Virtual environment navigation tasks and the assessment of cognitive deficits in individuals with brain injury

Sharon A. Livingstone, Ronald W. Skelton

Department of Psychology, University of Victoria, P.O. Box 3050 STN CSC, Victoria, BC, Canada, V8W 3P5

Received 31 January 2007; received in revised form 7 July 2007; accepted 9 July 2007

Available online 17 July 2007

Abstract

Navigation in real environments is often impaired by traumatic brain injury (TBI). These deficits in wayfinding appear to be due to disruption of cognitive processes underlying navigation and may in turn be due to damage to the hippocampus and frontal lobes. These wayfinding problems after TBI were investigated using a virtual simulation of a Morris Water Maze (MWM), a standard test of hippocampal function in laboratory animals. The virtual environment consisted of a large virtual arena in a very large virtual room whose walls provided views of a naturalistic landscape. Eleven community-dwelling TBI survivors and 12 comparison participants, matched for gender, age and education were tested to see if they could find a location in the arena marked by one of the following: (a) a visible platform, (b) a single proximal object, (c) a single proximal object among seven other distracter objects, or (d) distal features inside and outside the room. The proximal objects allowed participants to use egocentric (body-centered) navigational strategies that rely on relatively simple stimulus-response associations. The absence of proximal cues forced the participants to rely on distal features of the environment (room walls, landscape elements) and tested their ability to use allocentric (world-based) navigational strategies requiring cognitive mapping. Results indicated that the navigation of TBI survivors was not impaired when the proximal cues were present but was impaired when proximal cues were absent. These results provide more evidence that the navigational deficit after TBI is due to an inability to form, remember or use cognitive maps.

Keywords: Spatial navigation; Traumatic brain injury; Virtual reality; Morris Water Maze; Hippocampus; Learning and memory; Spatial cognition; Allocentric and egocentric strategies; Wayfinding; Landmark

1. Introduction

Traumatic brain injury (TBI) is caused by a blow to the head and is characterized by a wide array of changes ranging from social and emotional to cognitive [23,39]. Many individuals suffer from anterograde amnesia [4,49,53] and a less well-studied problem, loss of spatial ability, that manifests as difficulty with wayfinding (finding one’s way around in both familiar and unfamiliar locations) [1,4]. The current research investigated the cognitive deficits in wayfinding as well as those cognitive mechanisms that are spared.

Cognitive changes associated with TBI have been linked to damage in the temporal region and especially to the hippocampus, which is vulnerable to injury [8,26]. After temporal lobe damage, anterograde amnesia [4] and spatial deficits [7,51] may be present. Right medial damage is linked to deficits in spatial learning and memory (for review see, [4,9]) and impaired route learning [5]. Also, surgery to right temporal regions can lead to impairments in both spatial memory and object location [16,28,45,47].

Other cognitive processes required for wayfinding have been linked to other anatomical areas. For example, the presence of topographic disorientation (a failure to orient and navigate, including the feeling of being lost) is associated with damage to the parahippocampus [5,18,19] as are wayfinding deficits [1,4,18]. Poor route learning/memory is correlated with lesion sites including bilateral parietal, right or bilateral medial inferior occipito-temporal and lateral temporo-parieto-occipital [18]. Wayfinding difficulty in a real environment has been associated with damage to right medial temporal, inferior medial occipital (right or left), and right parietal regions [5], although the authors noted that parietal lesions alone do not cause lasting
wayfinding deficits. It is beginning to appear that the representation of stimuli relative to the eye, head, and trunk is found in the parietal cortex whereas the representation of location within the environment is found in the hippocampus ([12], p. 25).

The nature of the spatial deficits after TBI is not well understood. Some consider topographic dissociation to be a combination of deficits of amnesia (recall) with or without agnosia (recognition) [38]. However, others suggest that the amnesic/agnosic distinction may be an over-simplification [4,28]. One problem is that there is no standard way of measuring deficits in wayfinding or their component processes. Further, all existing measures of spatial deficits have limitations. Two dimensional, paper and pencil style neuropsychological tests (see examples in [27,48]) do not address the question of real world (i.e., three-dimensional) wayfinding. Rehabilitation tasks that require real-world wayfinding are mainly limited to simple stimulus-response type measures of spatial ability [11,46]. Further, these tests have been set up in one indoor or outdoor location and cannot be administered in any other geographic location. Two tests, both called the “Route Learning Test” have been found to be sensitive to impairments in route learning ability in early dementia [3] and Alzheimer’s disease [13], but neither have been replicated elsewhere, perhaps because they are both specific to the geographic location where they were developed. Nevertheless, results to date are encouraging, and suggest that it would be desirable to develop new measures of spatial impairments that can be administered at any geographic location, as long as the tests have good reliability, stimulus control, and ecological validity.

