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Abstract

Purpose – *VirtuNav is a haptic-, audio-enabled virtual reality simulator that facilitates persons with visual impairment to explore a 3D computer model of a real-life indoor location, such as a room or building. The purpose of this paper is to aid in pre-planning and spatial awareness, for a user to become more familiar with the environment prior to experiencing it in reality.*

Design/methodology/approach – *The system offers two unique interfaces: a free-roam interface where the user can navigate, and an edit mode where the administrator can manage test users, maps and retrieve test data.*

Findings – *System testing reveals that spatial awareness and memory mapping improve with user iterations within VirtuNav.*

Research limitations/implications – *VirtuNav is a research tool for investigation of user familiarity developed after repeated exposure to the simulator, to determine the extent to which haptic and/or sound cues improve a visually impaired user's ability to navigate a room or building with or without occlusion.*

Social implications – *The application may prove useful for greater real world engagement: to build confidence in real world experiences, enabling persons with sight impairment to more comfortably and readily explore and interact with environments formerly unfamiliar or unattainable to them.*

Originality/value – *VirtuNav is developed as a practical application offering several unique features including map design, semi-automatic 3D map reconstruction and object classification from 2D map data. Visual and haptic rendering of real-time 3D map navigation are provided as well as automated administrative functions for shortest path determination, actual path comparison, and performance indicator assessment: exploration time taken and collision data.*

Keywords *Haptics, Simulation, 3D reconstruction, Indoor navigation, Virtual environment, Visually impaired*

Paper type *Research paper*

I. Introduction

As estimated by the World Health Organization, in 2010 there were approximately 285 million people around the world who were visually impaired, referring to those whose vision is limited or occluded to some extent, of which 39 million were blind (World Health Organization, 2012). According to recent sources (Blind Children UK, 2014), the incidence of visual impairment is on the increase, with a 9 percent rise from 2006 to 2014 of children registered with partial sight or blindness. Vision is commonly divided into two principle categories; visual acuity, measuring acuteness or clarity of central vision with foveal fixation and recorded in feet, meters, decimal or LogMar and peripheral vision, referring to how much people can see around the central vision and often measured in degrees. It is important to note that peripheral vision can be of equal or even higher importance when considering one's entire functional vision.

Visual impairment is a severe reduction in vision that cannot be corrected with glasses or contact lenses and reduces a person's ability to function at certain or all tasks. It can be caused by any

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anomaly stopping the light effectively getting to the back of the eye, issues with the health and function of the central or peripheral retina or problems with the interpretive faculty of the brain. A vast array or problems can cause visual impairment, including: glaucoma, age-related macular degeneration, retinopathy of prematurity, stroke, diabetes and many other systemic and genetic disorders.

Visual impairment and restriction of environment contributes to loneliness, depression, social isolation (Evans *et al.*, 1982; O'Donnell, 2005), and activity and participation restrictions (Evans *et al.*, 1982; Crews and Campbell, 2001; Jacobson, 2005). Almost 50 percent of visually impaired persons feel "moderately" or "completely" isolated, socially and environmentally (Pey *et al.*, 2006). Less than 25 percent are offered mobility training to assist in independent travel (Douglas *et al.*, 2008) and around 15 percent claim to not participate in leisure activities external to their home (Douglas *et al.*, 2006). Clark-Carter *et al.* as cited in Jacobson (2005) determined that at least 30 percent of visually impaired persons do not independently travel outside their homes. Further, Passini *et al.* as cited in Jacobson (2005) found that blind people will follow familiar or known routes when moving between locations, due to the stress and anxiety caused by exploration. Fear and uncertainty are perceptual difficulties that inhibit the mobility of those with sight impairment (Gustafson-Pearce *et al.*, 2005; Jacobson, 2005). There is much greater risk of unintentional injury during exploration, such as falling or collision related accidents, compared with sighted individuals (Manduchi and Kurniawan, 2011). A visually impaired person must frequently overcome the challenges of navigation between locations (Arizona Office for Americans with Disabilities, 2007; Jacobson, 2005), including both physical (Manduchi and Kurniawan, 2011) and perceptual barriers (Gustafson-Pearce *et al.*, 2005).

Those who are significantly impaired or blind may use navigation aids for mobility, such as walking sticks or guide dogs; the former predominantly when there is significant loss of peripheral vision to detect objects away from one's central vision. Users with minimal central vision loss will experience little trouble with object identification or perception of surrounding obstacles. Several assistive devices are available (Jacobson, 2005), such as handheld GPS's, yet navigation remains potentially dangerous due to unfamiliar obstructions such as chairs and tables as well as hazardous areas including staircases and ledges (Mau *et al.*, 2008). There is an identified increased risk of social isolation and the avoidance of exploring new environments due to sight impairment. Assistive technologies can help bridge this gap.

