

Use of a virtual-reality town for examining route-memory, and techniques for its rehabilitation in people with acquired brain injury

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ABSTRACT

Route learning difficulties are a common consequence of acquired brain injury, and virtual environments provide a novel tool for researching this area. A pilot study demonstrated the ecological validity of a non-immersive virtual town, showing performance therein to correlate well with real-world route learning performance. The first patient study found that a rehabilitation strategy known as 'errorless learning' is more effective than traditional 'trial-and-error' methods for route learning tasks. The second patient study, currently in progress, will assess whether naturalistic route learning strategies of map and landmark use can be combined effectively with errorless techniques. A final study will investigate the relationships between route learning performance and scores on a select battery of neuropsychometric tests.

1. INTRODUCTION

Impaired wayfinding ability is a little-investigated cognitive deficit associated with many cases of acquired brain injury (ABI). In one of the few studies to estimate the prevalence of wayfinding difficulties in ABI, Barrash et al (2001) found that almost a third of all patients sampled experienced new difficulties finding their way since their injury, and this figure rose to 86% for individuals with injury to particular cortical regions (including the hippocampal and parahippocampal area and parts of the medial and inferotemporal cortices). Wayfinding is an important skill for everyday life, and the question of how best to rehabilitate individuals who suffer wayfinding impairment merits investigation.

It is possible that practical difficulties arising in the study of route learning have contributed to a lack of research in this area. The problem of finding a route near to the recruitment site that is novel to all participants is a difficulty common to many studies of navigation (e.g. Kirasic et al, 1984), but may be particularly important where participants have specialised transport needs and may not be able to easily travel to distant sites. Physical impairments of some participants with ABI could also make learning long or outdoor routes difficult or fatiguing, and deficits in concentration or executive function could make experiments into route learning in the outside world potentially hazardous. However, in recent years, virtual reality has been used successfully in a number of route learning studies (see Darken and Peterson, 2001 for a review) and circumvents many of the practical difficulties associated with real-world studies (e.g. Haq et al, 2005).

Brooks (1999) successfully used a virtual simulation of a real-world scenario to help a patient with severe amnesia learn routes around a hospital by consistent repetition. Virtual reality is particularly suited to assessing the impact of multiple trials on memory, as it tends to allow for more repetitions of a route in a given time than a real-world setting (e.g. Darken and Banker, 1998), and also will not cause the physical fatigue possible in multiple repetitions of a real-world route.

The present series of experiments also employed a virtual-reality town to investigate memory for novel routes in people with acquired brain injury. The overall aim of the study was to compare the usefulness of various route-learning techniques, and in particular to compare errorless learning, a technique thought to stimulate implicit (or procedural) memory with trial-and-error memory, a technique relying upon more explicit strategies. While several previous studies have employed virtual reality environments to assess wayfinding, the majority have either used simple, maze-like environments (e.g. Grön et al (2000)), have focused on direct transfer of spatial learning from a virtual simulation of a real-world space to the real space

itself (e.g. Brooks et al, 2000), or have used virtual environments as a means for conducting brain imaging scans to assess the functional neuroanatomy of wayfinding (e.g. Hartley et al, 2003). The present study, by contrast, sought to use a complex and lifelike virtual environment as a stand-alone research tool, in which to compare route-learning strategies.

This article first describes the virtual environment used for the investigation of route learning. A study conducted to test the ecological validity of the virtual town is then reported. Three studies using the virtual town to investigate route learning techniques for people with ABI are then described. The first of these, which is completed, is a comparison of two techniques known as errorless and errorful learning. The second, which is in progress, is an investigation of the benefits of combining errorless learning with naturalistic strategies for route learning. The final study, also currently in progress, looks at the relationships between neuropsychometric test profiles and route learning performance under various conditions.

2. THE VIRTUAL ENVIRONMENT

A desktop, interactive computer-generated virtual town was employed. The software was called 'Driv3r', developed by REFLECTIONS Interactive Limited, an Atari Studio. Recent growth and investment in the computer gaming industry means that mainstream computer games offer some of the most convincing and sophisticated virtual environments available, along with being relatively inexpensive. The virtual town selected from Driv3r was based upon the real-world town of Nice, and contains a large network of streets and buildings. The game also features drivers and pedestrians moving around the town in realistic patterns.

