Navigating and Shopping in a Complex Virtual Urban Mall to Evaluate Cognitive Functions

S Sangani, J Fung (Member: IEEE)
School of Physical and Occupational Therapy
McGill University
Montreal, Canada
Feil/Oberfeld/CRIR Research Centre
Jewish Rehabilitation Hospital
Montreal, Canada
joyce.fung@mcgill.ca, samir.sangani@mail.mcgill.ca

S T Koenig
Institute for Creative Technologies
University of Southern California
Los Angeles, USA
skoenig@ict.usc.edu

R Kizony
Dept. of Occupational Therapy
Sheba Medical Center
Tel Hashomer, Israel
rkizony@univ.haifa.ac.il

R Kizony, PL Weiss
Dept. of Occupational Therapy
University of Haifa
Haifa, Israel
rkizony@univ.haifa.ac.il, tamar@research.haifa.ac.il

***Abstract*—Complex virtual environments (VEs) provide a multisensory, three-dimensional representation of real environments enabling their use in rehabilitation research to characterize and probe cognitive and motor abilities. This paper describes the application of a complex VE to characterize different motor and cognitive (executive) functions associated with navigating and shopping in an urban mall. The complex VE was created using relatively simple graphics and modeling tools, and recently implemented on a self-paced treadmill to allow moving in the VE through voluntary locomotion. Navigation and shopping in the virtual mall was controlled by a combination of different keystrokes and mouse buttons.**

Keywords—functional virtual environments; executive functions; instrumental activities of daily living

I. INTRODUCTION

Virtual environments (VEs) provide a complex, ecologically valid controlled environment for systematically evaluating cognitive functions associated with activities of daily living such as navigating through a mall and shopping for a list of items. VEs can be designed to promote active user participation, naturalistic interaction and at the same time provide clinicians and researchers opportunities to objectively and quantitatively assess the behavior of participants while they carry out realistic tasks in safe but challenging environments [1].

Recent technological advances have generated a lot of interest in the development of systematic workflows for creating context-specific, complex VEs using simple graphics and modeling tools which enable a researcher or clinician to readily include a variety of functional tasks or computer tools [2,3]. Systematic workflows enable the creation of complex VEs using photorealistic three-dimensional (3D) models to help researchers and clinicians design a number of interactive and functional simulations [2]. In addition, various simulation technologies permit the development of VEs that may be presented via different forms of visual display devices and operated via interface devices which allow the user to interact and engage in tasks within the environment. Several studies have described systematic workflows for developing context-specific VEs [2,4] and the common theme in all these studies is the presence of 3D models created using realistic measures and textures to give the user a feel of a real-world environment within the simulation.

In a previous pilot study, we described the use of such a workflow to create an enclosed section of an urban shopping mall [3]. The present study focuses on the applications of this complex environment in different experimental paradigms. It is part of a large-scale, multidisciplinary research project to create a “Rehabilitation Living Lab” within the setting of an urban shopping mall. The ultimate goal is to optimize social inclusion of persons with disabilities by creating enabling physical and social environments. The concept of “Living Labs”, as a research paradigm for sensing, prototyping, validating and refining complex solutions in multiple and evolving real life contexts (http://livinglabs.mit.edu/), is the definitive realization of participatory design to identify true user behaviour [5].

To enhance engagement and increase motivation of the user, developers and designers need to take into account end user needs and expectations [6]. Shopping in an urban mall is a complex task which involves the use of cognition (especially executive functions) as well as locomotor abilities required to navigate to the particular store of interest. The four-item shopping task used in the present study was adapted and modified from previous studies investigating the use of a virtual supermarket [7] as an evaluation tool for executive functions for people with stroke [8,9]. The results of these

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studies showed that the four-item shopping protocol provides a realistic and meaningful task to the subject, enabling the assessment of their cognitive and executive functioning in ecological environments. The VEs in these studies were presented in a two-dimensional (2D) environment with the participant navigating by hovering their hand over on-screen arrows. In contrast, the present study provides a first person perspective of the 3D environment, displayed either as a monoscopic desktop or a stereoscopic environment. A recent study [10] has shown that both types of 3D environments are effective in rehabilitation paradigms, and the choice of environment should be dependent on the task as well as the target group of study participants. In the present study we utilized a 3D desktop environment where the user can navigate and rotate their viewpoint using a keyboard and mouse to move in the VE, thus providing a visual flow similar to that obtained during real-world navigation. In order to compare subject behavior in two different types of ecological VEs, a modified version of the four-item shopping task [9] was also implemented via the SeeMe Virtual Interactive Shopper (VIS) platform (http://www.virtual-reality-rehabilitation.com/).

