Annual Review of Cybertherapy and Telemedicine

Volume 3 Year 2005 ISSN: 1554-8716

Interactive Media in Training and Therapeutic Intervention

Editors:
Brenda K. Wiederhold, PhD, MBA, BCIA
Giuseppe Riva, PhD, MS, MA
Alex H. Bullinger, MD, MBA

Interactive Media Institute

Spatial Ability and Navigation Learning in a Virtual City

J-H. Lee, Ph.D.[1,2], R. Mraz, B.A.Sc.,P.Eng.[2], K. K. Zakzanis, Ph.D.[3],
S. E. Black, M.D.,Ph.D.[4], P. J. Snyder, Ph.D.[6], S. I. Kim, Ph.D.[1], and S. J. Graham, Ph.D., P.Eng.[2,5]

[1] Department of Biomedical Engineering, Hanyang University, Seoul, Korea
[2] Imaging Research, Sunnybrook & Women's College Health Science Centre, Toronto, ON, Canada
[3] Division of Life Sciences, [4] Department of Medicine-Neurology, and [5] Department of Medical Biophysics, University of Toronto, ON, Canada
[6]Pfizer Global Research & Development, Groton, CT, USA

Abstract*: Background & Significance of the Problem: Virtual environments (VEs) can be used to assess spatial memory and navigation skills, although the behaviour elicited is inherently complex. The purpose of this study was to investigate the ecological validity and interrelationship between virtual navigation tasks and several neuropsychological tests.*

Methods/Tools: Forty-two participants (mean age: 70.42) took part in the study, of which eighteen were recruited from the Cognitive Neurology Clinic at Sunnybrook & Women's College Health Sciences Centre (S&W) based on diagnosis of mild cognitive impairment (MCI). Subjects completed the Groton Maze Learning Test (GMLT; a hidden maze task developed by one of the authors [P.J.S.]) and several neuropsychological tests, including the MMSE,[1] the Rey Complex Figure Test,[2] Benton Visual Retention test,[3] Trail-Making Test (Forms A and B),[4] and Digit Span.[5] Sixteen of the participants (9 normal, 7 MCI) also undertook a VE navigation task.[6] Behaviour elicited by the VE task was characterized in terms of two components, as estimated by factor analysis: a VE memory index, and a VE movement index.

Results: The VE memory index was significantly associated with the results of a conventional memory test (Rey Complex Figure), and the VE movement index was significantly associated with measures of the Trail Making Test. Compared with normal participants, participants with mild cognitive impairment (MCI) showed a significant reduction in the memory-related measures in the PGRD Maze Learning Test and memory tests (particularly RCFT), and the MCI group deviated significantly from the correct route, particularly in novel environments. Performance in the VE navigation-learning task was significantly associated with measures of visual memory and the executive function in conventional neuropsychological tests.

Conclusion: The results of this study demonstrate that VE technology can be used to assess spatial memory and navigation skills, and that measures of this behavior in a VE are related to those of conventional neuropsychological tests. Our results also demonstrate that the MCI group showed a significant reduction in memory-related measures in the GMLT and the neuropsychological tests. In particular, differences between the groups were evident in the immediate and delayed recall in the Rey Test. However, because of the small sample size, statistically significant results were not found between groups in the VE navigation task.

Novelty: The interrelationship between the VE task, the GMLT, and neuropsychological assessments is important for administration and interpretation of these computerized tests in the future.

Recently, the development of virtual environment (VE) technology has enabled a systematic and laboratory-based investigation of spatial navigation in humans.[1] VE technology has been used successfully to assess the acquisition of spatial knowledge,[2] sex differences in spatial navigation,[3] theta oscillations in electroencephalography,[4] age changes in route learning,[5] and regional brain activation patterns in neuroimaging studies.[6] However, VEs have limitations in such research: typically, participants must perform solely on the basis of visual information and must become familiar with the use of interfaces such as a mouse or joystick to direct movements. Nevertheless, it has been shown that cognitive maps developed using VEs are comparable to those acquired in the real environment.[7] Several studies have confirmed that representations learned in VEs are transferable to real space.[8]