The proposed solution addresses the difficulty associated with indoor navigation for greater social and environmental engagement, to help those with visual impairment by providing a support tool that offers haptic (force) feedback and audio prompts as navigational aids. Since perceptual understanding of space has a direct effect on action (Manduchi and Kurniawan, 2011), the software facilitates semi-automatic recreation of a real-life environment in 3D virtual space, offering a support system for indoor exploration, for the user to attain heightened spatial awareness and gain a better understanding of their surroundings in which they are immersed. The user moves through and interacts with the environment using a haptic device and keyboard. The system tracks user progress as they navigate through the virtual indoor space and around embedded objects. The software provides visual and haptic feedback as well as audio cues, representing the objects and associated collision by the user, in 3D. A virtual environment (VE) provides a safe space for users to familiarize themselves with the location before visiting it in physical presence, helping to overcome physical challenges and fear of accident-related injury. VirtuNav provides navigational assistance and an accurate representation of real world indoor locations in a VE, with objective and subjective validation.

Targeted system users are those with almost complete central vision loss. Children and teenagers may prove a more receptive participant demographic as they are quickly adaptable to new technologies as opposed to the elderly; to use and interpret haptic feedback faster, adapting more quickly to the application. To provide a safe, seamless integration to the system, a VE has been created for the user to explore that reconstructs how they may perceive the natural world. Technological advancements have been made in the research to address visually impaired navigation using virtual reality (VR) schemes. However, a 3D, customized approach that efficiently extracts and reconstructs map data, as an assessment and guiding tool in VR, is lacking. The existing research and identified deficit are examined in the following section. The remainder of the paper presents the design and implementation, testing and findings of the application to address this technological and research deficit through development of an assistive technology for exploration and wider environmental engagement, less mobility restriction and toward reduced isolation.

II. Literature review

Several studies examine the extent to which fear and uncertainty inhibit visually impaired persons to engage with their environment (Gustafson-Pearce *et al.*, 2005; Crews and Campbell, 2001; Jacobson, 2005), leading to social isolation and subsequent health issues including depression (Evans *et al.*, 1982; O'Donnell, 2005). Perceptual barriers were examined in a study conducted by Gustafson-Pearce *et al.* (2005) to determine which factors restricted visually impaired navigation of pedestrian crossings with a range of artifacts. To determine significant factors, a questionnaire was completed by 224 sighted and sight impaired individuals, and research findings indicate that deficiencies in the mental mapping of equipment and sound artifacts through lack of priori knowledge can inhibit mobility or travel for the visually impaired (Gustafson-Pearce *et al.*, 2005). In a study examining elderly, sight impaired groups (above 70 years old), research findings revealed visual impairment to be "a significant risk factor for additional medical conditions, activity limitations, and participation restrictions" (Crews and Campbell, 2001). In an in-depth literature review, Jacobson (2005) concludes that improving mind mapping of visually impaired persons via enhancement of wayfinding and orientation skills leads to improved quality of life, mobility and independence. 3D immersive, interactive technology that is customized to map data are lacking but may assist in heightened spatial awareness, to overcome perceptual and physical barriers that restrict mobility. The research challenge of constructing such an environment to assist in mind mapping is identified.

Existing research initiatives have developed devices and/or software solutions that cater to the needs of the visually impaired for determination and navigation of a location, of which Lahav *et al.* (2008), Yatani *et al.* (2012), and Sugiyama *et al.* (2011) focus on outdoor navigation using handheld devices. Two VR research-based solutions that focus on indoor navigation include BlindAid (Schloerb *et al.*, 2010) and the Kulturhuset Prototype (Huang, 2010). The BlindAid system (Schloerb *et al.*, 2010) consists of a VE replica of a real environment where the scenario is a single, horizontal level such as a floor of a building. This system applies haptic feedback and audio cues to test the user's ability to navigate the environment as well as how comfortably and accurately they move about the corresponding real world environment. The user moves through the VE using the haptic device and receives force feedback when the avatar, represented as a moving dot on the screen, comes into contact with an object in the VE (Schloerb *et al.*, 2010). As reviewed by Lahav *et al.* (2012), the haptic feedback provided is similar to that of the forces exerted during use of a long cane. The system is comprised of three interfaces: a user interface with the VE through which the user navigates, an evaluation interface for the purpose of recording a user's behavior and an editor mode which enables one to create the VE by importing AutoCAD files into the system (Lahav *et al.*, 2012). During the system's usability testing, participants preferred the VE to provide clear spatial information and to reserve unique textures for designated areas (such as stairs), as opposed to complicated textures which confused users (Lahav *et al.*, 2012).

In Stockholm, a program was developed as part of a thesis study to observe the impact of haptic and audio on VE navigation (Huang, 2010). The 3D reconstruction that is haptic- and audio-enabled was modeled on a real-life location in Stockholm known as Kulturhuset (Huang, 2010). The user navigated about the VE using the PHANToM Omni 3 Degree of Freedom (3DoF) haptic device, representing a virtual "walking stick." Some of the techniques implemented in the Kulturhuset prototype included magnetic force reflection for collision response and simulation of environmental sounds. Audio feedback associated with a collided object invoked a sound file, either in the form of speech or non-verbal cues. Magnetic force was attached to a virtual escalator and upon moving close to the escalator, the avatar attached to the force until the user reached the second floor, at which point the force was disabled. During the testing phase, many users found it difficult to identify and use this magnetic force appropriately until informed about it by the administrator (Huang, 2010). The volume of an environmental sound was increased or decreased based on the user's distance from the object producing the sound, and many users found that this feature helped them navigate through the VE and find specific objects more easily (Huang, 2010).