3. EXPERIMENT 1: ECOLOGICAL VALIDITY OF THE VIRTUAL ENVIRONMENT

3.1 Introduction

While several studies have demonstrated good general equivalence between virtual and real world route learning (e.g. Koh et al, 1999; Skelton et al, 2000), virtual environments can vary considerably, and so a pilot study was conducted to assess the ecological validity of the specific virtual town selected for the present series of experiments. Participants' route learning in the virtual town was compared, using several measures, with their route learning in the real world.

3.2 Method

3.2.1 Apparatus. The software was played via a Sony 'Playstation 2 games console', connected to a 19-inch colour television screen via SCART cable. Participants were seated at a distance of approximately one metre from the screen. A standard, manually operated 'control-pad' was used by the experimenter to control movement through the town. Whilst individuals were told to imagine they were driving through the town, the experimenter actually moved the virtual character in a 'running' motion, down the centre of the road. A first-person viewpoint was selected so that the participant could not see the body of the character, and was free to imagine travelling in a car. It was desirable for participants to imagine being in a car because (a) this kept consistency with the real-world study in which people travelled by car, and (b) moving in the middle of the road gave a better view of relevant landmarks and junctions than moving along the pavement.

3.2.2 Procedure. 14 neurologically healthy individuals were 'driven' around a route within the virtual reality town described above, before being returned to the start point and asked to try and direct the experimenter, verbally, around the route they just saw. They were also taken by car to a residential area in the real-world city of Birmingham, UK, where they were driven around a route of similar length and with the same number of turns. They were then returned to the route start-point and asked to direct the experimenter around the route, in the same way as in the virtual task. The order in which the virtual and real-world tasks were administered was counterbalanced to control for order effects.

3.3 Results

A paired-samples t-test showed no significant difference between numbers of wrong turns taken on the real versus the virtual route ($t = -.563$, $df = 13$, $p = .583$). Furthermore, a strong correlation was observed between the number of errors made in the virtual and real towns ($r = .807$, $n = 14$, $p < 0.0005$). There were also statistically significant correlations ($p < 0.05$) between the extents to which individuals reported using several popular strategies in the real and virtual environments. Individuals appeared to use cognitive maps, landmarks, a position-encoding process known as 'dead reckoning' and guess-work to similar extents in both settings.

3.4 Conclusions

These results suggest that the virtual task is a good approximation of real-world route learning, not only through demonstrating an impressive correlation between performance across real and virtual versions of the task, but also through illustrating individuals' tendency to use common wayfinding strategies to comparable extents across tasks. The ecological validity of the virtual town demonstrated in this study, coupled with support in the literature for the ecological validity of virtual environments in wayfinding studies in general (e.g. Koh et al, 1999) supported the decision to use the virtual environment in the following experiments.

4. EXPERIMENT 2: A COMPARISON OF ERRORLESS VERSUS ERRORFUL ROUTE LEARNING IN FOR PEOPLE WITH ACQUIRED BRAIN INJURY

4.1 Introduction

Errorless learning is the name given to learning episodes in which effort is made to prevent errors from occurring during the 'encoding' stage of information processing. It can be contrasted with the well-known 'trial-and-error', or 'errorful' learning method in which individuals improve their performance by learning from their mistakes. It is thought that errorless learning works by exclusively strengthening *correct responses* in memory, thereby minimizing competition or interference from any possible incorrect responses when one attempts to remember or use the information (i.e. at the 'retrieval' or 'response' stage).

Errorless learning has been used with particular success with individuals with acquired brain injuries (e.g. Baddeley and Wilson, 1994), as well as with people with other cognitive deficits, such as learning difficulties (Sidman and Stoddard, 1967) and dementia (e.g. Winter et al, 1999). It has been suggested that people with certain cognitive impairments benefit more from errorless techniques because where they are unable, or less able than neurologically healthy individuals, to consciously correct errors that occur during learning, errorless learning allows for *implicit* consolidation of correct responses. This theory is consistent with findings that populations benefiting most from errorless learning tend to display profiles of spared implicit memory alongside impaired explicit memory (e.g. Faulkner and Foster, 2002; Kuzis et al, 1999) There is also that evidence errorless learning promotes implicit knowledge in neurologically healthy participants (e.g. Maxwell, 2001). However, there is ongoing debate around the precise cognitive mechanisms sub-serving errorless learning, and there is some evidence for a role of spared explicit processing (e.g Kessels et al, 2005)