Recent efforts to study human spatial memory and navigation have involved the use of maps or model environments. For example, Galea and Kimura[9] required participants to learn a route through a town drawn on a large sheet of paper. Although the elements of such an environment can be well controlled by the experimenter, it is not clear that learning a route by perusing a 2D drawing of an environment uses the same spatial skills as navigating in a more ecologically valid environment.[10] Many studies suggest that such navigation is not the same as a table-top test of spatial memory, and that direct inferences cannot be made about one from the other. On a table-top, all information is within one field of view (i.e., allocentric perspective); this is not the case in a complex environment, in which much of the relevant information is unseen at any specific time (i.e., egocentric perspective).[1] Patients with topographical memory impairment, who present with well intact table-top spatial and geographical knowledge tests, have been described in the literature.[11] The opposite type of impairment has also been observed. Maguire and Cipolotti[12] reported a patient with selective preservation of navigation ability in the context of profound verbal and visual memory impairment and poor geographical knowledge, confirming the double dissociation between navigation and table-top spatial tasks.
There have been few studies investigating the ecological validity of tests of spatial skill. Sonnenfeld[13] concluded that paper-and-pencil spatial performance is independent of true wayfinding or navigation ability. Kirasic[14] found no significant relationship between elderly individuals' performance on psychometric tasks and their navigation ability. However, she found that performance on a photographic-slide route-simulation task correlated significantly with real-world spatial performance. Recently, Nadolne and Stringer[15] reported that from a battery of clinical tests administered to stroke patients, one test of visual memory correlated with an environment-specific directional-orientation criterion task, but no clinical test correlated with route navigation ability. In addition, performance on a task based on ecological simulation correlated well with route navigation ability. Collectively, these studies first suggest that tasks simulating the spatial environment realistically may have greater ecological validity than traditional psychometric measures. Second, they indicate the need for further validation of ecological simulation tasks.

To summarize, computer-simulated 3D VEs have recently been shown to measure human navigational abilities and spatial memory successfully in reasonably realistic settings that are both novel and well controlled. In this study, we investigate the relationship between a virtual navigation-learning task, several neuropsychological tests that measure visual memory abilities, and a computerized, table-top maze-learning test that measures spatial memory and learning. Participating in the study were a group of healthy elderly adults, as prior studies of navigation have demonstrated that elderly adults show more difficulty than younger adults in learning and retrieving routes.[16] A second group included patients with selective memory complaints and diagnosed with mild cognitive impairment according to standard criteria.

METHODS

Participants

Forty-two participants (32 healthy elderly, 18 MCI patients) with a mean age of 70.42 (±7.75) years (range 58–84 years) were recruited from the Cognitive Neurology Clinic at Sunnybrook & Women's College Health Sciences Centre (S&W) in Toronto. The two groups were matched with respect to their scores on the Mini-Mental State Examination (MMSE), years of education, and age. All were paid US$50 for participating. Only a subset participated in the VE task, and within this group the data for 14 participants were lost as a result of a computer malfunction and withdrawals from the study because of nausea or dizziness induced by VE exposure. The final sample size for the navigation trials in the VE was 16 (9 healthy elderly, 7 MCI patients).

Neuropsychological Tests

Each participant performed: the Rey-Osterieth Complex Figure Test (RCFT; copy, immediate recall, delayed recall); the Trail Making Test (A and B); the Digit Span subtest (forwards and backwards) from the Wechsler Adult Intelligence Scale-Revised; the Dementia Rating Scale (total, attention, initiation, construction, conceptualization, and memory components); and the Mini-Mental Status Examination.

The PGRD Maze Learning Test

The PGRD Maze Learning Test,[17] a computer-based neuropsychological measure of immediate- and short-term retention of visuospatial information, is based on the original work of Milner.[18] The goal is to learn over a series of trials how to navigate from table-top perspective through a hidden maze and capture a target. Participants pressed on a touch-screen to reveal the maze under a matrix of tiles. There were untimed and timed components for either a 4 × 4 or a 10 × 10 Chase Test.

VE Navigation-learning Task

A virtual city (adapted from Mraz et al.[19]) was created in which the user could navigate using a projection screen, a 6-DOF head tracker, and a joystick. Participants were initially trained to move in virtual space by traversing an elementary maze consisting of 12 turns over a fixed distance. Subsequently, participants were shown a path through the city with video playback in egocentric perspective, and alternately watched the route or attempted to navigate it themselves. They were instructed to navigate as accurately as possible without bumping into objects, to pay attention to “the rules of the road” by staying on the sidewalk, and to pay attention to where various objects in the city were located with respect to each other. A set of three learning trials was performed for one path (Path A), followed by one learning trial for a second path (Path B). Short delay (5 min.) and long delay (20 min.) recall trials were also performed, during which Path A was navigated from memory.

PROCEDURES

Informed consent was obtained from each participant, based on approval of the S&W Research Ethics Board. Data collection for all participants occurred in the following order: (1) the CDR and the MMSE; (2) the neuropsychological tests; (3) the PGRD Maze Learning Test (Trials 1 to 10, delay, and reverse); (4) the VE navigation-learning task followed by completion of the Simulator Sickness Questionnaire[20]. Statistical analysis was performed using commercial software (SPSS 11.0).