Wayfinding is a complex behavior that encompasses decision-making about navigational goals, formation and maintenance of intent to travel, and spatial navigation. It has a motor component (movement in space) and a cognitive component (mechanisms for identifying environmental information and selecting strategies). Studies of the anatomy of wayfinding, based largely on laboratory animals have dissociated two basic cognitive strategies distinguished by what stimuli are used and which anatomical structures process them (for reviews see [1,34]). The first strategy is cognitive mapping [52] and has been termed “allocentric” because it is environment centered and relies on configurations of spatial stimuli (such as landmarks and objects in the environment). Recently, cognitive mapping has been proposed to draw on distal or “directional” landmarks for orientation and on configurations of more proximal or “configural” landmarks for place recognition [22]. Cognitive mapping has been associated with the medial temporal lobe and the hippocampus ([35,36]; for theoretical review see [54]). The second basic strategy type consists of responses to simple cues and has been termed “egocentric” because it is centered on the organism and leads them to turn left or right or go straight ahead based on one or a few landmarks. Egocentric strategies, the basis of route learning, consist of following a sequence of distal or proximal visible landmarks, left or right turns or left/right turns in response to particular stimuli along the route. In animals, such strategies are associated with activity in the caudate [54].

One of the foremost methods of dissociating egocentric from allocentric strategies is the Morris Water Maze (MWM) [30,32] and modifications of it. The MWM consists of a large, round featureless pool filled with cool opaque water and requires laboratory animals to find and escape onto a fixed-location platform hidden just below the surface. Because a variety of different start positions are used, and because there are no local landmarks to indicate the platform location, the optimal performance of the task requires the formation of a cognitive map—a constellation of distal extra-maze cues. In other words, the MWM is best solved using an allocentric strategy. Rats with damage to the hippocampus or frontal lobes show slowed acquisition of direct swim paths to the platform, and poor search patterns for the platform if it is removed from the pool (i.e., on special “probe” trials) [24,31]. Additions of cues to the platform location (called “visible” when they are at the platform and “landmark” when they are nearby) enable the use of egocentric strategies and are quickly solved by rats with lesions to the hippocampal formation [14,25,44]. In one recent study, rats in the MWM were shown to use both egocentric and allocentric strategies at different points of individual trials [20].

Human studies have begun to confirm the use of strategies similar to those observed in animals, with corresponding anatomical localization. The right hippocampus has been associated with spatial (allocentric) behavior in a human imaging study using virtual navigation tasks, while the caudate was associated with egocentric behavior [29]. This result is consistent with the recent discovery of place cells in the human hippocampus [15]. Bohbot et al. [10] have confirmed that for non-injured participants the use of a spatial strategy is correlated with activity in the hippocampus while the use of a non-spatial strategy is correlated with activity in the caudate. Furthermore, patients with damage to the medial temporal lobe had difficulty using a spatial strategy.

As several authors have pointed out, normal wayfinding depends on the internal availability of strategies and their appropriate selection [10,21,33]. Often, strategies are selected spontaneously [21] and the cognitive mechanisms associated with wayfinding strategies may reflect the use of allocentric (spatial) or egocentric (non-spatial) systems [10,21,34] that can be combined during the wayfinding process.

In sum, after TBI, wayfinding deficits could result from impairments in several different cognitive processes: (1) the ability to maintain an intent to reach a particular destination, (2) the ability to use egocentric strategies to guide wayfinding actions (e.g., moving toward a distal landmark or turning at a proximal one), (3) the ability to use allocentric strategies to learn/remember landmarks and configurations of stimuli in a cognitive map (e.g., following a route or making detours and novel routes) and (4) the ability to discern and select appropriate combinations of wayfinding strategies.

The purpose of the present study was to investigate the pattern of preserved and impaired cognitive mechanisms of wayfinding among survivors of TBI. We expected that community-living survivors of TBI would be able to maintain intent to reach the goal (at least for 20–30 min) and use proximal landmarks to find it. However, we expected that survivors of TBI would not be as able as controls at finding a goal when allocentric spatial navigation was required. Finally, we expected that when both
allocentric and egocentric (landmark) strategies were equally appropriate to finding the goal, that survivors would tend to use an egocentric (landmark) strategy.

2. Methods

2.1. Participants

Eleven adult participants (9 men, 2 women) between the ages of 22 and 55 with a history of brain injury were recruited from the Vancouver Island Head Injury Society in Victoria, BC. Comparison participants were 12 adults (10 men, 2 women) between the ages of 20 and 50 and were recruited through an advertisement placed in local newspapers. Comparison participants reported no history of neurological disorders and as a screen for TBI were asked if they had ever been hospitalized for loss of consciousness. The University of Victoria Human Research Ethics Committee approved the research and informed written consent was given by all participants prior to each testing session.