The primary goal of our study was to assess the functionality of the complex shopping mall (CSM) VE by implementing a shopping protocol which involved navigating to a store and purchasing a given list of pre-selected items. We also compared the performance within the mall of healthy young to healthy older adults. As data collection was carried out in two different sites (Canada and Israel), we also made the simulations culturally specific, such as the display of shopping items, prices and language used.

II. METHODS

We conducted a pilot study on four healthy young (28.1 ± 2.5 years) and three healthy older adults (66.2 ± 2.7 years). All participants signed an informed consent form approved by the Institutional Review Board of the University of Haifa, in accordance with the 1964 Declaration of Helsinki. Participants had no history of neurological impairment and were recruited in a convenience sample. We also recorded personal characteristics such as prior use of computer and routine computer applications (e.g., Window's Office) and videogames as well as educational background and profession. These characteristics were later used to assess differences in individual responses due to familiarity with computer games or with computers in general.

A. Complex shopping mall (CSM) VE

We used an enclosed section of an urban shopping mall to create the CSM VE that was implemented in the present study and designed using a systematic workflow using relatively simple computer graphics and modeling tools [3]. The workflow was inspired by and adapted from that originally proposed by Koenig et al. [11]. The workflow was then revised based on the design aspects of the study protocol and several changes were made including the software used for creating the 3D models. Trimble SketchUp Pro was initially used to create the 3D models, but Blender, an open source 3D creation tool, was used more recently to give precise control over the number of polygons/vertices of an object during modeling. Switching to Blender was also beneficial in terms of making updates to the model as Unity (v4) can now import Blender format (blend) files without requiring them to be exported to another (FBX) format. This also resulted in a significant increase in the real-time performance and appearance of the simulation. Further modifications to the model included light mapped textures applied to static objects, as well as modifications to the graphical user interface (GUI) in order to make the simulation more interactive and user-friendly. Figure 1 illustrates a few of the above-mentioned changes made to the earlier version of the simulation (left) [3].

The viewpoint of the participant in the VE was rendered from a first person perspective thus enabling the participant to observe the environment as they would in the real world. We defined three starting locations and two locations for final destinations which represented entrances to the store (kiosk) located in the shopping mall. For the present study we used a single fixed starting location in order to compare the trials collected across all study participants. Since the model was created to scale, each location and the traversed route was saved as a series of 3D positions along with the angle of rotation. Distance travelled from the start location to the store was then calculated from this raw data. This raw data was also used to overlay the path taken by the user on the "birds-eye" viewpoint of the complete floor captured by a camera placed in scene. This allowed the researcher or clinician to visualize the overall path taken to the store and analyze it for investigating planning and navigational strategies in complex VEs.

Movement within the CSM was controlled using a keyboard, wherein the arrow keys advanced the user by a preset speed in the direction corresponding to the keys pressed (up, down, left, and right). Two additional keys were defined ("K" and "L") to allow the user to rotate the view in the left and right directions respectively. The user could thus steer by pressing one of the two rotation keys and modify their movement path accordingly. Once the users entered the store, they used the mouse to interact with the menu items and the shopping cart. After completing their shopping, the users had the option to quit the store by pressing the corresponding on-screen button (Figure 2). The user could then voluntarily quit the trial if they believed that the shopping was complete by pressing the keyboard key "Q". In order to test the modified four-item shopping task in the CSM and characterize the interaction of the user in the store, we implemented only one store so that we could analyze the responses and identify different underlying parameters (e.g.: zooming on individual menu items as the mouse hovers over them, etc.) which could then be easily replicated for additional stores in the future. A

Figure 1. Modification of the complex VE of enclosed section of mall. Left: Original VE; Right: New VE based on the revised workflow.

video of the user's view of the store was also captured once the subject entered the store so that it would record all user interactions for post-session analysis. These videos were then analyzed to quantify various aspects of relevant behavior such as errors made when shopping, time spent on purchase decisions, money spent on purchasing items, etc. In addition, time spent navigating to the store as well as that spent within the store was also saved for later analysis.

The graphical user interface of the CSM simulation was modified compared to its earlier version [3] to make it easier for the researcher/clinician to adjust various parameters of the simulation such as movement speed, audio, position of birds eye map by clicking on different icons and visual indicators. Several portions of the simulation were translated to Hebrew since the primary site of data collection was in Israel. In addition, the store banners along with the individual store items were also changed to represent the local kiosks in Israel. This was an important step since it is more intuitive for the user to purchase virtual items which they are familiar with from everyday life. Figure 2 illustrates the menu items used in the VE at the two research centers in Canada and Israel respectively.