RESULTS

An index of memory was estimated from the neuropsychological tests by factor analysis: memory index=0.934×Z(Rey delayed recall) +0.904×Z(Rey immediate recall)+ 0.611×Z (forward digit span)+0.530×Z(CDR memory). Internal consistency of the memory index was $\alpha = 0.772$. This memory index and the data from learning tests were compared to determine whether performance on paper-and-pencil tests was similar to that on the computerized tests. Consistently high and significant correlations were found between the memory index and measures of the PGRD Maze Learning Test. In contrast, only two measures of the VE task were significantly correlated with the memory index: time to completion on Trial 1 and Long Delay Recall. This initial finding was then used to perform an additional factor analysis providing an overall VE navigation index, consisting of a memory component and a movement component. The VE movement index was composed of measures in only Trial 1 (distance traveled and wrong turn metrics, specifically excluding time) because the other trials involved repeated exposure:

VE memory index = Z(long delay time) + Z(Trial 1 time)

	VE navigation	VE movement	VE memory
VE movement	0.94**		
VE memory	0.58*	0.32	
Memory index	-0.24	-0.13	-0.55*
Rey immediate recall	-0.25	-0.12	-0.60**
Rey delayed recall	-0.21	-0.05	-0.54*
Trail Making Test A	0.35	0.46**	0.08
Trail Making Test A error	0.49	0.41*	0.08
Trail Making Test B error	0.58*	0.47**	0.23

p<0.05, ** p<0.01

Table 1. Pearson Correlations between the VE indexes and Neuropsychological Tests

VE movement index = 0.870×Z(wrong turn) + 0.734×Z(distance) + 0.598×Z(double wrong turn)
VE navigation index = VR memory index + VR movement index

The VE indices were subsequently analyzed to confirm the validity with the neuropsychological tests. Table 1 illustrates that the VE navigation index was more highly correlated with the VE movement index than with the VE memory index, and showed significant correlation with the Trail Making Test (A error, and B error), which measured an executive function and visuomotor tracking. The VE movement and memory indices were not statistically correlated with each other. The VE movement index also was significantly correlated with the TMT measures (A, A error, B error), whereas the VE memory index was correlated with measures of the Rey immediate recall and delayed recall.

A two-factor repeated-measures ANOVA was used to analyze the measures across the trials of the PGRD test and the VE navigation-learning task, for both normal and MCI groups. With respect to the PGRD test, a significant main effect of the trials was revealed for completion time, $F(1,37)=84.595$, $p<0.01$, indicating improved performance as the trials progressed. There was no effect of group (normal versus MCI) on overall performance, nor was there an interaction between group and trial number. Other measures (movement, error, and perseveration) of the PGRD test gave the same results. On some specific measures that were difficult or required greater memory resources, however, such as the delay and reverse tests, there were significant differences between healthy elderly and MCI patients. These findings were mirrored in the neuropsychological tests and are shown in Table 2.

For the VE navigation-learning test, a significant main effect of trials for completion time and single wrong turns was found: $F(1,12)=12.725$, $p<0.01$; $F(1,12)=7.824$, $p<0.05$, respectively. As

	Variables	Normal	MCI	t
PGRD maze learning test	Trial2_rule break Delay time Reverse time	0.26±0.45 41.05±14.36 46.95±16.57	0.83±1.04 55.95±23.81 65.98±25.51	-2.372* -2.52* -2.82**
Neuropsychological tests	CDR total CDR initiation Rey Immediate Recall Rey Delayed Recall Memory index	140.00±3.12 36.67±0.64 18.94±6.13 18.58±5.53 52.56±11.00	137.28±4.82 35.33±2.40 11.33±6.39 10.62±5.93 37.77±11.68	2.22* 2.61** 3.90** 4.41** 4.14**