The majority of studies supporting the efficacy of errorless learning in ABI have been based around verbal learning. For example, Baddeley and Wilson (1994) studied word-stem completion, Hunkin et al (1998) studied list learning, Winter et al (1999) studied name learning, and Glisky and Delaney (1996) studied the learning of factual statements. Some studies have successfully applied errorless learning to vocational domains, for example Andrewes (1999) trained a participant in a filing task via errorless learning. Very few studies have assessed errorless route learning for people with acquired brain injury, although Brooks (1999) had great success in helping a severely amnesic patient to learn routes via a virtual simulation of those routes, in which he employed aspects of errorless learning. However, as the focus of the study was on virtual reality, and there was no controlled errorful comparison condition, it is not possible to unequivocally attribute the success to the errorless aspects of learning per se.

Evans et al (2000) failed to demonstrate an advantage for errorless techniques in two different route learning tasks, actually finding a benefit for trial-and-error learning in one. They note that lack of success of errorless learning could be due to ceiling effects, or due to a lack of participant involvement in errorless conditions. In addition, perhaps as a result of the difficulties surrounding running route learning studies described in the introduction, the tasks employed were quite abstracted from naturalistic 'route learning.' Participants learned routes from one piece of furniture to another around a two-dimensional sketch of a room, and learned routes across a grid of images. It is conceivable that a more realistic route-learning task may benefit more from errorless learning, particularly when one considers the fact that there is often a procedural element to real-world route learning route-learning (Allen and Willenborg, 1998, Garden, et al, 2002), and errorless learning has been linked with effective procedural knowledge acquisition (Maxwell, 2001).

The present study, therefore, sought to use an ecologically valid virtual environment to clarify whether errorless learning would be an effective technique (and more effective than errorful learning) for helping people with acquired brain injuries to learn routes.

4.2 Method

20 participants with acquired brain injuries were recruited from several sites (rehabilitation centres and hospitals) across the West Midlands, UK. Participants with language difficulties severe enough as to be likely to compromise understanding of task instructions were excluded, along with participants demonstrating visual neglect (assessed by the star cancellation task from the Behavioural Inattention Test, Wilson et al 1987). Participants had to have acquired their brain injury more than months prior to the experiment, and had to have a self-reported memory impairment (which was later confirmed via neuropsychometric testing).

4.2.1 *Apparatus*. The apparatus was the same as that used in Experiment 1.

4.2.2 *Procedure*. Participants learned one route in an errorless way, watching the entire route correctly through to completion three times before attempting to call out directions themselves. Another route, they learned in an errorful (or 'trial-and-error') way, being shown the correct route only once before being asked to take two practice attempts (during which errors typically occurred) at calling out the directions before the final, 'test' trial. When participants in the errorful practice trials called out an incorrect direction, they were taken a short distance down the incorrect street before being corrected by the experimenter. In this way, participants always saw each route through to completion three times before their final test, but in the errorless condition they saw it correctly each time, while in the errorful condition they saw the route plus, potentially, several incorrect detours along the way. The detours were corrected after a short time (5 seconds) in order to ensure that the two conditions were as similar as possible, apart from the errorful condition allowing participants to briefly leave the correct path. This was deemed important, to allow potential poor performance in the errorful condition to be attributed to the errors themselves, rather than simply to participants in this condition spending considerably longer walking around, experiencing more anxiety, or witnessing more junctions.

4.3 Results

A paired-samples t-test revealed that significantly fewer mistakes on the test route were made under errorless learning conditions than under errorful conditions ($t=2.631$, $df = 19$, $p = 0.016$). The mean number of errors made during the errorful test trial was 4.65 (S.D.2.35), compared with 3.4 (S.D. 1.54) during the errorless test trial.