B. Virtual Interactive Shopper

The Virtual Interactive Shopper (VIS) was developed for the SeeMe video capture VR system [12]. It enables the creation of a shopping mall composed of different stores that can be changed and adapted according to the habits and preferences of the shopper, including the need to handle a budget. The version used in this study presented a supermarket with several different shopping aisles (Figure 3) as described by Hadad et al. [9].

C. Clinical Tests

Two subtests from the Behavioral Assessment of Dysexecutive Syndrome [13], the Zoo Map Test (ZMT) and Key Search Test (KST), were used to characterize user's planning as part of their executive functions. The KST characterized the user's ability to plan an efficient and effective course of action as well as their ability to monitor their own performance. The ZMT is sensitive to executive function deficits associated with planning a navigational route. For both tests we considered a profile score of ⩽ 2 to indicate deficits in executive functions [14].

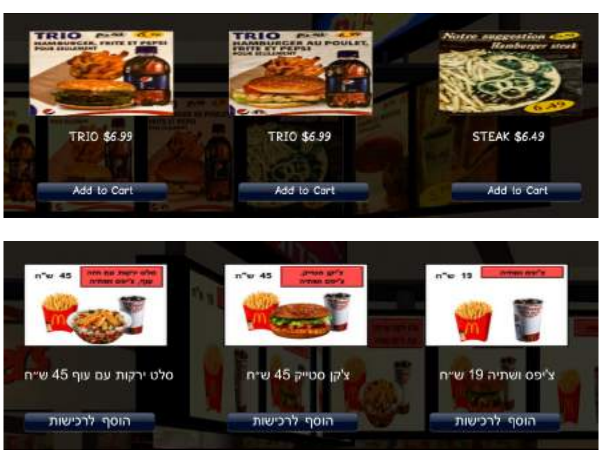

Figure 2. Display of store menu items and shopping cart in English (Top) and Hebrew (Bottom)

Figure 3. Two screenshots of the Virtual Interactive Shopper (VIS). The numerical figures on the left represent the price (larger font) of the item below which is a number that represents how many of those items were "purchased" (smaller font)

D. Feedback Questionnaires

After the end of the trial the participants were asked to respond to the Short Feedback Questionnaire (SFQ) and System Usability Scale (SUS). SFQ [15] provides a subjective evaluation of the VR experience in terms of several different parameters including the user's sense of presence, perceived difficulty of the task and any discomfort users may have while interacting with the VE (where 1 is a low score and 5 is a high score). The SUS on the other hand provides a global view of the subjective assessments of usability as the user's perception of the interaction with the system [16]. Scores range from 0 to 100 whereas higher scores indicate that participants were able to effectively interact with the different elements of the simulation.

E. Training

The training session for the CSM included navigation on a separate floor which was positioned directly above the atrium where the shopping stores were located. The user was thus habituated to various aspects of the VE (lighting, audio etc.) while at the same time trained to follow the given instructions in order to explore different aspects of navigation using the keyboard. A single training trial was conducted per subject. A similar training protocol was used for the VIS. Subjects bought a single item in a different store in order to become familiar with navigation and how to purchase items.

F. The modified four-item shopping task

Study participants performed the "modified four-item task" in both the CSM and in the VIS environment. The order of simulations (CSM vs. VIS) was counter-balanced to avoid carry-over effects. Participants were required to buy four different grocery items that appeared on a written list within a given budget. They would not exceed the budget, provided that they did not select products that were more expensive, e.g., those of a different company or quality. The shopping list was printed in large letters and placed beneath the monitor displaying the VE, so that the participant had access to it at all times during the trial. The participant was free to choose the order in which the items were bought, irrespective of the order in which they were printed on the list. The outcome measures included the task completion time (TCT), length of path traversed in the environment (PL), total shopping time (TST), number of products purchased by mistake (NM), and the order in which the four items were purchased.

G. *Locomotor task*

The locomotor strategies used while navigating in the complex VE were evaluated by employing a locomotor task in which the subject had to navigate from a given start location to the target location by walking on a self-paced treadmill (Figure 4). This task was conducted in Montreal, Canada on a single subject (Age: 29) to test the feasibility of the system as well as to complement the data collected from the training task of the CSM (wherein the user navigated using a keyboard) conducted in Israel. This collaborative effort allowed us to focus the complementary expertise of the two centers (Israel and Canada) on implementing and evaluating the complex VE in two different scenarios. The complex VE was implemented on an advanced locomotor system which combined the use of virtual reality with a self-paced treadmill mounted on a motion platform [17]. Specialized software, D-Flow (Motek BV), controlled and synchronized the instantaneous treadmill speed with the VR scene progression and the platform movement. The participant wore a safety harness and polarized glasses to have a 3D perception of the complex VE. A single trial of habituation to walking on the treadmill was conducted. This was followed by a single trial of walking at a self-selected speed from a start location to the target location. In this trial the participant was able to rotate the view by controlling the vertical axis of a joystick (Saitek x52) using their left hand.