The research findings reveal the utility of computer-based, interactive simulations to assist in sight impaired navigation to achieve heightened environmental familiarity, yet a 3D haptic-, audio-enabled, customized environment based on selectable image map data are lacking. This work addresses that research challenge. Further, through testing and validation, the work considers the extent to which exposure to the simulation improves familiarity and mind mapping capabilities for visually impaired navigation within an indoor environment. The social impact of this technology is toward improved spatial awareness within an unfamiliar location to build confidence and reduce perceptual and physical barriers, for a higher incidence of exploration and community engagement.

III. Methodology

Software design considerations identified key features for enhancing visually impaired navigation via simulation. Pre-knowledge of the anticipated route and landmark occurrences are advantages to navigation and a means to access and aid mobility performance (Gustafson-Pearce *et al.*, 2005; Jacobson, 2005). Abstract concerns such as safety or getting lost, as well as the construction of mental maps relating to perception of difficulty (Gustafson-Pearce *et al.*, 2005) are also important considerations. Image-guided solutions can provide specific features or object occurrences to build confidence and reduce hesitation when interacting with the environment (Gustafson-Pearce *et al.*, 2005). Further, sound cues can provide signals for specific objects to alert the user to their presence in the environment, for hazardous areas such as stairs, escalators (Gustafson-Pearce *et al.*, 2005). Reliance on haptic and audio cues, as well as the creation of cognitive maps are important concerns for visually impaired navigation (Jacobson, 2005). Map recognition provides measurement of configurational knowledge (Jacobson, 2005). Further, tactile and audio maps presented to visually impaired users and sketch map interpretations provide suitable testing platforms for assessment of cognitive mapping ability (Jacobson, 2005), as do creating models or walking an inferred route (Ungar, 2000).

To address the key considerations and contribute toward the literature and associated research findings, a practical, low-cost assistive application based on a real-life indoor location for visually impaired users to explore has been developed. The system tracks the progress of the user as they navigate through the virtual indoor space and around objects such as furniture. The software provides adequate visual and haptic feedback as well as audio cues, to represent the objects and associated user collision in 3D. Through testing and validation, appropriate haptic feedback and audio cues are achieved to a level of acceptable user discernment, to reflect object interactions as they would occur in reality and assist in object identification. Since a VE provides a safe space for the users to familiarize themselves with the location before visiting it in physical presence, the software offers navigational assistance and reconstruction of real world facilities and embedded obstacles.

Two independent parties interact with the system: users, who explore the environment directly and administrators, who manage user information and obtain results. Administrators can create or delete users from the system, retrieve information about user progress and generate maps for the users to interact with. The administrator can manage the user profiles, adding detail such as percentage of visibility in each eye, a unique username and password, gender, age, and race. The additional details can be used later to customize one's result query, as well as for research analysis. The administrator can query the software based on a number of selected parameters, such as visibility range, age group, a specific user or a collection of users. Tabulated and graphical representations of the results are provided. They have the ability to create the maps that will be explored by the users. This is examined further in Section IV.

The visually impaired user's role is to navigate through the VE and interact with embedded objects. The VE is a 3D reconstruction of the map selected by the administrator. The user interacts with the VE and objects using a Novint Falcon 3 DoF haptic device supported by keyboard functionality. The user can move forward, back and sideways within the VE, and rotate 45 degrees to the left or right. Sounds are emitted by objects in the VE at different volumes depending on the distance. As the user navigates, collision with objects triggers a force response through the haptic device paired with an audio response. The user may press a button to hear a sound identifying the name of an object.

Models of standard indoor objects such as tables and chairs are created and stored, for access and placement upon generation of the VE. A map source represented by image data are input to the application and the boundaries of the location, such as the room perimeter, as well as the object locations within it are stored as coordinates. Boundaries of the VE are generated automatically by the software. Haptic and audio cues are associated with objects represented in the VE, modeled on their real world attributes. The real environment represented by the map source is assumed as static, with all objects within the space accurately mapped to the digital map source received. Non-static objects, such as human movement, are not mapped to the digital map source as they do not aid in environment familiarity. Force feedback simulates rigid body interactions which are suited to object interactions at the macro-level, as evident from the findings of Lahav *et al.* (2008), where user feedback indicated that the object's micro-level haptic properties are not useful in object detection or identification.

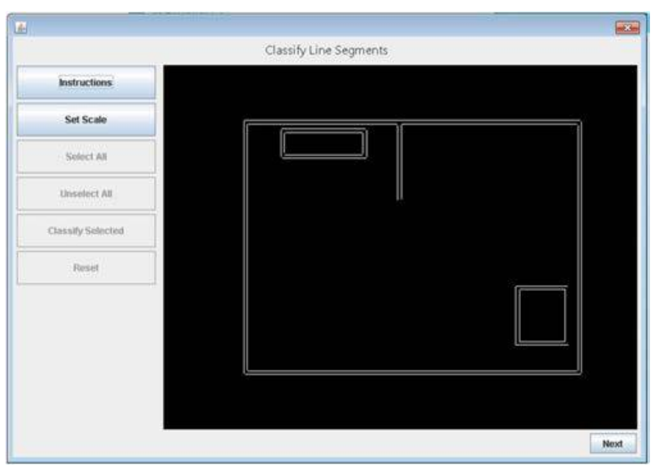
Embedded processes were semi-automatic, for data registration, and object and wall reconstruction. Automating the map generation process reduced administrator time spent in preparation for user testing, for faster generation of results. Line segment recognition enabled wall boundaries or objects to be labeled automatically. Algorithms that provided room scale estimation from raster data to metric units were also included in the automation process. To optimize rendering time, realistic textures were not applied to objects. Similarly, fine haptic feedback pertaining to varying degrees of firmness was not simulated, preventing the user from being overwhelmed with too much stimuli. User-prompted voice-over identification is included to assist in user navigation, providing another feature for object identification in addition to haptic feedback. Simplified environmental sounds were added for greater user immersion and orientation. From Schloerb's (2010) findings, the use of background sounds helped users remain oriented in the VE and as such, are included in this application.

