Assessing navigation in real and virtual environments: A validation study

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Abstract: For navigation ability, a transfer of knowledge from virtual training environments to real-world scenarios has been shown in several studies in the past. The purpose of this investigation is to demonstrate the equivalence of a series of navigation tasks in complex real-world and virtual buildings. Instead of testing knowledge transfer in very simple environments, identical tasks were performed in either version of a complex building. 29 participants were shown twelve landmarks, followed by a battery of tasks which were carried out in the real building by half of the participants, whereas the other half performed identical tasks in a virtual model of the same environment. No significant differences or effects were found, but due to the multifaceted nature of the gathered data and large variability within groups, overlap of both groups' distributions was minimal. To discover the underlying factors of this variability, further research is needed.

Keywords: Navigation ability, virtual environment, assessment tool, rehabilitation training, brain injury

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INTRODUCTION

Navigation is a highly complex skill of moving oneself, a craft or vehicle through novel and familiar environments. A variety of cognitive functions such as memory, visual and spatial perception and problem solving are involved in this important skill. Without the ability to navigate, humans are highly restricted in their independent living. If any of the involved cognitive functions is affected by a brain injury, the amelioration of navigation deficits is an important part of cognitive rehabilitation. However, navigation training during rehabilitation is often restricted to very few locations like the hospital or the patient's home. When faced with such limitations it is desirable to use simulations to retrain patients' lost abilities in a wide range of environments. Until now, knowledge transfer between real and virtual environments (VEs) and differences between several modes of knowledge acquisition have been studied. The results of these studies have been mixed.

In a study by Richardson, Montello and Hegarty (1) healthy participants learned the layout of a complex building either from a map, the real building or a VE similar to the real building. Test performance in the real building yielded significantly poorer performance by the VE group. After multiple training sessions within a large virtual building Ruddle, Payne and Jones (2) were able to demonstrate near-perfect route finding abilities of their participants. Koh, von Wiegand, Garnett, Durlach and Shinn-Cunningham (3) compared real-world training with the participants' exposure to immersive, non-immersive visualizations and also an architectural 3D model of the same environment. During training participants were free to explore the environment. While the authors concluded that training in virtual and real space are comparable, no actual navigation behavior was required during the testing phase and only estimations of bearings and distances were reported.

Taken together, many navigation studies have been limited in several ways. They only involve learning a single predefined route or judgements of bearings and distances from stationary viewpoints. This type of learning is valuable when demonstrating training effects from VEs to the real world, but is not sufficient to specify how people navigate through their surroundings. It is even less appropriate for making predictions of real-world navigation behavior which is desirable in a clinical context. Looking at predefined routes or knowledge of landmarks poses obvious restrictions compared to finding your way through a complex environment. Moreover, when people navigate in their daily life, their goals and priorities change often and unforeseen circumstances and obstacles arise, so that a single predefined route is not always a viable solution. Routes cannot always be rehearsed in advance and the navigator has to make inferences about alternative routes and the overall spatial layout of the environment. Assessing such configurational knowledge about the environment in addition to route knowledge is a step in the right direction. Witmer, Bailey, Knerr and Parsons (4) trained their participants in a complex office building and assessed route and configurational knowledge. However, their study is still limited to a predefined route and landmarks along that route. The authors' results suggest that using VEs for route learning is superior to maps, but inferior to real-world training.

Examining navigation behavior in all its complexity, this present study explicitly compared human navigation in a large real-world building and its virtual counterpart. The measurement of navigation behavior is part of a planned framework for training, assessing and eventually predicting cognitive skills in a clinical context, with focus on patients with brain injuries. With such focus it becomes important to assess how and why people are getting lost. Thus, an important aspect for this study's design is the high demand which is placed on the participants' navigation skills to provoke situations of temporary disorientation. The developed virtual reality simulation is intended for use in the day-to-day routine in rehabilitation settings. As such, usability, flexibility and compatibility with the needs of brain-injured individuals are of highest importance. To satisfy the requirements of clinicians, several navigation parameters which are relevant for predicting a patient's performance outside of the rehabilitation hospital were analyzed. Lastly, it was hypothesized that those critical parameters of navigation ability - namely walked distance, received cues, amount of decision errors at intersections, distance estimations and pointing errors - are similar in complex real and virtual environments. Navigation time, number of stops a participant makes and total time spent standing still during navigation are predicted to be higher in the VE, as these variables are expected to be influenced by the VE interface.