III. RESULTS

The shopping experience in the CSM was comparable to the VIS, as shown by the SFQ and SUS scores. All 7 subjects enjoyed the experience and felt a high level of presence in both VEs. The mean ± SD of the SFQ scores for healthy young adults was 4.27 ± 0.45 (VIS) and 4.17 ± 0.55 (CSM). They also found both simulations to be effective and usable with the mean ± SD SUS ratings for healthy young adults were 87.0 ± 7.6 (VIS) and 82.5 ± 8.3 (CSM). Participants seemed to prefer the VIS VE over the CSM and this could be related to the difficulty in navigating the 3D virtual space in CSM using a keyboard.

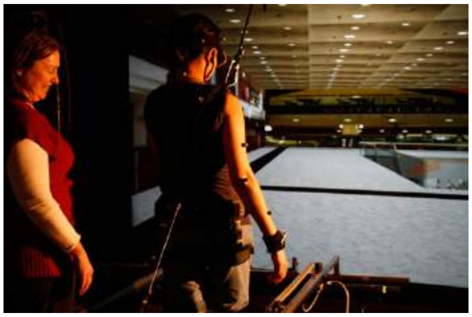

Figure 4. Self-paced treadmill locomotion in a complex VE (CSM)

A. *Performance in VEs (VIS and CSM)*

The results of the performance in CSM of both healthy young and older adults are shown in Table 1. Task completion time in the training session was longer in older adults (mean ± SD = 203.4 ± 35.3 s) compared to the younger participants (mean ± SD = 104.6 ± 4.4 s). Figure 5a illustrates the path taken by both groups while navigating the training floor of the CSM. The healthy young adults had a smooth navigation path compared to older adults which may explain their short task completion times. A similar behavior was observed during navigation to the store in the main shopping trial (Figure 5b). Task completion time as well PL of participant 1 in the older adult group was longer than other participants in the same age group (Table I). This was due to the fact that participant 1 visited the store from both entry points (Figure 5d, solid black line).

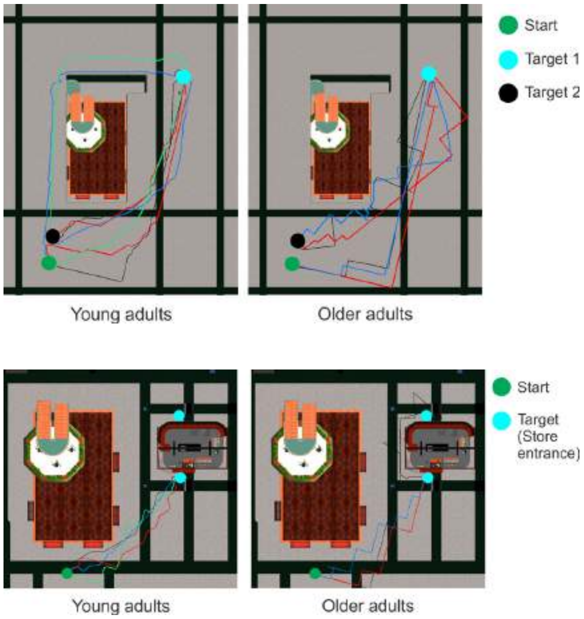

Figure 5. Navigation in training (a) and main shopping floor (b) of CSM (each solid line represents response of a single subject). Healthy young adults had a smooth navigation path compared to older adults.