IV. Implementation

A. Floor plan segmentation and object classification

To produce a 3D room reconstruction, a 2D map is input to the system (as an image) and the walls as well as embedded objects are extracted and classified. The first algorithm in the pipeline converts the image floor plan input to a set of line segment coordinates, via thresholding. The coordinates as output from this algorithm are used to create line segments which represent the reconstructed floor plan. An interface for the classification of lines and placement of additional furniture objects is presented to the administrator, comprising three screens. The first screen (Figure 1) allows the administrator to group line segments together to represent walls or objects

Figure 1 User interface for classification of existing line segments



by clicking on the desired line segments, classify them via a drop-down menu and set a real-world value for a single line segment. The program then calculates a scale to be applied to real-world values for the remaining segments, using this value.

The second screen (Figure 2) allows the administrator to place additional furniture by selecting the desired object and clicking within the floor plan to generate a bounding box representing the object. The third screen (Figure 3) allows theuser's default starting position and orientation, at the center of the image facing north, to be modified.

B. 3D reconstruction of the indoor scene

The map (Figure 4) is recreated in the software x3D using classified line segments and any placed objects. x3D uses the object center, its rotation or orientation, its position, and its size to reconstruct it in 3D. The wall is created using the "Box" tag which requires *x*, *y*, *z* values which represent the element length, height, width. These values are predefined and calculated at the back end. The predefined

Figure 2 User interface for optional placement of additional furniture objects

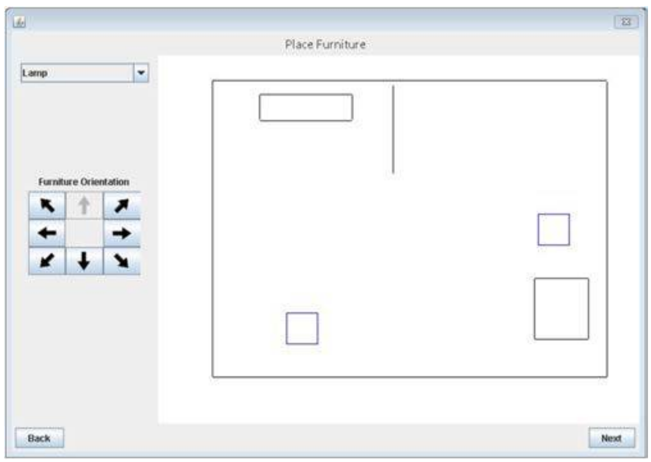


Figure 3 User interface for selecting a user starting position and orientation

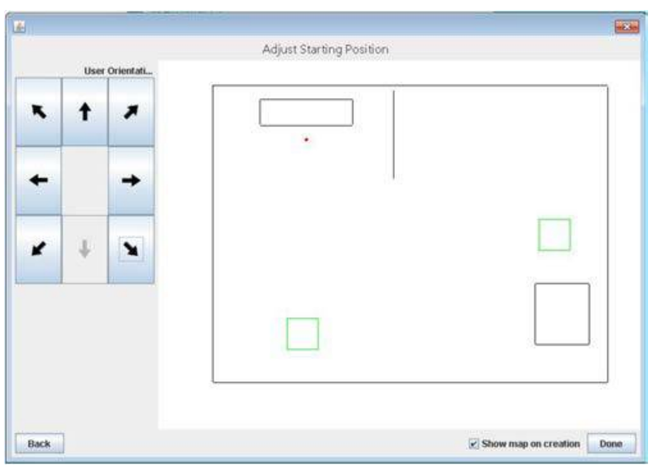
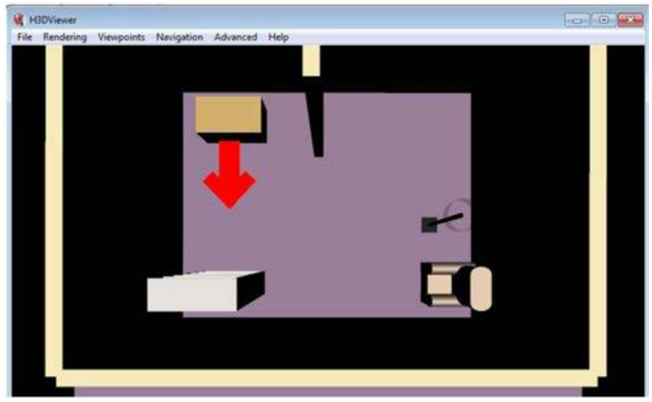


Figure 4 3D recreation of a map in x3D (top-down view)



Note: The red arrow represents the user's starting position and orientation

height value of walls is calculated by dividing 3 by the meters per pixel calculated by the segmentation and classification process; the thickness of the walls is calculated by dividing 0.1559 by the meters per pixel; divider values were determined as industry standard average values (Meyers-Levy and Zhu, 2007) for ceiling height (three meters) and plaster wall thickness (0.1559 meters).