2.2. Apparatus

The apparatus consisted mainly of a single virtual environment, the “Arena Maze”, designed to be an analogue of the MWM. It was built using UnrealEd®, the editor supplied with Unreal® (Epic Megagames) and presented using a desktop personal computer with a 19 inch monitor using an 800 × 600 resolution. The virtual environment consisted of a large round arena contained within a large room with large windows giving a panoramic view of a realistic world outside consisting of mountains, hills, and a large body of water with an island (Fig. 1A). The wall of the arena was just high enough to prevent the participant from leaving the arena, and low enough to present an unobstructed view of the room and world outside (see [43] for details). Trials always started at one of the 4 cardinal points of the arena (i.e., closest to one of the four walls arbitrarily designated north, east, south, and west, or N, E, S, and W, respectively) (Fig. 2A). The basic Arena Maze was used to test allocentric navigation. Variations in the basic Arena Maze were used to test different spatial abilities (Table 1).

The Arena Maze had four types of trials, in the following order: exploration, visible, invisible, and probe (see Table 1 for the purpose of each). During exploration trials the room and arena were empty. During “visible platform” trials a large circular platform was visible on the floor of the arena (Fig. 1A) in the center of a different quadrant for each trial. During “invisible platform” trials, the platform was located in the center of the SE quadrant and was invisible until stepped on, at which point it rose with the usual sound. The start position of the exploration trial was by the big window in the south wall. Start positions for the other three types of trials were always just inside the arena, at one of the 4 cardinal points and varied in a fixed, pseudorandom order (Fig. 2A).

The first variation on the Arena Maze was the “Single Object Maze” (Fig. 1B) and was designed to train and test egocentric navigational abilities. The platform was invisible and located near the edge of the arena in a different position each trial (order was SW, E, W, SE). A single object was perched on the arena wall, close to the invisible platform, to indicate its location (refer to Fig. 2B for relative positions of platforms and objects). All trials began from the north start position.

The second variation was the “Ambiguous Maze”, so called because it could be solved equally well using an egocentric or an allocentric strategy. This maze was identical to the Arena Maze in terms of appearance, except there were eight objects perched on the arena wall at equal (i.e., 45°) intervals around the circumference (Figs. 1C and 2C). Because the location of the objects and the platform were fixed, the object closest to the platform was always the same. This object was intentionally chosen to be distinctive in size, shape and color. Thus, the platform location could be identified either by its position in the room (i.e., allocentrically) or by the nearest object (i.e., egocentrically). The platform location and start positions were identical to those used in the Arena Maze. The initial exploration trial started inside the Arena and there were no visible platform trials.
### 2.3. Materials

There were four ancillary tests designed to investigate the participants’ sense of presence, their strategy usage, and their memory of stimuli within the Arena Maze, and three tests designed to probe their memory, spatial perception and wayfinding in everyday life (see Table 1).

#### a. “Where’s the door?” Test
A pointing task to assess the participant’s “presence” in the virtual room.

#### b. Strategy Questions
A series of questions to determine how participants located the platform in the Ambiguous Maze.

#### c. Object Recognition
A test to determine how many objects participants recognized from the virtual rooms. From a sheet depicting objects present (10) or not present (6) in the virtual rooms, participants indicated which they remembered being present.

#### d. Room Reconstruction
A test to assess the degree to which participants remembered the layout of the room (and windows) and associated the platform with the correct position within the layout.

#### e. Rivermead Behavioural Memory Test (RBMT)
A standardized neuropsychological test of episodic verbal, visual, and spatial memory (see [55] for information about reliability and validity).

#### f. Clock Drawing task
A standardized neuropsychological test of visual hemifield neglect (see description in [48]).

#### g. Everyday Spatial Questionnaire
A series of questions designed to determine the participants’ everyday navigational abilities [42].

### 2.4. Procedures

#### 2.4.1. Design

This study compared navigation ability between two groups under three different spatial conditions. The two groups were people with TBI and those without TBI, matched for age, gender and education. The three different spatial conditions (described above) were the Arena Maze, Single Object Maze and the Ambiguous Maze. Platform locations were discernable by location in the room (Arena Maze), a landmark object nearby (Single Object Maze), or both (Ambiguous Maze). These three conditions were given in that order. Ancillary tests were given to assess what was learned in these mazes and whether performance in the virtual mazes correlated with errors of memory or spatial ability in everyday life.

#### 2.4.2. Organization

Participants first gave their informed consent and then completed a questionnaire providing details such as age, gender, education, and for TBI survivors, the nature of injury and an estimate of the duration of post-traumatic amnesia. Table 1 shows the order of experimental tasks, beginning with the maze tasks and concluding with ancillary tests of memory, perceived spatial ability, memory for the virtual environment, presence in the virtual environment, and possible hemi-neglect.