METHODS

Participants

36 healthy, right-handed participants from the Christchurch community aged 40 or above and unfamiliar with the tested building volunteered for this study. Only 29 participants were included in the analyses as three participants withdrew from the study due to symptoms of simulator sickness, two participants were familiar with the tested environment and two participants were excluded due to missing data after a technical failure of a recording device. The specific age group was chosen to include users with a wide range

of computer experience and to assess the age bracket of patients with stroke who are expected to be a primary target group in the future. Age of the participants ranged from 51 to 72 years in a real-building group while the age for a VE group ranged from 42 to 66 years. Male and female participants were equally assigned to both groups – six male and nine female participants in the real-building group and five male and nine female participants in the VE group.

Design

Participants were assigned to either a real-world or VE group in a randomized blocked design. Each participant was shown the same set of 12 target locations within the real version of a complex building on campus of the University of Canterbury, New Zealand. Following the initial learning phase, a series of pen and paper tasks for assessment of spatial abilities were completed. Finally, half of the participants returned to the real building to find the previously shown locations while the other half was asked to complete the same tasks in the virtual version of the campus building.

Materials

Real and virtual environment

The assessed environment was the seven-floor Erskine Building at the University of Canterbury, New Zealand. The building's lower four floors were chosen for their complexity and unusual layout. Several staircases throughout the building allowed for a large amount of possibilities to traverse from one landmark to the next.

The virtual model of the building was created using Google SketchUp 7 Pro. Textures were imported from photographs and floor plans were used to model the building to scale. Floor plans and measurements were displayed with Autodesk Design Review 2011. Interactions within the VE, data collection, interface and visual and navigation analysis tools were developed with the game engine Unity (version 2.6). The VE was displayed using a three-screen back projection system with a field of view of 180°. However, due to technical limitations only 120° of the environment were displayed on screen so that the left and right edges on screen appeared slightly stretched. Each screen measured 2.44m x 1.83m. The participant was seated 2.2m in front of the center screen. This set up allowed the participants to show natural orientation behavior by turning to the side screens for searching the environment. The VE was rendered using a quad-core PC with three Nvidia GeForce GTX260 graphics cards running in SLI and a Matrox TripleHead2Go graphics expansion module. Participants used a standard three-button computer mouse to navigate through the environment.

Pen and paper tests

Spatial abilities were measured with the Object Perspective Taking Test (OPTT; 5), Mental Rotations Test (MRT; 6) and the Card Rotations Test (CRT; 7). In addition, orientation ability was assessed with the Santa Barbara Sense of Direction Scale (SBSODS; 8). Simulator sickness was assessed using the Simulator Sickness Questionnaire (SSQ; 9). Computer experience was measured with an adapted version of the Computer/Internet Experience and Skills Questionnaire for: Internet Diabetes Trial at Harborview (10).

The OPTT is a test for spatial ability which requires judgements of bearings from imagined viewpoints. The test's score is the average of the absolute deviations from the correct angles over all of the test's twelve items. The MRT and CRT require the correct identification of test objects in comparison to target objects. Test and target objects are three-dimensional line drawings for the MRT and random two-dimensional polygons for the CRT. The number of attempted test objects divided by the number of correctly identified test objects is used as test score. The SSQ is a self-report measure for severity of simulator sickness symptoms.

Navigation Test

Navigation through the Erskine Building consisted of two phases. During an initial learning phase, all participants were guided through the building on a predefined path which passed 12 target locations on four different floors. The total length of the learning route was 498 meters. The lower four floors contained a total of 26 decision points where participants had to choose between alternate paths.