Furniture, such as chairs and tables, are created as separate x3D files. If certain line segments are classified as furniture, the appropriate furniture model is added to the map. The furniture is made on a one unit (one meter) scale and as such requires scaling to fit the dimensions of the map. The aforementioned meters per pixel value is used to scale each furniture model before they are placed in the map. The height and location of the model to be placed appropriately in the map is retrieved. Audio files and event handling are written within each model and therefore all instances of the models will react similarly. Once received, a python file saves the meters per pixel value and adjusts the user's walking speed based on the value. Background or ambient noises are placed in the map as well as a footsteps sound effect. The footsteps location is bound to the location of the user to ensure that it is heard wherever the user travels. Dynamic passing of values between two nodes is enabled. In this instance, the position of the source of the footstep sound effect is bound to the position of the ViewPoint, or camera, defined earlier in the construction.

C. Haptic rendering of the scene and event handling

Haptic rendering is the process of updating forces to the user during real-time model manipulation, during room and object exploration. The Novint Falcon, popular for simulating realistic force feedback in video games, constitutes the haptic interface in this work. Within the haptic response, bumpy or smooth surfaces in textures are simulated. Users can interact with these surface types using the 3DoF device, to differentiate between various surfaces, such as discerning variability in surface hardness to assist with object identification.

Visual and haptic rendering algorithms are those that compute changes in topography due to user interaction. These are implemented here using a variety of languages and API's that facilitate fast development and real-time response times, including H3DAPI, x3D, and Python. H3DAPI allows for the use of C++ and OpenGL for visual and haptic rendering for advanced programming and provides rH3DViewer and H3DLoad for real-time rendering. The solution offered ease of event handling through Python scripting and capabilities for fast haptic rendering. A combination of x3D, an XML based file format to display graphics, and Python are used for ease of graphics creation and event handling. Several <PythonScript> nodes are placed to allow for event handling using Python scripts. Several <ROUTE> nodes are also added to pass values from nodes to the Python code and vice versa. A python file triggers audio cues when the stylus of the haptic device (or proxy) comes in contact with a furniture object in the 3D VE.

A different python code is used to capture the location of the camera as the scene updates as well as the forces on the proxy to detect collision, to create a log of the user's progress. When a positive force is detected on either x, y, or z components of the proxy, the location of the collision is written into a log file. A python code, the camera controller, is used to capture keyboard input and the location of the haptic device to move the camera about the VE. When one of the arrow keys is pressed or the correct number is pressed on the numerical pad of the keyboard, the camera is moved by applying a forward vector on the identity matrix of the camera location. Other keys allow the camera to move backwards, sideways and also to rotate. If a collision is detected, any forward camera motion is stopped until the collision is resolved. Footstep sounds are triggered during forward or backward camera movement.

D. Shortest path graph creation

After the user has explored the environment, it is of interest for the administrator to compare the actual path traversed with a shortest possible path, to examine variance. A shortest path algorithm has been constructed to determine that which the user could have taken during map exploration. The starting position, map width and length as well as a collection of classified line segments are taken as input to the algorithm. The width and length are divided by a constant integer N to divide the map into an $N \times N$ grid. To ensure that the entire map is divided evenly, the modulus of the greater of the width and length is added to the quotient when divided by N. A graph is then created by forming a node (a square with side length of the quotient calculated) from the indicated user starting position within the map which is the root of the graph. The graph serves as a collection of bidirectional nodes that represent areas where the user is able to walk within the map.

The recursive algorithm begins with the root node and considers all eight possible surrounding nodes for validity. As each node is created (clockwise from left of the current node), the algorithm ensures that: first, the node center is not outside the map boundaries; second, that the node does not intersect with any of the classified line segments; and third, that the node has not been previously classified as invalid. If the node is valid, it is connected to the current node. The evaluation continues for all eight possible nodes the user can move to from the current node. When the current node is deemed complete, the recursive algorithm is called on all of the current node's interconnected children. The recursive algorithm terminates if the node it receives is an invalid node or has already been evaluated.

E. Path finding within the map

Another algorithm is implemented to determine the actual path taken by the user within the map. A collection of points is input and regarded as points of interests (POI) in the map. These POI, including the starting positions, are the locations required of the user to reach as part of a quantitative analysis for their degree of learning. Each of the POI is mapped to the closest node in the generated graph except the starting position, which is excluded as it already belongs to the root node. Points located within invalid areas are also mapped to the closest possible valid node. Calculation of the Euclidean (straight line) distance between the given point and the center of each valid node provides comparative measurement: the larger the distance, the farther the user from the optimal (shortest) path.