The first task in virtual space was the Arena Maze. Before starting, participants received instructions detailing the tasks they would be required to complete. Participants were informed about the exploration trial, the visible platform and the invisible platform trials, and told to go to each platform as quickly and directly as possible. Once participants indicated they understood the instructions, they were introduced into the virtual room and allowed to explore as long as they liked. They were encouraged to approach and look out all windows to view the landscape outside the room. The participants then began the visible platform trials and their latencies to find the platform were recorded with a stopwatch. After the four visible platform trials, the participants were informed that the platform would be invisible and that they would have to search to find it, but that from then on, it would always be in the same place. At the end of the first trial (and the first few successive trials if necessary), participants were encouraged to stay on the platform and look around the room if they wanted. Participants were also informed in advance that on one of the trials (the probe trial) the platform would be hard to find. They then completed the 10 invisible platform trials and a probe trial.

Next, participants were given instructions for the Single Object Maze. They were told that for the next task the platform would be in a different place each time and that they should try to find it as quickly and directly as possible. Five trials were then completed.

At the start of testing in the Ambiguous Maze, participants were given brief instructions and an opportunity to explore the room from inside the arena. They were encouraged to examine the objects perched on the wall. They were then given the same instructions as for the invisible trials and probe trials of the Arena Maze, except they were not told that the platform would be in the same place.
each time. As in the Arena Maze, participants were encouraged to stay on the platform and look around the room on the first few trials. After 10 invisible trials and the probe trial, participants completed seven ancillary tasks.

2.4.3. Ancillary tasks

a. “Where’s the door?”: After the probe trial, while the participant was still in the virtual room, they were positioned to face the golden urn (the southeast corner) and asked to point to the location of the door (i.e., the North wall). Responses were scored as follows: (3) pointing backwards (behind them), away from the computer screen (as if the virtual room wrapped around them), (2) pointing to one side of the computer screen, (1) pointing at a location on the screen, and (0) unable to point to location of the door.

b. Strategy questions: Participants answered a series of questions about how they found the platform in the Ambiguous Maze. Specifically, they were asked if they found the platform using one object, a combination of objects, or the location of the platform in the room. Answers were coded for mention of particular objects or room features.

c. Object Recognition: From the stimulus sheet of 16 objects (6 of which were foils) participants identified those which they thought were present in the Ambiguous Maze. Hits, misses and false alarms were recorded and the percentage of participants who recognized objects nearest to the platform location was calculated.

d. Room Reconstruction: Participants arranged laminated pictures of the four walls around a picture of the arena floor and placed a scale picture of the platform on the floor to match their relative positions in the virtual room. Scores from 0 to 4 were given according to the accuracy of the layout (for details see [42]).

e. The Rivermead Behavioural Memory Test (RBMT): After a short break (about 10 minutes), participants completed this twenty minute standardized test of recognition and recall for verbal, visual and spatial material. Standard profile scoring was applied according to the test instructions [55].

f. Clock Drawing task: Participants were asked to draw the face of a clock with the numbers correctly positioned and with the hands set at ‘twenty to four’. Drawings were scored according to the procedures adapted from [50] and [57], and as described in [48].

g. Everyday Spatial Questionnaire: Participants indicated the frequency with which they encountered problems of spatial learning, memory, and navigation in their daily lives by marking on a line at the appropriate place between “never” and “every time”. For details of the questions and Likert-like response scale, see [42].

2.5. Analysis

Performance in the virtual mazes was assessed using three conventional measures adopted from the MWM paradigm: latency (time to reach the platform), distance (distance traveled to the platform) and dwell time. Dwell time in each of the four quadrants of the arena was measured on the probe trial and the percentage of time spent searching in the quadrant of the arena where the platform was normally located was calculated. These data were extracted from “Demo” files recorded during navigation in the virtual environments and analyzed using TRAM® software (written by Ludek Nerad, see [43]). Demographic variables were collected and used to match participants and estimate the severity of TBI. Ancillary variables, used to assess spatial learning and memory and to correlate performance between virtual and everyday environments, are described above in the section on ancillary tests. Data were recorded, summarized, and graphed in Excel. Simple analyses like t-tests, effect sizes and correlations were conducted in Excel and checked with SPSS. More complicated analyses (like repeated measures MANOVA) were conducted using SPSS (Version 12).

3. Results

3.1. Visible platform trials

All participants were able to use the game controller successfully and were capable of following instructions in a manner necessary for competent performance in the virtual mazes. TBI survivors were able to navigate to a visible platform in the arena almost as quickly and just as directly as comparison participants (Fig. 3). Although TBI survivors took significantly longer to reach the platform than comparison participants did (p < 0.04, d = 0.95) the mean difference was only 1 s and the statistical significance seemed largely due to the low variance among the comparison participants (see Table 2 for means, variance and t-test results). There were no differences in distance (p = 0.8, d = 0.11), or in travel speed (p = 0.13, d = 0.65) (see Table 2). One participant had a right hemiparesis but was able to successfully complete the exploration and other tasks using a gamepad that was fixed to the table top.