* p<0.05, ** p<0.01

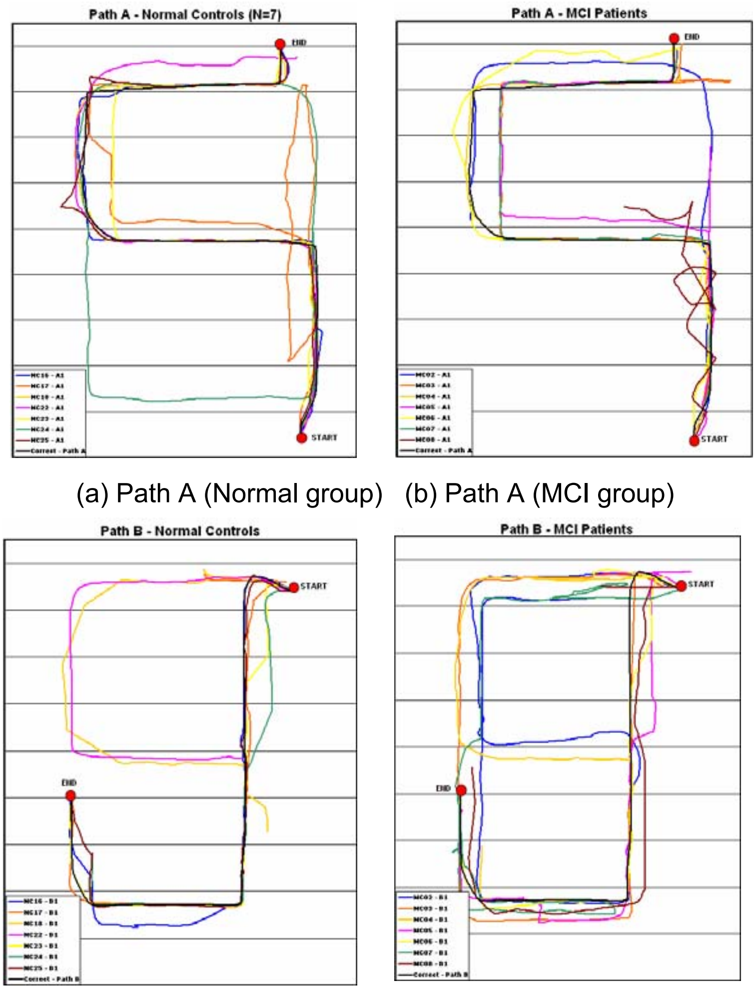
Table 2. Performance of Normal and MCI Groups on Tests (summarized results)

above, there were no group or interaction effects. No specific measures showed significant differences between the groups analogous to those shown in Table 2.

DISCUSSION

The results of this paper demonstrate that VE technology can be used to assess spatial memory and navigation skills, and that the measures of this behavior in a VE are related to those of newer and conventional neuropsychological tests. The VE *memory* index was related to the RCFT (immediate and delayed), but the VE *movement* index was related to the Trail Making Test, which is known to assess visuomotor skills and executive function. The VE memory index was strongly correlated with the time variables of the PGRD Maze Learning Test and the memory index of the neuropsychological tests (from Trials 2 to 9, r=0.514~0.625). These results suggest that navigational-learning in a VE is very useful in the assessment of spatial memory. Although not directly assessed in this study, it is likely that the VE navigational-learning task can provide reliable and valid measures of real-world functional abilities. Additional research is required to address this question.

Several results suggest that clinically relevant impairments in navigation skills, spatial orientation, and memory are often apparent in the early stages of dementia and MCI.[21] Our results demonstrate that the MCI group showed a significant



(a) Path A (Normal group) (b) Path A (MCI group)

(c) Path B (Normal group) (d) Path B (MCI group)

Figure 1. The navigational routes taken by participants.

reduction in a subset of the memory-related measures in the PGRD Maze Learning Test and in the neuropsychological tests. In particular, differences between the groups were evident in the immediate and delayed recall in the RCFT. These results were not observed for the VE navigation-learning task, which could be due to the reduced sample size for this component of the study. It is also of interest to visualize the navigational differences between the groups when performing the VE task (Figure 1).

Although most of the normal group (except two participants) did not deviate from the correct path, the MCI group tended to deviate from the correct path, particularly Path B (Figure 4(d)). These results suggest that the MCI group encountered greater difficulty than the normal group in the novel environments. They also highlight one of the recognized challenges in the interpretation of behavior elicited in virtual environments. Given that the behavior can be complex, it is likely that characterizing behavior in terms of simple metrics such as time to completion fails to encapsulate the richness of the data.

Although there are no differences in the effects of sex in the current study, studies with larger sample sizes across the groups are needed before it can be definitively concluded that MCI groups have inferior spatial memory and navigation skills irrespective of age and sex. Future studies need to investigate how age, sex, and strategy affect spatial memory and navigation learning in normal, MCI, and Alzheimer patients.

ACKNOWLEDGMENTS

This work was supported through grants from Pfizer, Inc., the Canadian Foundation for Innovation, the Ontario Premier's Research Excellence Award, and the Ontario Research and Development Challenge Fund. The authors thank Le-Anh Ngo and Mark Boulos for their assistance in testing the participants.