4.4 Discussion / Conclusion

Participants with memory impairment resulting from acquired brain injury benefited more from errorless than from errorful methods when attempting to learn routes through a virtual town. This is consistent with findings from previous studies that have shown errorless learning to be an effective strategy in the learning of verbal information (e.g. Baddeley and Wilson, 1994). It is somewhat inconsistent, however, with findings from Evans et al's (2000) studies of errorless versus trial-and-error route learning. There are several possible reasons for this. It is possible that the virtual town task used in our study was more engaging than the paper-based route learning assessments used by Evans et al, because it was relatively novel and stimulus-rich. Boredom in errorless learning tasks, which are, by nature, very repetitive, can have an impact on performance, as participants may not pay full attention during learning trials. Tasks which are novel or interesting to complete may be more suited to errorless learning, therefore, as they are more able to hold participants' attention.

The fact that errorless learning was more effective than trial and error in the route learning task described here is theoretically important, as it is one of few studies to apply errorless methods beyond the realm of verbal learning. Further research into practical applications of errorless learning for everyday tasks could be potentially very fruitful.

The virtual reality town provided the ideal setting for studying errorless learning, as multiple and consistent trials can be presented without any distractions. There may be a place for virtual reality in training people with acquired brain injury in a range of diverse practical skills, using errorless principles.

5. EXPERIMENT 3: ERRORLESS LEARNING IN CONJUNCTION WITH NATURALISTIC STRATEGIES FOR ASSISTING PEOPLE WITH ACQUIRED BRAIN INJURIES IN ROUTE-LEARNING

A study in progress is exploring the relative effectiveness of two popular naturalistic strategies (for helping people with ABI to learn routes more effectively). The naturalistic strategies being combined with errorless learning are landmark use and cognitive map formation. A pilot study with neurologically healthy individuals, using the virtual town, found that the use of landmarks as memory cues correlated with the average accuracy of individuals' route-recall ($\rho = -.483$, $n = 40$, $p = 0.005$). This is consistent with findings in the literature that efficient wayfinders tend to rely on landmarks to assist them (Kato and Takeuchi, 2003). The creation of a mental map of an environment is another key strategy that, although not as popular as landmark use, has also been seen to be employed by particularly good wayfinders (Prestopnik and Roskos-Ewoldsen, 2000, Billingham and Weghorst, 1995). Additional reasons for choosing these two strategies are that they are relatively easy to promote the use of, and that landmarks and maps could be argued to broadly tap verbal and visuo-spatial capacities, respectively.

It will be of theoretical interest to see whether errorless learning's efficacy can be improved by using it in conjunction with additional strategies, as the vast majority of errorless learning studies have not attempted to combine errorless learning with any other techniques. Discovering the efficacy of naturalistic strategies is also an important aim in itself. Anecdotal evidence from participants tested to date suggests that people favour tried-and-tested, familiar methods like the use of landmarks and maps, over novel 'rehabilitation' strategies like errorless learning.

It is predicted that naturalistic strategies will increase the benefit of errorless learning, through promoting deeper encoding of information. However, there is the possibility that the introduction of additional strategies will prove distracting, or will hinder the success of errorless learning by promoting more 'explicit' learning.

6. EXPERIMENT 4: PSYCHOMETRIC TEST PROFILES AND ROUTE LEARNING PERFORMANCE

An ongoing study, using participants from all of the patient studies described above, will assess the relationships between scores across a range of psychometric tests and route learning performance.

A battery of psychometric tests was selected based upon findings from previous route-learning studies. 6 tests, that have been previously found to correlate with measures of route learning performance, were chosen.

The tests that were chosen were as follows:

- The Block Design subtest of the Wechsler Adult Intelligence Scale - Revised (Wechsler, 1981). A test in which participants use 4-9 small blocks with two red, two white, and two split-coloured faces to reproduce patterns of increasing complexity. This test was selected because performance has been seen to correlate with route-learning performance on a real life driving task (Uc et al 2004a) and to predict accuracy on a landmark positioning task (Cutmore et al, 2000).
- The Money Road Map Test of Direction Sense (Money, 1965). In this test, the experimenter traces a route marked around a simple road map, and participant calls out the direction to take at each junction, without rotating the map. Performance on this egocentric mental rotation task has been shown to correlate with performance on a virtual reality maze task (Moffat et al, 1998).
- The Controlled Oral Word Association Task (Benton and Hamsher, 1976) involves the participant generating as many words beginning with a given letter as possible, within a minute. Moffat et al (1998) found that females' performance correlated with maze learning ability, and Uc et al (2004a) found performance of people with Alzheimer's dementia correlated with route learning performance on a driving task.
- The Rey Osterrieth Complex Figure Task (Rey, 1941, Osterrieth, 1944), in which participants copy, reproduce immediately, and reproduce after a 30-minute delay, a complex geometric design. Scores on this test correlated inversely with the number of wrong turns taken by participants (with Alzheimer's dementia and with acquired brain injury) in a real-life driving task (Uc et al, 2004a,b)
- The List-learning subtest of the adult memory and information processing battery [AMIPB] (Coughlan & Hollows, 1985). In this test participants are asked to learn a list of 15 words called out to them over 5 trials. The number of incorrect turns taken by participants with Alzheimer's dementia and

with acquired brain injury correlated inversely with scores on a very similar test, the Rey Auditory Verbal Learning Test (Rey, 1964).

- Digit Span and 'Spatial Span' subtests of the Wechsler Adult Intelligence Scale - III (Wechsler, 1981) were selected as tests of working memory. They involve, memorising and repeating increasingly long sequences of numbers and sequences of block-taps, respectively. Working memory is implicated in route learning, as increasing working memory load through allocating concurrent tasks appears to impair route learning. (Garden et al, 2002)

Statistical analyses will be carried out in order to assess:

- a. Whether there is a correlation between route learning performance and any of the psychometric tests described.
- b. Whether the advantage of errorless over errorful learning varies in line with participants' degree of impairment on certain psychometric tests.

If sufficient numbers of participants can be recruited, analyses will also be carried out to assess whether psychometric test performance predicts how effective landmark and map strategies are across participants. For example, do participants scoring high on Rey Complex Figure perform particularly well in the map strategy condition, because they have good visuo-spatial memory, or does verbal memory score correlate with performance in the landmark condition, with people tending to memorise landmarks verbally?

If relationships between psychometric tests scores and success of specific wayfinding strategies can be identified, by this or future studies, the practical applications are exciting. As part of rehabilitation programmes, administration of short neuropsychometric tests could potentially allow for patients with route learning difficulties to be provided with the most appropriate learning strategy for them.

7. GENERAL CONCLUSIONS

There has been great success in the use of virtual reality in route learning studies in general (e.g. Darken and Banker, 1998), but few studies of patients with acquired brain injury have used simulated environments to examine route learning. The present series of experiments demonstrates that virtual environments can be put to effective use in investigating rehabilitation strategies for people with acquired brain injuries. Furthermore, the ecological validity of the virtual reality town employed, demonstrated by comparing performance on a real and virtual version of a route learning task, shows that non-immersive, relatively inexpensive equipment can be a valid and productive research tool.

The present studies used the virtual reality town purely as a testing environment in which to compare various strategies. Many studies have striven to demonstrate the transfer of knowledge gained in a virtual environment to a real-world setting. While this is obviously a valid concern, the present study demonstrated the usefulness of the virtual world as a stand-alone arena for research. It is not essential that the virtual tasks completed in the present studies impact upon people's everyday route learning performance. The value of the virtual reality town was that it served as a controlled environment in which to address research questions. This use of virtual reality may be open to further exploitation in the future.

Having said this, a weakness of the studies is that it cannot be claimed, unequivocally, that the findings from the virtual town will apply to real-world route learning. There is a possibility that some feature specific to the virtual environment influenced performance in such a way that results would not apply in the real world. Real-world replications of the studies conducted in the virtual world would be the only sure way to reject this possibility, and future research addressing this question would be valuable. However, findings from the pilot study of good equivalence between performance and strategy use across the virtual town and the real world are reassuring.

Overall, virtual reality appears to be a very promising tool for researching route learning, and may be especially useful when assessing individuals with mobility difficulties or cognitive difficulties for whom route-learning in the real world may be impractical. Virtual reality is particularly well suited to the consistent repetition of learning material required when studying errorless learning, and it is suggested that more general applications of virtual reality for errorless learning research may be fruitful.

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