible, simulating a realistic scenario of a regular day. Firstly, the user must accustom to the interior of a house and explore the different rooms by performing easy assignments. As they advance, the environment becomes more and more complex, presenting a small town with many neighborhoods, streets, parks, shops and office buildings. The small town represents a hub level, connected with many others: the interior of an office building, a mall and two different universities.

Fig. 1 – Realistic realm: small town.

In the game, the user must solve several tasks, in a precise order, based on increased levels of difficulty. The tasks actually represent common activities, in a natural order, and are completed by reaching a certain hotspot. Some hotspots represent areas which must be reached in order to complete a certain task (the user must go to the living room, to the park or to a friend's house, for instance), while other hotspots need to be activated, as they represent specific actions performed by the user (opening a door, taking the elevator or paying for items at the mall). A travel system is also present and can be customized based on the purpose of use, in order to help the user travel between two specified points in the environment. Therefore, the user can have the feeling of taking the elevator to travel from one floor to another or taking the bus to travel between two distant destinations. The users feel free to explore the environment for as long as they wish, completing tasks and acquiring essential competencies, maintaining a perfect balance between challenge and achievability [12, 13].

The mini-games represent an important part of the virtual training environment, as they can be used to train and test specific skills. Our game currently contains 9 different games – 1: the sound of vision game structure of the current

paper. These games are frogger, tunnel (an easier version of the maze), maze, asteroids (also known as space fighter), catcher, crowdsurfing, pick-uUps (also known as hot 'n cold), decoys (similar to pick-ups, but with decoys and objects that must be picked up) and slalom (an easier version of frogger, with stationary obstacles).

5.2. VALIDATION PROCESS

For the validation part, we asked three different visually impaired users, who didn't have any previous contact with the virtual training environment, to test the game and provide their feedback. The general impression about the design and concept of the environment was positive, while the mini-games were appreciated as being fun and useful for training specific skills. Several useful suggestions have been provided, such as adding even more sounds for realism or reorganizing the quests' order, to assure a lower level of difficulty in the beginning, when the user must accustom to the new environment. However, when the users tested the virtual environment with the headset (Fig. 2), they found it difficult to navigate based only on the audio information coming from the device. This can be easily explained as the objects from the virtual training environment have specific labels attached to them, which are interpreted and coded specifically by the headset. At the moment, only a few labels are implemented, aspect which will be improved in the near future. The future tests will involve the use of both headset and vest in order to assure a better understanding of the environment and a smoother navigation.

Fig. 2 – User testing a scene from the virtual training environment with the headset.

6. CONCLUSIONS

This paper presented the sound of vision training strategy for improving the visually impaired people's sound localization and navigational skills in a gamified 3D virtual environment, based on audio and haptic rendering. The key perspective was to make the training focused on realistic tasks but at the same time highly entertaining. Many detailed aspects of the design propose brand new solutions to provide immersion, motivation, entertainment and user retention/engagement. All these aspects, such as virtual environments structure, interaction modalities, scenarios, narratives, character development, personalization and even highly specific multiplayer interactions, were described in the previous chapters. However, limitations lay in the employed input modalities: audio and haptic. The game aims to improve sound localization through training, although it will never reach the accuracy and resolution of the visual sense. As future directions, the design will continue to be refined and enriched during next stages, based on users' feedback obtained through the prototypes' testing (and in particular, the specific tests investigating differences between performance and training in similar real and virtual contexts. Notably, the project consortium envisages to make the training environments available as an open source and open access project, in order to facilitate further developments of additions to the training spaces and scenarios by gaming communities and 3rd parties and to stimulate the development of other applications for the visually impaired, based on virtual environments, in the areas of education and entertainment.

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