TABLE I. NAVIGATION PARAMETERS IN CSM

Young Adults			Training Trial		Main Trial	
Sub	***Age***	***Sex***	***TCT (s)***	***PL (m)***	***TCT (s)***	***PL (m)***
1	24.5	F	104.6	75.8	97.4	18.3
2	29	M	106.2	75.7	107.4	18.3
3	29	M	109.0	75.7	74.7	18.3
4	30	F	98.6	78.2	121.8	18.4
Mean ± SD			**104.6 ± 4.4**	**76.4 ± 1.2**	**100.3 ± 19.8**	**18.3 ± 0.1**
Older Adults						
1	69	F	236.9	86.7	540.8	52.6
2	63.5	M	206.8	76.7	139.9	19.1
3	66	F	166.6	78.9	227.8	18.3
Mean ± SD			**203.4 ± 35.3**	**80.8 ± 5.3**	**302.8 ± 210.7**	**30.0 ± 19.6**

TABLE II. CLINICAL SCORES AND PERFOMANCE IN THE MODIFIED FOUR-ITEM SHOPPING TASK (CSM AND VIS)

Young Adults						
Sub	***KST***	***ZMT***	***TST (s)***	***NM***	***TST (s)***	***NM***
1	4	3	77.4	0	115	0
2	2	3	87.6	0	172	1
3	3	4	57.5	0	92	0
4	0	2	102.2	0	180	0
Older Adults						
1	1	0	352.7	1	545	0
2	4	4	106.1	0	199	0
3	4	0	197.4	0	236	0

Healthy young adults completed the shopping task in less time (CSM, 81.2 ± 18.8 and VIS, 139.6 ± 43.0) compared to healthy older adults (CSM, 218.7 ± 124.7 and VIS, 326.7 ± 189.9) in both VEs (Table 2). In addition, healthy older adults who obtained a score of zero on the zoo map test (Sub 1 & 3) had longer task completion times in both VEs which may indicate the sensitivity of the task and ecological complex VEs to assess cognitive abilities. However it should also be noted that based on the personal characteristics recorded for these participants, they had less exposure to computers and no exposure to video games (in contrast to the other participants); this may account for their longer task completion times. All participants purchased the correct four items based on the list given to them and thus did not exceed their given budget. NM in Table II represents the number of times the participant purchased an item not on the list. However, the two subjects who did make mistakes while shopping (S2, young adult in VIS and S1, older adult in CSM) corrected them and purchased the correct item before exiting the store.

The locomotor task (Figure 4) was conducted as a pilot test to assess the functionality of CSM in experimental paradigms involving locomotion on a self-paced treadmill. The movement in the CSM using the self-paced treadmill was very smooth and the subject found it extremely engaging due to the multi-sensory aspect of the complex VE that also included realistic lights and sounds. Turning in the CSM however proved to be difficult as the subject could not hold on steadily to the joystick for rotating the view due to the self-paced nature of the task. When the subject did try to turn the joystick he/she had to come to a stop and then continue moving forward after turning the joystick, similar to the behavior observed in healthy older adults when using a keyboard for navigation.

IV. CONCLUSIONS

The findings of this pilot study demonstrate the potential use of complex VEs to assess cognitive and motor functions associated with Instrumental Activities of Daily Living such as shopping. The results of the training task in the CSM indicated the difficult nature of navigating in 3D open spaces where one has to frequently modify the field of view in order to progress in the direction of the target.

The results of the study demonstrate that young adults were able to navigate this open space with a relatively smooth trajectory compared to healthy older adults who tended to stop at more frequent intervals, similar to the behavior observed when changing directions using the joystick during the locomotor task on the self-paced treadmill (although the underlying cause may be different in both cases). In the present study the participants were exposed to a single training trial which may not have been sufficient for those with limited computer experience (Sub 1 and 2, older adult group) to become accustomed to the various keyboard and mouse interactions. This may be one of the reasons underlying their higher task completion times. It is thus important to make sure that participants get as much time as needed in the training session to become accustomed to the VE as well as to the interfaces used to interact within the VE. Future studies will implement a longer training session.

The two VEs utilized in the present study, CSM and VIS, were able to produce similar outcomes such as increased shopping times (TST) for the healthy older adults compared to young adults. In addition, the combination of the modified four-item shopping task and the complex VE implemented on a self-paced treadmill resulted in the creation of a functional task within a simulated environment that appears to be suitable for assessing cognitive and locomotor functions relevant to real-world functional tasks as well as providing additional insight into how participants integrate cognitive functions with locomotor strategies to accomplish IADL. Future studies will look at additional parameters such as time spent on individual items as well as identify items that are challenging for a particular subject so that they can be targeted while designing context-specific intervention tasks. Overall, the high ratings of usability of both VEs (VIS and CSM) suggest that complex VEs of this type contribute to participant motivation. Continued feedback from the participants will help to ensure that the simulation protocols are feasible relevant to the study group.

Additional studies are needed to determine the effectiveness of these complex VEs as diagnostic tools for evaluating motor and cognitive deficits in neurological populations such as stroke. The capability to adapt and change different parameters of such complex VEs make them powerful tools for clinicians to design therapeutic paradigms involving everyday tasks to probe context-specific motor and cognitive abilities.

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