References

1. Maguire, E. A., Burgess, N., & O'Keefe, J. (1999). Human spatial navigation: cognitive maps, sexual dimorphism, and neural substrates. *Current Opinion in Neurobiology* 9:171–177.
2. Gillner, S., & Mallot, H.A. (1998). Navigation and acquisition of spatial knowledge in a virtual maze. *Journal of Cognitive Neuroscience* 10:445–463.
3. Astur, R.S., Ortiz, M.L., & Sutherland, R.J. (1998). A characterization of performance by men and women in a virtual Morris water task: a large and reliable sex difference. *Behavioural Brain Research* 93:185–190.
4. Kahana, M.J., Sekuler, R., Caplan, J.B., Kirschen, M., & Madsen, J.R. (1999). Human theta oscillations exhibit task dependence during virtual maze navigation. *Nature* 399:781–784.
5. Moffat, S.D., Zonderman, A.B., & Resnick, S.M. (2001). Age differences in spatial memory in a virtual environment navigation task. *Neurobiology of Aging* 22:787–796.
6. Gron, G., Wunderlich, A.P., Spitzer, M., Tomczak, R., & Riepe, M.W. (2000). Brain activation during human navigation: gender-different neural networks as substrate of performance. *Nature Neuroscience* 3:404–408.
7. Ekstrom, A.D., Kahana, M.J., Caplan, J.B., Fields, T.A., Isham, E.A., Newman, E.L., & Fried, I. (2003). Cellular networks underlying human spatial navigation. *Nature* 425 (6954):184-188.
8. Regian, J.W., & Yadrick, R.M. (1994). Assessment of configurational knowledge of naturally- and artificially-acquired large-scale space. *Journal of Environmental Psychology* 14:211–223.
9. Galea, L.A.M., & Kimura, D. (1992). Sex differences in route-learning. *Personality and Individual Differences* 14:53–65.
10. Sandstrom, N.J., Kaufman, J., & Huettel, S.A. (1998). Males and females use different distal cues in a virtual environment navigation task. *Cognitive Brain Research* 6:351–360.
11. McCarthy, R.A., Evans, J.J., & Hodges, J.R. (1996). Topographic amnesia: spatial memory disorder, perceptual dysfunction, or category specific semantic memory impairment? *Journal of Neurology Neurosurgery and Psychiatry* 60:318–325.
12. Maguire, E.A., & Cipolotti, L. (1998). The selective sparing of topographical memory. *Journal of Neurology Neurosurgery and Psy-*

chiatry 65:903–909.

13. Sonnenfeld, J. (1985). Tests of spatial skill: A validation problem. *Man-Environment Systems* 15:107–120.
14. Kirasic, K.C. (1988). Aging and spatial cognition: current status and new directions for experimental researchers and cognitive neuropsychologists. In J.M. Williams & C.J. Long (eds.), *Cognitive Approaches to Neuropsychology*. New York: Plenum.
15. Nadolne, M.J., & Stringer, A.Y. (2001). Ecologic validity in neuropsychological assessment: prediction of wayfinding. *Journal of the International Neuropsychological Society* 7:675–682.
16. Kirasic, K.C. (1991). Spatial cognition and behavior in young and elderly adults: implications for learning new environments. *Psychological Aging* 6(1):10–18.
17. Peter J. Snyder (2001). *PGRD Maze Learning Test*. Pfizer Inc.
18. Milner, B. (1965). Visually-guided maze learning in man: Effects of bilateral hippocampal, bilateral frontal, and unilateral cerebral lesions. Neuropsychologia, 3, 317-338.
19. Mraz, R., Hong, J., Quintin, G., Staines, W.R., McIlroy, W.E., Zakzanis, K.K., Graham, S.J. (2003). A platform for combining virtual reality experiments with functional magnetic resonance imaging. *CyberPsychology & Behavior* 6(4):359-368.
20. Kennedy, R., Lane, N., Berbaum, N., & Lilienthal, M. (1993). A Simulator Sickness Questionnaire (SSQ): A New Method for Quantifying Simulator Sickness. *International Journal of Aviation Psychology* 3:203-220.
21. Passini, R., Rainville, C., Marchand, N., & Joanette, Y. (1995). Wayfinding in dementia of the Alzheimer type: planning abilities. *Journal of Clinical and Experimental Neuropsychology* 17(6):820–832.

Contact

Simon J. Graham, Ph.D., P.Eng.
S650-Imaging Research
Sunnybrook & Women's College Health Sciences Center
2075 Bayview Ave.
Toronto, ON, M4N 3M5 Canada
Email: simon.graham@sw.ca