3.2. Invisible platform trials

As expected, TBI survivors took more time to find the platform, taking longer and more circuitous routes (Fig. 3). Group differences were significant for both latency (p = 0.002, d = 1.68) and distance (p = 0.02, d = 1.1) but there were no group differences in speed.

3.3. Arena Maze probe trials

Relative to comparison participants, TBI survivors were not only less able to find the invisible platform quickly and directly,
they were also less able to focus their search for it in the correct location during probe trials. Dwell times in the correct quadrant of the arena were significantly different between the two groups (p = 0.04, d = 0.95).

3.4. Arena Maze spatial scores

Recently, Skelton et al. [43] developed a spatial score to better assess overall performance in the virtual mazes. The score incorporates latency, distance and probe dwell time and the formula is as follows:

\[
\text{spatial score} = (0.5 \times \text{probe } z\text{-score}) - (0.25 \times \text{latency } z\text{-score}) + 0.25 \times \text{path length } z\text{-score}
\]

On this measure of spatial performance, TBI survivors scored worse than comparison participants (p = 0.002, d = 1.4). This is important because this omnibus score takes all measures of navigational performance (i.e., lack of hesitancy, directness of route, certainty of location) into account.

3.5. Single Object Maze

The dual purpose of the Single Object Maze was to provide participants with training in associating a target location (the platform) with a single proximal landmark object and to test their ability to do so. The results showed that the training was successful and that TBI survivors were able to find an invisible platform if it was clearly marked by a proximal landmark. Fig. 3 clearly shows the effect of training on TBI survivors (and comparison participants): performance on late trials was much better than on trial 1. The lack of impairment of TBI survivors on this task is indicated by the finding that there were no significant group differences in either latency (p = 0.16, d = 0.63) or distance (p = 0.13, d = 0.68) and consequently no differences in speed (p = 0.12, d = 0.68). Although the longer mean latencies and distances of the TBI survivors on trial 2 seemed to indicate that they learned the Single Object Maze more slowly than the comparison group, this effect was due to one outlier on this trial (see the symbol on Fig. 3 for a plot of latency with the outlier removed.)

3.6. Ambiguous Maze invisible trials

In the Ambiguous Maze, TBI survivors demonstrated their ability to navigate using a proximal landmark even if it was one of many possible landmarks and removed some distance from the invisible platform. By the last four trials (7–10), TBI survivors found the platform as quickly and as directly as comparison participants and there were no significant differences in
group performance with respect to latency \((p=0.11, d=0.68)\). Even in early trials (2–5), there was no significant difference between groups in latency to the platform \((p=0.07, d=0.79)\) although TBI survivors did take slightly more travel time. These findings indicate that TBI survivors were not impaired at associating a landmark with a destination, nor at discriminating a salient landmark from one that is not as good at indicating the position of the destination.

3.7. Ambiguous Maze probe trials

In the probe trial at the end of the Ambiguous Maze trials, TBI survivors were just as certain of the location of the invisible platform as comparison participants. There was no significant difference between the groups in their ability to focus their search for the platform as measured by percentage dwell time in the correct quadrant \((p=0.12, d=0.63)\).

3.8. Ambiguous Maze spatial score

According to the omnibus measure of wayfinding performance (the spatial score), TBI survivors were significantly worse than comparison participants over all the trials of the Ambiguous Maze \((p=0.03, d=0.97)\). However, by the end of testing (i.e., during the last four trials), there was no significant difference between the two groups \((p=0.95, d=0.02)\).

3.9. Difference between performances in three mazes

The key question of the present study is whether the addition of proximal landmarks to a navigation task makes it possible for survivors of TBI to overcome their navigational impairment in the Arena Maze. Statistically, this question is answered by the significance of the interaction between Maze (Arena Maze versus Ambiguous Maze) and Injury (TBI or no TBI). This interaction was significant for latency \((p<0.01, r=0.56)\) (Fig. 4) and was close to significant for distance \((p=0.09, r=0.38)\). Values for \(r\) (effect size) on the ANOVAs were computed for contrasts. As expected, there was no significant difference found for speed \((p=0.42, r=0.14)\), nor was there a significant difference for dwell time in probe trials \((p=0.33, r=0.21)\). However, most importantly, there was a significant interaction in spatial scores \((p=0.048, r=0.44)\) that arguably provides the most complete picture of performance in these virtual mazes.