Alternate paths were classified as either optimal, suboptimal or wrong. The optimal path was defined as the shortest single route which takes the participant from start to target. A wrong path is a decision which leads towards a wrong floor (i.e. target is up but participant goes down), along a route which does not lead to the target at all (i.e. dead end or wrong room) or any decision which is a direct turnaround on a path which leads optimally or sub-optimally to the target. All chaotic movement which cannot be classified as walking a defined path was considered a wrong decision. All remaining path choices were evaluated for the travel distance they require to reach the target, assuming that all following choices minimize travel distance. The shortest of these paths is suboptimal, all others are wrong. Optimal decisions were analyzed separately whereas suboptimal and wrong decisions were combined to an error score. Suboptimal decisions were scored as an error with a factor of one and wrong decisions were scored with a factor of two. The error score is the sum of all non-optimal decisions.

Half of the twelve target locations were secluded and allowed no direct line of sight to the other locations whereas the other half was in a more central location with higher visibility towards other locations and the layout of the building. However, it was impossible to control the order and amount of exposure that each location received during the initial learning route in such a complex environment. The hidden locations naturally received less exposure whereas the central locations were seen more often during route traversal. Before walking along the learning route the participant was instructed to pay attention to the target locations and more importantly, to get a good sense of the overall layout of the building. Instructions also included the fact that the traversed learning route and order of target exposure were irrelevant for the following navigation test. Further, it was mentioned that all target locations were again to be rehearsed before starting the navigation test. Participants had to stay with the experimenter at all times. Walking speed along the route was held constant. Orientation behavior was strictly encouraged and initial instructions emphasized that the participant was free to do what he/she normally does when being in a novel environment.

During the assessment phase of the experiment participants were expected to demonstrate configurational knowledge from the very beginning by starting from a different building entrance and finding new ways through the building. Half of the target locations were designated navigation targets while the other half was used for pointing tasks. Instructions, order and nature of tasks were the same for all participants and both groups. Navigation and pointing tasks were always alternated in a sequence which did not match the learning route.

For navigation tasks participants were instructed to find the shortest way to the given target without using elevators or asking people for help. There were no route restrictions and all of the lower four floors were available for use. Cues were given systematically whenever participants asked for help or indicated that they were lost. Further, whenever a participant took more than two consequent wrong turns at a decision point or when no progress was made on a wrong floor (>4 decision points without leaving the floor towards the correct floor), a cue was given. Cues were categorized to either state that the participant is on the wrong floor, to verbally identify the correct floor, to give a semantic cue about the target, to guide towards the correct side of the building, and to explain in detail how to get to the target. Cues were given gradually in the listed order except when a participant asked specifically for a cue. Participants' navigation performance in the real building was recorded on video. All videos were later analyzed using VirtualDub to extract the timing of all tasks, cues, stops and to plot the exact route on a floor plan using Autodesk Design Review 2011. In addition, the plotted paths on the floor plans were rewalked in the VE with accurate timing to visualize and analyze the data. That is, by transferring all data into the VE, distances, number of stops, angles and viewpoints were easily computed and displayed in 3D space with pinpoint accuracy. For visual and computational analysis of the participants' routes, the original VE was modified using the Unity game engine to allow the experimenter to visualize all data, rewalk routes and carry out distance and angular calculations after the experiment was finished.

As soon as a navigation target was reached, a tripod with an attached protractor was set up at a predefined pointing location. The tripod had a wooden plate mounted on top with an attached clock-hand. The protractor was hidden underneath the wooden plate to prevent giving any cues to the participant. The clock-hand was used by the participant to indicate the direction in which the pointing target was expected to be. The absolute deviation from the correct angle was recorded. Pointing targets were always on the same floor and not visible from the participant's position. Participants were not allowed to leave the location where the tripod was set up. After pointing towards the pointing target, the participant was asked to estimate the egocentric Euclidian distance towards the same target. The participant's answer was scored as a percentage of the actual target distance. Lastly, an empty floor plan (only the outer walls of the current floor of the building) was provided in which the participant had to draw his current and also the position of the pointing target. The location of two building entrances was shown on the floor plan to give the participant a better sense of distance and location. To analyze the participant's answers, the floor plan was divided into a three by three array of sections. The deviation from the correct section was counted so that diagonal movement was not allowed. The highest possible error score for any response is therefore four, given that the participant's mark is in the opposite corner of the building from where the correct target location is.