Two path finding algorithms were considered to determine the optimum path between every node of interest: the A* path finding algorithm and the Jump Point Search (JPS) path finding algorithm; an extension of the A* algorithm. The A* considers both the cost of going to a node, expressed as a function G, from the origin and a heuristic value, expressed as a function H, from the node to the target (Lester, 2005). The combined value, expressed as a function F, determines if a node will be part of the optimal path from the origin node to the target node (Lester, 2005). In JPS, possible nodes are pruned depending on the direction from the origin node to the target node (Harabor, 2011). This enables quicker optimal path derivation compared to the performance time of A* (Harabor, 2011). The A* is implemented here to generate the shortest path between several nodes of interest since path finding within a generated map occurs in administrative view, where rendering is not real-time.

F. Path comparison

Each time the system undergoes visual re-rendering, the user position is sent to a file. Within this file, each point is mapped to the nearest valid node within the graph. Based on the administrator's chosen POI, a sub-path is derived from the user's complete path where the user starts from one of the POI to the next or until the end of the path (the next point is never reached). Euclidean distance is calculated to compare the user's sub-path and the shortest path from the selected POI.

G. Training modules

Various training modules were developed for user familiarization and training with the system, to introduce various components, from haptics device use to 3D navigation:

1. Haptic Module: the purpose of this module is to allow the user to familiarize themselves with the haptic device, haptic feedback, 3D sensation, and various 3D shapes. The user moves the device, which moves the stylus on the screen. The user is asked to identify the shape or texture using the haptics device. The first lesson tasks the user to touch a cube. The second lesson tasks the user to identify three different, curved shapes: a sphere, a cylinder and a cone. The third lesson tasks the user to identify the surface texture of three cubes and feedback on the spring effect on a fourth cube, for surface discernment and to experience spring effects toward usability and pleasantness.
2. Audio Module: this module allows the user to familiarize themselves with different types of audio cues, such as footsteps for movement, collision sounds and ambient noise. The user moves the stylus and upon collision with an object, playback of an audio cue results. The administrator switches between various audio prompts and checks if the user can identify each one. A Python file detects the collision and plays the audio based on the type selected by the administrator at the front-end.
3. Movement Module: this module allows the user to familiarize themselves with movement controls. These movement controls are mapped to three sets of keys: the number keypad, the QWERTY keypad and the arrow keys. In this lesson, the user may try out the movement controls and select their preferred set of keys. A Python file handles the user's changes in position when the keys are pressed.
4. Integration Module: this module combines all of the aforementioned modules into a haptic and audio-enabled VE. The user will be asked to navigate through this fully integrated VE. A speech component has been created, which is extended from the Speech 0.5.2 module which uses the built-in Windows speech synthesizer to convert text to audio. A string can be passed to this module in order to be read out by the speech synthesizer; such as "Hello." When the "t" key or "0" key is pressed, the name of the object last collided with is read.

V. Testing

This section outlines both usability and functional testing, for application verification and validation. In total, seven tests were conducted, including qualitative testing via surveys and quantitative testing, through capturing the position of the user over time, number of collisions and location of collisions. User ages varied from nine to 55 years and their anonymity was retained throughout testing. Test conditions were safe and testing procedures were explained to each participant. Participants were sighted although blindfolded throughout the entire testing procedure, simulating late-onset blindness and test subjects had no priori knowledge of the testing environment. In his literature review of cognitive mapping of visual experiences for comparison between congenitally blind, late-onset blind and sighted persons, Ungar (2000) determined that in many of the case studies he examined, congenitally blind participants were found to perform spatial tasks at the level of sighted participants, such as in tests of spatial inference and "that lack of visual experience does not prevent the acquisition of spatial representation." Further, in most studies research findings determined that early-blind participants performed to the level of late-blind and sighted participants in tasks that involved spatial memory (Ungar, 2000). In cases where early-blind participants performance was worse, it was determined that differences may be due to behavioral or coding strategies that provide a tendency rather than an inability toward specific spatial performance (Ungar, 2000).

A. Test 1

Prior to the user undergoing haptic navigation testing in the simulated or real indoor location, each user underwent a series of training modules, as discussed in Section IV G. A usability survey was conducted to assess their performance and level of comfort within these training modules. In all, 21 users were tested, with the following statistics: ages ranged between nine and 55 years old. Male:female gender ratio of 52.38:47.62 percent. User feedback determined that simple shapes were easy to identify, while complex shapes were difficult. Users suggested that adding audio and frictional surfaces to objects could make identification easier and help discern objects from haptic device boundaries and that audio may help more than frictional surfaces. Users concluded that existing movement control options were satisfactory and intuitive to learn.

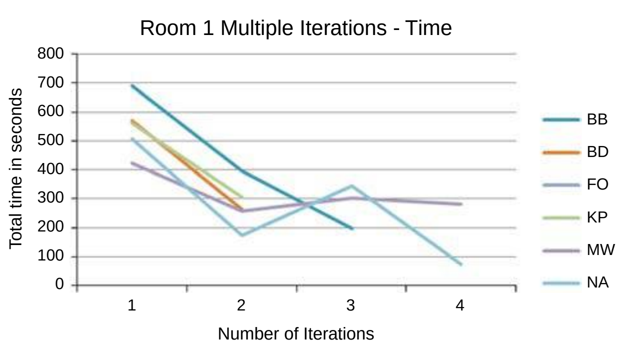
B. Test 2

Users from Test 1 were asked to explore a simple map without furniture (Room 1) and then provided with a usability survey on their interactions with the VE. Eight users completed Test 2, with the following statistics: ages ranged between 14 and 37 years old. Male:female gender ratio of 50:50 percent. Based on survey results, users found it easy to locate the walls, and generally easy to follow along them. The speech component, for identifying the last object hit, was deemed helpful. The assumptions for Test 1 were proven since audio cues were helpful in users discerning objects apart and from walls.