![Comparison of latencies in the Arena Maze (AM) with latencies in the Single Object (SO) and Ambiguous (AMB) Mazes. The latencies of TBI survivors were better in both the SO and AMB trials than in AM trials whereas latencies of comparison participants were about the same for all three mazes.](image)

Results from the Single Object Maze also showed the navigational benefit of adding proximal landmarks (Fig. 4). The interaction between maze (Single Object Maze and Arena Maze) and injury was significant for latency \((p=0.01, r=0.56)\) but not distance \((p=0.07, r=0.27)\) or speed \((p=0.08, r=0.14)\). There was no probe trial after the Single Object Maze, and so the spatial score could not be computed.

3.10. Ancillary tasks

3.10.1. ‘Where’s the door?’ task

TBI survivors and comparison participants performed well on the ‘Where’s the door?’ task, with all participants achieving scores of either 2 or 3 on a 4 point scale (0–3), indicating that they considered the virtual space to wrap around them in real space (See Table 3).

3.10.2. Strategy questions

After the Ambiguous Maze, when asked whether they found the platform by its “location in the room”, 50% of the comparison participants agreed, but none of the TBI participants agreed. Both TBI survivors (64% or \(n=7\) individuals) and comparison participants (75% or \(n=9\) participants) said they used the cue object (golden urn) to locate the platform, but nearly twice as many comparison participants said they used room or world cues (50% versus 27% of TB survivors). In other words, TBI survivors were less likely to look beyond the Arena wall, and none of them appeared to use a configuration of local and distal cues.

Table 3

<table>
<thead>
<tr>
<th>Test</th>
<th>TBI (mean ± S.E.M.)</th>
<th>Comparison (mean ± S.E.M.)</th>
<th>(t(21))</th>
<th>(p)</th>
<th>Cohen’s (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Where’s the door?</td>
<td>2.6 ± 0.79</td>
<td>2.9 ± 0.84</td>
<td>1.59</td>
<td>&lt;0.13</td>
<td>0.6</td>
</tr>
<tr>
<td>Object Recognition (% hit on cue)</td>
<td>91%</td>
<td>92%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Room Reconstruction</td>
<td>2.6 ± 0.79</td>
<td>3.3 ± 0.9</td>
<td>1.07</td>
<td>&lt;0.30</td>
<td>0.42</td>
</tr>
<tr>
<td>Rivermead Behavioural</td>
<td>15 ± 1.6</td>
<td>19.4 ± 1.0</td>
<td>2.33</td>
<td>&lt;0.03*</td>
<td>0.95</td>
</tr>
<tr>
<td>Everyday Spatial Questionnaire</td>
<td>54 ± 8.0</td>
<td>42.6 ± 4.2</td>
<td>1.24</td>
<td>&lt;0.23</td>
<td>0.52</td>
</tr>
</tbody>
</table>

* \(p<0.05\).
3.10.3. Object recognition task

TBI survivors and comparison participants were equally able
to recognize objects from the Ambiguous Maze when asked
within 15 min of completing the task. 90% of both TBI sur-
vivors and comparison participants recognized the cue object
(golden urn) which was the one closest to the platform location
while just over 50% of TBI survivors and 80% of comparison
participants were also able to recognize the two objects (a barrel
and a wooden box) located on either side of the golden urn.

3.10.4. Room Reconstruction task

When tested after the Ambiguous Maze, 36% of TBI sur-
vivors and 58% of comparison participants were able to position
the four walls and the platform in the correct configuration
(Fig. 5). However, the difference in Room Reconstruction scores
was not significant ($p = 0.3, d = 0.42$). When the performance of
the participants was examined to see whether they could cor-
correctly arrange the four walls of the room, 82% (9 of 11) of TBI
survivors and 92% (11 of 12) of comparison participants were
perfect. Two TBI survivors (18%) and one comparison partici-
3.10.5. Rivermead Behavioural Memory Test

tant (8%) scored 0 on the task, demonstrating poor knowledge
of the configuration of the virtual room.

3.10.6. Clock Drawing task

Relative to comparison participants, TBI Survivors were
impaired on this test of episodic memory ($p = 0.03, d = 0.95$).
Two participants scored in the severely impaired range (0–9) and
one participant scored quite well, in the normal range (22–24),
but the other eight were all in the poor (17–21) to moderately
impaired (10–16) range. However, the RBMT did not corre-
late well with other measures in the study. Although there were
consistent correlations between RBMT scores and scores in the
proximal landmark mazes when all participants were included,
these correlations appeared to be largely due to the contribution
of the comparison participants. Within the TBI group, perfor-
mance on the RBMT did not correlate with any other ancillary
measure of brain injury deficit or spatial behavior in the Arena
Maze ($r < 0.40, p > 0.05$).

3.10.7. Everyday Spatial Questionnaire

TBI survivors reported more difficulty with ordinary spatial
tasks (including object location and problems with navigating in
real space) than did comparison participants, but the difference
was not statistically significant ($p = 0.23, d = 0.52$).