Procedure

Participants were tested individually with each session lasting two to three hours. The experiment started at the Psychology Building at the University of Canterbury, New Zealand. After an initial briefing participants gave written informed consent. During the first 15 minutes questionnaires for demographic background, computer experience and the SBSODS were completed. Next, the participant was taken to the Erskine Building. The experimenter led the participant along the predefined learning route through the building and explained all twelve targets. After leaving the training environment, the participants returned to the Psychology Building where they completed the MRT, OPTT and CRT. Before navigation performance was tested, a list of the twelve targets was presented. Feedback and further explanations were given about all targets until the participant felt confident and no questions remained. For the navigation assessment half of the participants were guided towards a different side entrance of the Erskine building. The other half of the participants was tested at the VisionSpace Theatre of the HIT Lab New

Zealand. A simple environment with two visible targets was used as a practice scenario for navigation and pointing tasks. After each participant was comfortable with using the mouse, the virtual assessment started at the exact same virtual side entrance which was also used for the real-world assessment. The remainder of the testing session was identical for both groups as described previously.

Statistical Analysis

The basis of the present study is a comparison of real and virtual navigation with a prediction of equivalence being made between both groups. This by itself poses a problem, because most statistical procedures are designed to test for differences between groups. Further, the absence of a significant difference is not to be interpreted as both groups being equivalent (11). Tryon (12) and Tryon and Lewis (13) suggest the use of a range (delta) which is defined by the extreme points of adjusted inferential confidence intervals (ICIs) of both groups. If delta is smaller than a predefined range of indifference, statistical equivalence is established. However, the range of indifference needs to be determined on substantive grounds which is not a trivial task for any research question.

In conclusion, a hybrid approach to statistical analysis has been chosen. Firstly, both groups were compared with t-tests for independent means seeking to find a significant difference. Effect sizes for all comparisons were also calculated following the procedures of Cohen (14). Lastly, the ICIs for both groups were calculated and their overlap was determined. The overlap measure indicates the percentage of participants which are included in the overlapping area of both groups' ICIs.

RESULTS

Levene's tests for homogeneity of variances were conducted for all comparisons of navigation performance and pen and paper tests. The variances for Total Time of Stops differed significantly between the VE and real building group ($F(1,27)=14.89$, $p=0.0006$). No other Levene's tests showed a significant difference. Lilliefors' tests for normality indicate that none of the distributions reported in this study differed significantly from a normal distribution.

As expected, most critical navigation parameters did not show a significant difference at $\alpha = 0.05$ (see table 1). Performance in the pen and paper tests was not significantly different between the real-world and VE group. There was no effect evident for the CRT ($d=0.19$). MRT, and OPTT showed small effect sizes of $d=0.48$ and $d=0.41$ respectively.

For navigation distance no significant difference was observed. Participants in the VE group on average travelled 46 meters further than participants in the real environment. Cohen's d was found to be small for this comparison ($d=0.37$). Confirming our expectations, there was a significant difference between navigation time of both groups. Participants spent significantly more time navigating through the virtual Erskine Building which resulted in a large effect size ($d=1.76$). Variance for the VE group was large and individual performance ranged from 501s to 2111s. Navigation time was based on the total time for all six navigation tasks. Pointing tasks were not included in this measure.

The number of cues that were given to the participants did not differ significantly between both groups. However, a medium effect size ($d=0.6$) indicates that there was a difference in the number of help cues the VE group and the real-building group received even though this difference did not reach significance. This might also be due to the large variance in the VE group where two participants received 20 and 21 cues respectively. When both participants were excluded from the analysis, the effect size was reduced to

0.24. A t-test for independent means showed no significant differences between both groups when the outliers were removed ($t(25)=-0.622$, $p=0.539$).