C. Test 3

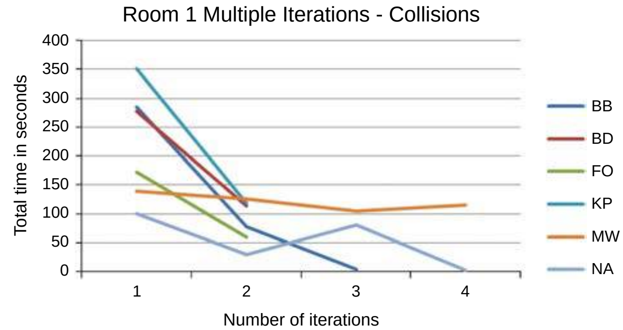
Users were guided by the administrator through a virtual room to see whether they became more familiar with the room progressively, over the series of iterations. The first iteration was carried out by eleven users, the second iteration by six of the 11 users, the third iteration by three out of the six users and the fourth iteration by two out of the three users. Their performance was measured by tracking the amount of time spent in the room and the number of collisions over the number of room iterations (Figures 5 and 6). Upon conducting the user survey and analyzing results

Figure 5 Amount of user time spent within map, iterations 2-4



Note: To preserve user anonymity, two-letter acronyms denote each user (listed on right)

Figure 6 Amount of user collisions within map, iterations 2-4



Note: To preserve user anonymity, two-letter acronyms denote each user (listed on right)

attained, it was determined that as the number of iterations through the map increases, the layout becomes more familiar. It was also apparent that when the user remembered the number of steps between room corners it reduced the time taken to make decisions regarding movement.

D. Test 4

This test required users to find furniture pieces in the middle of the room. The user is first told that the objects are "[…] close to the door and north-east of the starting position." As the user explores the map, the user is told, after each successful rotation or pause, what direction the objects are relative to the direction the user is facing. Users can stop the test at any time to restart the map and to test estimated object positions. The goal of this test is to assess the user's mind mapping ability and spatial awareness to find new object locations relative to known object locations. After each successful test, the user is asked to sketch the estimated location of furniture objects. Four users performed this test with the following statistics: ages ranged between 14 and 37 years old; an average age of 27 years. Male-to-female gender ratio of 50 percent. User feedback from the survey deemed that as the number of iterations through the map increased, the environment became more familiar. Further, remembering the number of steps between room corners reduced time taken for decision making.

E. Test 5

This test required users to move from one location to another, based on instructor commands. Users are instructed to go through the following points, under the agreed terminology that the starting position of the user is in the bottom left corner of the room, facing north: the door, then the top right corner of the room, followed by the top left corner of the room and finally returning to the starting position. The goal of this test is to assess the user's mind mapping ability and virtual muscle memory to recall the location of these points. Four users undertook this test with the following statistics: ages ranged between 14 and 37 years old; an average age of 27 years. Male:female gender ratio of 50:50 percent. From survey results it appeared that older users, aged 35-37, from total age range 14 to 37 years for all participants, are more comfortable following their mental map and virtual muscle memory to reach known destinations. However, even after becoming familiar with the virtual space, it was observed that participants are hesitant to stray away from familiar paths.

F. Test 6

This test required users to traverse the virtual room as far as possible while keeping the wall on their left. The user continued to move forward unless a corner was encountered and the user needed to turn. This test contains the same set of rules as Test 3 except the user does not attempt to traverse the room anti-clockwise. The user may stop the test at any time to gather and reinforce the mental map they have created and start over. The user may also explore the rest of the room to add details to their mental map. The goal of this test is to assess the user's mind mapping ability and memory when applied to a large map. At the end of the test, the user is asked to sketch the room as determined by their mind map. Three users were asked to perform this test with the following statistics: ages ranged between 14 and 37 years old; an average age of 28 years. Male:female gender ratio of 66.67:33.33 percent. User feedback determined that it was difficult to traverse large maps and create mind maps of them. This was mainly due to the vast amount of information encountered, including the size of the room, shape of the room, number of steps taken, audio prompts, haptic prompts, keyboard usage and haptic device usage, and time-based location recall. Through practice, it was determined that users could learn to walk through the VE by taking one step at a time. Through repeated exposure to the VE, results indicate that users become more familiar with the shape of the room and the necessary number of steps. It was evident that in-corners and out-corners can affect users' understanding of surfaces.