4. Discussion

In the present study, participants with moderate to severe TBI
were as capable as comparison participants at navigating in the
presence of clear proximal landmarks. That is, they were as capa-
ble in the visible platform trials, the Single Object Maze, and
the Ambiguous Maze. However, relative to the comparison par-
ticipants, they were impaired when required to navigate without
proximal landmarks, that is, in the Arena Maze. The group dif-
fferences in latency, distance, and dwell time in probe trials in the
Arena Maze were consistent with those found in previous work
and confirm that TBI survivors have difficulty navigat-
ing in virtual environments using only distal landmarks. These
findings indicate that the TBI survivors had difficulty construct-
ing, remembering or using cognitive maps of large-scale space
during spatial navigation. That is, TBI survivors had a deficit in
cognitive mapping ability.

The differences observed between the two groups were likely
not due to TBI survivors having difficulties with the procedural
aspects of the virtual environment tasks. Both groups had equal
experience with gamepads and with computer games including
tree dimensional games. Visible trial performance was similar
for the two groups, indicating that TBI participants understood
and remembered task instructions and were able to move easily
in the virtual environment. These trials also showed that TBI
survivors were able to perform the simple navigational task of
guidance to a visible target platform. TBI survivors had good
recognition memory for objects present in the Ambiguous Maze
and did not exhibit signs of fatigue, dizziness (by observation
and self-report), or spatial hemi-neglect (by the Clock Drawing
Test). Finally, the deficit did not appear to be due to a failure
of imagination such that the TBI survivors were unable to imag-
3.10.8. Ambiguous Maze

ing themselves in the virtual environment. On the “Where’s the
Door” test, all but two of the TBI survivors pointed to a place in
space that had the virtual environment from the desktop wrap-
ing around them in real space. In other words, they had a good
sense of “presence” in the environment.

Findings of the present study indicate that there are some
important abilities that are spared after TBI and that contribute
to wayfinding, namely the abilities to associate a landmark with a
destination, to discriminate that landmark from other distracting
stimuli, and to navigate to a destination using that landmark. In
the Single Object Maze, TBI survivors learned to go directly to
an invisible platform demarcated by a single proximal landmark,
indicating that they had little trouble associating a landmark with

![Graph showing percentage of participants achieving each score on the Room Reconstruction task](image-url)
a destination. In the Ambiguous Maze, TBI survivors learned to
go directly to an invisible platform, some distance removed from
one of eight potential proximal landmarks, indicating that they
could not only associate that landmark with the destination, but
could also discriminate it from other landmarks and use it to
navigate efficiently.

Data from the Object Recognition test confirmed that TBI
survivors learned which object was closest to the destination
as well as comparison participants did, and self-reports of
strategy use indicated that TBI survivors (like comparison par-
ticipants) were aware that the destination could be found using
these proximal landmarks. Together, these findings indicate that
after TBI the ability to navigate using proximal landmarks is
spared.

The present findings clarify the nature of the navigational
impairment caused by TBI. Survivors were able to navigate to a
hidden target location when proximal cues were provided (Sin-
gle Object Maze) and when both proximal and distal cues were
provided (Ambiguous Maze). This suggests that the impair-
ments observed in the Arena Maze invisible trials were not due
to the complexity of the environment nor to the ability of TBI
survivors to navigate in the presence of both proximal and distal
cues, but rather, were specific to the absence of proximal land-
mark cues and the inability to effectively use a configuration of
distal cues. Indeed, self-report of strategy use in the Ambigu-
ous Maze indicated that half (n = 6) of the comparison group
used distal room cues (e.g., doors, windows, corners) to assist
navigation but that only one TBI survivor did so. These find-
ings confirm the interpretation that TBI impairs navigation by
interfering with the formation, retention or use of a cognitive
map.

TBI survivors exhibited significant wayfinding difficulties in
the Arena Maze but it is also true that on the vast majority of tri-
als, they did finally locate the platform. TBI survivors may have
used an alternative method (other than cognitive mapping) to
locate the hidden platform. Possible strategies include circling
the arena at a fixed distance from the wall, executing a grid-like
search pattern or using a verbally mediated strategy [42,43]. For
example, a participant might use a verbal route such as ‘go to the
door, turn to face the big window, then head to the left a little’. Ver-

cally mediated strategies can be used to find the hidden plat-
form in the Arena Maze but would be expected to generate much
longer latencies and distances than would a cognitive mapping
strategy.

These findings confirm and extend results obtained with
laboratory animals indicating that allocentric navigation via
cognitive mapping and egocentric navigation via stimulus-
response associations are mediated by different neural systems.
As described in the introduction, rats with HPC damage can
successfully navigate the MWM when proximal cues are added
[14,25,44] and normal rats use both allocentric and egocentric
strategies within trials [20].