Table 1. *Means, Standard Deviations, P-Values, Effect Sizes and Confidence Interval overlap for all navigation measures.*

Measure	Mean±S.D. Real Group	Mean±S.D. VE Group	df	P-value	Effect Size d	CI overlap %
Decisions Error Score	23.14±12.28	26.64±12.88	27	0.4684	0.28	21
Optimal Decisions	12.86±2.96	13.36±2.76	27	0.6477	0.17	29
Number of Cues	4.87±3.68	7.86±6.32	27	0.1281	0.6	3
Floor Plan Errors	6.73±3.37	7.57±4.29	27	0.5620	0.22	38
Distance Estimation	120.01±50.91	90.42±38.4	26	0.0944	0.66	3
Angular Pointing Errors	30.98±19.35	45.23±19.85	27	0.0608	0.73	0
Navigation Distance	443.61±132.92	490.1±118.09	27	0.3296	0.37	24
Navigation Time	674.73±248.78	1380.5±520.63	27	0.0001*	1.76	0
Number of Stops	17.73±10.43	40.36±17.63	27	0.0002*	1.61	0
Total Time of Stops	171.4±111.62	589.75±388.33	27	0.0004*	1.67	0
CRT	0.89±0.087	0.91±0.057	27	0.6037	0.19	23
MRT	0.82±0.07	0.85±0.06	26	0.2231	0.48	13
OPTT	38.16±23.83	30.22±14.8	27	0.2953	0.41	6

*Note: * indicates a significant difference at $p < 0.05$; CRT – Card Rotations Test; MRT – Mental Rotations Test; OPTT – Object Perspective Taking Test*

The comparison of navigation decisions is of central importance, as this measure directly quantifies how participants navigated through the real and virtual environment. As predicted, no significant differences were found for the number of optimal decisions and the decision error score. No effect was found for the number of optimal decisions ($d=0.17$) and a small effect was evident for the decision error score ($d=0.28$). Systematic errors when drawing navigation and pointing targets onto empty floor plans showed no significant difference. The effect size for this comparison was found to be small ($d=0.22$). No significant difference was found for distance estimations in both groups. Nonetheless, participants who were assessed in the VE appeared to consistently underestimate the true distances towards pointing targets ($d=0.66$). A large effect size for angular pointing errors ($d=0.73$) indicates that pointing errors were larger in the VE than in the real building. The difference between both groups was non-significant. The remaining comparisons for number of stops and total time spent standing still both showed large effect sizes ($d=1.61$, $d=1.67$) and significant differences between both groups. Participants navigating through the VE stopped significantly more often and spent more time without virtual movement.

In addition to the aforementioned analyses, inferential confidence intervals (ICIs) were calculated for both groups of all measures (12, 13). The amount of overlap, that is the number of data points in the overlapping range of both ICIs, is an indication for the equivalence of both groups. However, as a result of this analysis almost no overlap was evident (see table 1). Floor plan errors showed the highest overlap with eleven of the 29 participants in the overlapping range of the two groups' ICIs (38%). All remaining participants were located to the extreme left and right of the distribution of error scores

Correlations of pen and paper tests (MRT, CRT, OPTT) with our navigation parameters were non-significant throughout. Only CRT score and errors in the floor plan task correlated significantly ($r=-0.516$, $p=0.007$) such that higher CRT scores were associated with less errors in this task. Also, age and sex showed no significant relationship towards any of the navigation measures.

Computer experience of the participants in the VE group was correlated with all navigation outcome measures. Correlations were generally negative and non-significant. Computer experience and the number of optimal decisions along the traversed route were positively correlated ($r=0.564$, $p<0.05$) which suggests that participants with higher computer experience performed better in the VE.

The participant's experience with the VE was almost entirely positive. Few participants suffered from mild symptoms of simulator sickness and three participants had to withdraw from the study due to more severe symptoms. The average increase of the total score from pre-assessment to post-assessment was 32.21 (SD=40.37) over 18 participants.

DISCUSSION

In this pilot trial, validity of behavioral measures in a complex building was assessed and navigation performance in the VE and its real-world counterpart were directly compared. The navigation tasks focused on configurational knowledge of the building and the 29 participants were required to make inferences about the shortest routes which had not been part of their previously shown learning route.