G. Test 7

This test required users to traverse the physical counterpart of the room from Test 6. Users were taken, blindfolded, to the physical location of the reconstructed class room. This was the same room as simulated in Test 6. The user is placed in the same location and orientation as their virtual counterpart and are handed a walking cane substitute: a plastic toy golf club. The user then proceeded to replicate Test 6 but within the physical location until they reach the location they have reached during their virtual experience. The users were filmed throughout the entire process. The goal of this test was to assess the user's mind mapping ability and recollection from a virtual experience to real life, to finally determine whether virtual navigation can assist in physical navigation, and to what extent. The same three users were asked to perform this test with the following statistics: ages ranged between 14 and 37 years old; an average age of 28 years. Male:female gender ratio of 66.67:33.33 percent. User feedback revealed that objects could be anticipated and that the shape of the virtual room matched that of the real-life environment. However, the number of virtual steps and steps in real life were different, slowing down movement in the actual room as it was difficult to gauge its scale. The white cane substitute greatly mimics the actions used with the haptic device when exploring virtually. Results revealed that navigation within the virtual room assisted in spatial awareness of the physical room, and objects within it.

VI. Discussion

The advantages of providing tactile maps and auditory cues of introducing a visually impaired user to an environment and to improve abstract level spatial thought as well as for mobility training are documented in the literature (Ungar, 2000; Jacobson, 2005). Toward assisting in mental mapping for sight impaired persons during navigation, a virtual reconstruction of an indoor location with haptic and audio cues, derived semi-automatically from a 2D image-based floor plan has successfully been implemented and tested. First, the system is able to automatically import an image floor plan and the graphic is sent to an algorithm to determine the line segment coordinates and saved into a dummy text file for further pre-processing. As a separate component, the system is able to draw line segments from a text file. The user can classify these segments as walls or furniture. Pieces of furniture can dynamically be added into the map. The user's starting position can be initialized in the same interface. The classified line segments are reconstructed in 3D under the x3D format. Any classified furniture is derived from pre-created models and placed selectively within the scene. Haptic properties and Python support are added at this stage. Basic textures and environmental sounds are also added. The final result is presented to the user as a 3D virtual room with or without furniture, for navigation using the haptics device and audio prompts. All users tested were blindfolded to simulate late-onset visual impairment.

A novel, user-friendly and custom GUI has been created to enable a portal for using the application. The GUI integrates the processes into one single unit which allows administrators to provide an image file to create a 3D map. The administrator may also create or edit user profiles. A map may be selected from a list of pre-created maps and launched in the visual and haptic renderer. The user's location is tracked and stored in a file, which can be late accessed by the administrator. Object collisions are stored in a separate file that indicates the object hit and collision location. Both values are saved automatically and can be opened in the administrator dashboard. These values are used to calculate the length of time the user was in the VE, total number of collisions, as well as a visualization of the path taken, with the original image set as the background, and the location of collisions, all stored in a database.

Test results for all participants, aged nine to 55 in Tests 1 through 7, were collected, analyzed and examined to determine the extent to which haptic rendering and/or audio cues help a visually impaired user to navigate through the indoor location (virtually and in reality). Results of users' map traversals within the application are automatically stored into and retrieved from the database. Results show the total number of query results, the gender ratio of the test participants, their average age and average impairment values, as well as the specific performance of a user, including time for task duration and number of collisions, based on the maps they used, and the date and times of the day. Results are graphically displayed within the application in the form a pie chart for administrative purposes, to indicate the ratio of a user's object collision with various object constructs (such as chairs, tables and walls), a bird's eye view of the user's path in the map and a grid version of the map. The shortest path algorithm has been implemented and its development enables display on the grid. It is derived after selecting POI on the map via point-and-click. Users' traversals can then be compared with shortest paths.

Results of these tests indicate that a user's performance improves over time with exposure to the virtual indoor location using the VirtuNav application for navigation, both within the virtual room and for spatial awareness within the real (physical) location that has the same dimensions and construct as that which is recreated synthetically.

VII. Conclusion

VirtuNav provides an assistive technological solution for the visually impaired to navigate an indoor location in VR, to assist with mental mapping and become more familiar with a synthesized as well as real environment. VirtuNav enables the user to explore this generated model through a user interface that provides visual, haptic and audio cues for navigation about the environment. Unique features include map design, semi-automatic 3D map reconstruction and object classification from 2D map data, visual and haptic rendering of real-time 3D map navigation, and automated administrative functions including determination of shortest path taken, comparison with the actual path taken, and assessment of performance indicators relating to time taken for exploration and collision data. Test results indicate that user familiarity is developed after repeated exposure to the indoor location, revealing that haptic and audio cues can improve a visually impaired user's ability to navigate a room or building with or without occlusion. Spatial awareness and memory mapping were shown to improve with user iterations within the VirtuNav environment.

Research findings are expected to help a user overcome fear and anxiety by building confidence of the spatial layout of an indoor location, through repeated exposure to VirtuNav. This is toward more frequent and improved exploration and navigation, to heighten social and environmental engagement for the sight impaired. Implications of the research may help visually impaired children and adults more frequently and actively explore and engage with external locations outside their home, reducing levels of anxiety, loneliness, depression, and social isolation. However, further testing is warranted. More testing can include a greater variety of age groups, extent and type of visual impairment and location variation, and comparison with a congenitally blind population. Future work should include questionnaires to gauge the degree to which participants find the application useful in overcoming perceptual and physical barriers associated with navigation, and subsequent social and health benefits.

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