In this study, the location of the participant’s damage was
not identified for three reasons: First, because this is primarily
a behavioral study of cognitive losses and spared abilities after
brain injury; second, because it was impossible to obtain recent
scans of our participants or participants with recent scans; and
third, because it is almost impossible to document the extent of
damage throughout the many relevant regions of the brain after
TBI in a manner similar to that done after lesions in rodents.
However, there are grounds for speculating where their damage
was likely to have been. After brain injury (in humans) there is a
high incidence of temporal lobe damage [8,26,37], specifically
damage to the hippocampus [6], which is consistent with a selec-
tive impairment in allocentric navigation. Damage to the frontal
lobes is also common after TBI, but there is some controversy
as to whether research has clearly established a selective link
between frontal lobe damage and executive dysfunction. There
seems little doubt that frontal lobe damage can lead to execu-
tive dysfunction [2,40], however, in the current study, there was
little evidence of such dysfunction. Specifically, in the Ambigu-
ous Maze (which was procedurally as complex as the Arena
Maze), there was no evidence of lapses in attention or motivation,
failures to maintain intent, impulsivity, preservation, planning
of motor sequences, or other deficits of executive function in
goal-directed behavior.

Surprisingly, given the possible commonality of anatomical
basis, there was little relation between deficits in episodic mem-
ory as assessed by the RBMT and deficits in cognitive mapping
as assessed by the Arena Maze. As noted in the results, the partic-
ipants in the present study had a considerable range of everyday
memory function, ranging from severely impaired to within the
normal range. Despite this heterogeneity, scores on the RBMT
were not correlated with performance in any of the mazes we
tested. Admittedly, the RBMT assesses a wide variety of mem-
ory functions, but seems to be heavily loaded on one-trial fact
learning, with such episodic memory questions accounting for
10 of the 24 possible points. Route learning and orientation to
time and location account for 7 more, while remembering to
remember (i.e., prospective memory) account for 6 more, leaving
only 1 point for the semantic knowledge of who the Prime
Minister and US President are. In other words, the RBMT seems
to tax memory functions commonly ascribed to the hippocam-
pus [17]. The present findings indicate that the RBMT and the
Arena Maze not only assess different cognitive functions, but
that these functions do not share a common anatomical substrate.
One implication is that it is important to assess these different
functions separately.

Correlating deficits in the virtual environment wayfinding
tasks with deficits in real world wayfinding presents some dif-
ficulty since good tests of real world wayfinding deficits are
not readily available. It is important to establish that the vir-
tual reality testing used is ecologically valid before developing
assessment or rehabilitation tools based on virtual environments.
Performance in virtual environments, such as the one used here,
is thought to transfer readily to real world environments (for
review see [41]). The maze tasks described in the current study
have a number of advantages with respect to rehabilitation of
deficits in wayfinding: (1) the tasks are portable and work with
ordinary desktop computers, (2) participants could be tested and
re-tested in the same environment so the mazes have the poten-
tial to both assess and rehabilitate, (3) the tasks could allow for
practice of skills (including compensatory strategies) necessary
to improve wayfinding success, (4) the tasks are safe for partici-

ipants, and (5) the tasks could be adapted as ‘errorless learning’ [56] rehabilitation techniques.

The results of this study lead to the conclusion that TBI survivors have deficits in spatial cognition (specifically cognitive mapping) and that such deficits are long lasting. Navigational difficulties are clearly evident many years after the point of injury suggesting that neither spontaneous recovery nor rehabilitation have restored function. However, in this study, TBI survivors were able to navigate to an invisible target location using a single proximal landmark despite the complex conditions and the need to discriminate the correct proximal landmark from among multiple proximal landmarks. It is beyond the scope of this study to determine (and difficult to design a study that would determine) whether the deficit is in constructing the cognitive map of the room, in remembering it, or in using it to guide navigation. Nevertheless, the present results support the idea that spatial navigation is mediated by underlying cognitive mechanisms that can be selectively impaired or spared after a traumatic brain injury. The exact proportion of TBI survivors who have real world wayfinding problems needs to be determined, though in this and our previous two studies the proportions were greater than two thirds [42,43]. It also remains to be seen whether compensatory strategies learned in a virtual environment could improve the ability of a TBI survivor to navigate in real space. For example, TBI survivors could be trained to navigate using simple, single landmarks and then tested in a real world wayfinding task. Further research into the nature of spatial deficits and compensatory strategies after TBI might reveal these strategies to be sensitive markers of brain injury [18]. Regardless of what future research finds, the present study clearly indicates that there are spared cognitive mechanisms that might be activated to improve the quality of life for TBI survivors who experience wayfinding problems.

References