Most navigation parameters did not show a significant difference between the real-building and VE group. When participants were required to make decisions along their travelled routes, their decision errors and choices for the optimal, shortest route did not differ significantly between groups. In addition to the standard statistical analyses, effect sizes were calculated in order to further support the hypotheses of equivalence of both groups. Small effect sizes for both variables supported the initial null hypothesis tests. Another variable of importance is the number of cues which the participants received to find the navigation targets. Again, both groups did not differ significantly and a medium effect size was observed. Only after removing data of two participants who received most of the cues in the VE group, the effect was reduced to small size. Both participants had difficulties adjusting to the VE and using the navigational interface. Due to their difficulties to navigate adequately, abrupt viewpoint changes resulted in symptoms of simulator sickness so that breaks between navigation tasks were needed. Consequently, the removal of data points from this analysis seemed justified.

To further substantiate our hypotheses of equivalence, an additional analysis was conducted which uses the amount of overlap of inferential confidence intervals (ICIs). Overlap between scores of both groups was very low for all variables. The analysis revealed that a substantial amount of data points were located at the extreme positive and negative ends of the parameters' distributions. The finding of such small overlap of our groups in light of no significant differences and small effect sizes suggests that further research is needed to explain navigation behavior in complex natural environments.

A variety of other measures were used to quantify the participants' ability to find their way through the building and estimate the position of targets around them. None of these measures produced a significant difference, but effect sizes varied considerably between tasks. Distances in the VE were consistently underestimated which is in line with previous findings in the literature (e.g. 15). However, contrary to other experiments, our targets were not visible from the participant's viewpoint and had to be judged based on configurational knowledge of the building rather than visual cues.

The number of stops and the total time participants stopped on their routes were intended to assess the extent to which each person showed orientation behavior. Participants in the real building used such stops to search for landmarks and find their bearings. Unfortunately, many additional virtual stops were recorded due to difficulties with the computer mouse and issues with collision detection within the VE. With these limitations in mind, it comes as no surprise that a significant difference for both variables of stopping behavior was observed and the results of these analyses cannot contribute to the interpretation of navigation ability as intended.

In order to consider the use of VEs in cognitive rehabilitation the difficulty of three-dimensional environments has to be evaluated. Such quantification of difficulty is necessary to provide alternate versions of navigation tasks, classify routes and environments which patients are exposed to, and adjust training difficulty in the context of complex rehabilitation trainings. In recent experiments, researchers manipulated the number of turns or the length of the route, because they are simple to measure and implement in an experimental setting. However, most real-world environments cannot be compared to simple office corridors in a university building. Everyday scenarios like residential houses or shopping malls often have multiple floors and there is more than one viable path which leads to the target. For simulation of these scenarios different measures need to be found in order to assess complex behavior in a standardized, systematic way. How visibility, number of possible routes, results of pathfinding algorithms or other yet undefined variables influence the navigation performance in complex environments must be subject to further investigation. In addition, the relationship of VE performance and well-established clinical measures of spatial abilities needs to be examined. The results of Nadolne and Stringer (16) and Kozhevnikov and Hegarty (17) suggest that small-scale tasks like mental rotation place different demands on the cognitive system than navigating through the environment. Hence, more ecologically valid assessments are needed and the continued evaluation of VEs for such purpose seems justified.

In conclusion, the VE assessment has proven to be a useful tool for accurately capturing a complex skill like navigation ability. Through the strengths of virtual reality environments the capture, interpretation, and visualization of navigation data has been greatly improved. However, our results show no correlations with other measures of spatial ability and the complexity and high variability of our data did not allow for an unambiguous interpretation. This suggests that measuring navigation ability in all its facets is a highly complex matter which cannot easily be related to existing measures of configurational knowledge of environments. To further increase the validity of gathered navigation data, several improvements towards higher usability of the VE are necessary. Issues of simulator sickness, display distortion and model detail of the VE need to be addressed. With refined navigation measures and larger sample sizes more insights into the underlying factors of navigation performance variability are expected. Such insights are especially needed to utilize more ecologically valid assessments, because with higher ecological validity complexity of the assessment increases substantially.

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