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

by

Sharon Ann Livingstone

B.A., Malaspina University College, 2002

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in the Department of Psychology

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Abstract

Traumatic brain injury (TBI) damages many regions of the brain but damage to the hippocampus has been particularly linked to functional deficits in memory and wayfinding (i.e., finding one's way in familiar and unfamiliar environments). The current study investigated the nature of these wayfinding problems using a virtual simulation of a Morris water maze, a standard test of hippocampal function in laboratory animals. Eleven TBI survivors and 12 comparison participants, matched for gender, age and education were tested to see if they could find a location in a virtual room marked by a) a visible platform, b) a single object, c) one object of 8 different ones, or d) distal room cues (which requires cognitive mapping). TBI survivors were impaired at finding the location based on room cues but not when the other cues were present. These results indicate that TBI impairs cognitive mapping but not associative processes in wayfinding.

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Dedication

For my children, Angela, Heather and Ian …. thank you for believing in me.

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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 (Khan et al., 2003; Rappaport et al., 1989). Such changes are evident to varying degrees depending upon the severity of injury, but many individuals who suffer from TBI are faced with permanent life changes as a result. One of the most common complaints of TBI survivors is that they frequently experience memory loss most especially in the form of anterograde amnesia (Barrash, 1998; Squire, 1992; Van Zomeren & Van Den Burg, 1985). Along with this amnesia, many survivors will also experience loss of spatial ability and difficulty wayfinding where wayfinding is described as the ability to find one's way around in both familiar and unfamiliar locations (Aguirre & D'Esposito, 1999; Barrash, 1998). Spatial ability can be loosely defined as the ability to comprehend or navigate large-scale space. (Aguirre & D'Esposito, 1999) The spatial deficits associated with TBI are poorly understood but can be extremely debilitating. Furthermore there are no assessment or treatment options designed specifically to measure the cognitive deficits associated with poor real world wayfinding ability. The current research addresses the question of how to assess the specific cognitive mechanisms of wayfinding that may be compromised by TBI, as well as those mechanisms that may remain intact.

Epidemiology

The incidence of TBI has been estimated at 250 per 100,000 population (Frankowski, et al., 1985) in the United States and 230 per 100,000 in Canada (Pickett et al., 2001). The incidence of long-term disability is 100 to 150 per 100,000 young people and adults each year (Thornhill et al., 2000) and the rate of survival after TBI has been gradually

increasing with the advent of life saving medical technologies (Goldstein & Levin, 2001). TBI has a number of predictable causes including motor vehicle accidents (Khan et al., 2003; Rose et al., 1996), falls (Servadei et al., 2002; Thornhill et al., 2000) and personal violence (Thornhill et al., 2000; Rose, 1996). Also, TBI most commonly affects young adults and often leads to lifelong impairment in cognitive function (Khan et al., 2003; Thornhill et al. 2000). This cognitive impairment, along with social and emotional deficits, appears to be most disabling for the individual with TBI (Khan et al., 2003; Thornhill et al., 2000). Taken together, these statistics imply that TBI is a significant societal problem. Furthermore, the complex constellation of impairments associated with TBI demands focused rehabilitation (Khan et al., 2003). Cognitive therapies are commonly undertaken (Khan et al., 2003; Goldstein & Levin, 2001), but memory strategy aids are the only current treatment for cognitive deficits that has been based on strong empirical findings (Khan et al., 2003).

Anatomical Damage in TBI

The complex set of deficits often associated with TBI likely reflects the nature of damage to the brain. Typically, the regions involved include orbitofrontal cortex, the poles of the temporal lobes and the hippocampus (Bigler et al., 1997; Kotapka, Graham, Adams, & Gennarelli, 1992; Pang, 1989). Diffuse axonal injury also occurs (Adams et al., 1985; Bigler et al., 1997) contributing to ongoing and variable cognitive deficits Gaetz (2004).

Cognitive Deficits after TBI

TBI can lead to multiple social, emotional, and cognitive changes in the individual (Rappoport et al. 1989; Khan et al., 2003) as well as problems with language, attention,

concentration, planning and organization (Khan et al., 2003). More specifically, TBI may manifest in problems with facial recognition, story recall, semantic information processing, prospective memory and autobiographical memory (Baddeley, Harris, Sutherland, Watts, & Wilson, 1987). TBI can also be associated with retrograde and even more commonly, anterograde amnesia (Barrash, 1998; Squire, 1992) as well as deficits in spatial abilities including topographic disorientation and route finding problems (Lezak, 1995, p. 348-352). Research suggests that these memory and navigational deficits might both result from damage to the hippocampus.

The Role of the Hippocampus

Some of the cognitive changes associated with TBI have been linked to damage in the temporal region and specifically damage to the hippocampus. Such changes include anterograde amnesia (Barrash, 1998) and spatial deficits (Bigler et al., 1996; Tate & Bigler, 2000). Verbal memory deficits have been linked to left hippocampal damage (Bigler et al., 1996) while right medial temporal lobe damage has been linked to deficits in spatial learning and spatial memory (for review, see Barrash, 1998). Indeed, surgery to right temporal regions can lead to impairment of spatial memory and impairment in the learning of object locations and their relations to each other (Feigenbaum, Polkey, & Morris, 1996; Maguire, Burke, Phillips, & Staunton, 1996; Smith & Milner, 1981; Spiers et al., 2001). Bohbot et al., (2000) demonstrated that lesions to the hippocampus and parahippocampus are related to spatial memory deficits and Barrash et al., (2000) report that route learning is impaired after hippocampal damage. Ultimately, the hippocampus appears to be essential for encoding, storage, and even retrieval, of spatial details (Nadel, Samsonovich, Ryan, & Moscovitch, 2000).

Other anatomical considerations

While the hippocampus is strongly implicated in the context of spatial deficits after brain injury it is important to note that other brain regions contribute to the overall process of wayfinding and consequently, that damage to these areas may influence spatial ability in specific ways. For example, the presence of topographic disorientation (a failure to orient and navigate, including the feeling of being lost) has been associated with damage to the parahippocampus (Barrash et al., 2000; Grüsser & Landis, 1991; Habib & Sirigu, 1987) and appears to manifest as wayfinding difficulty (Aguirre & D'Esposito, 1999; Barrash, 1998; Grüsser & Landis, 1991). Disruption of route finding (route learning/memory) is correlated with lesion sites including bilateral parietal, right or bilateral medial inferior occipito-temporal and lateral temporo-parieto-occipital (Grüsser & Landis, 1991) although most classic case reports involve vascular lesions, tumours or organic disease rather than TBI. Barrash et al. (2000) conducted a study of 127 participants with stable focal lesions and found that right medial temporal, inferior medial occipital (right or left), and right parietal regions were implicated in wayfinding difficulty in a real environment (consistent with both classic case reports and modern reports of spatial deficits associated with hippocampal damage). The authors noted that the parietal lobe is probably not critical for route finding and that parietal lesions alone do not cause lasting wayfinding deficits. Mendez & Cherrier (2003) further suggest that parietal lobe damage is more frequently associated with visuospatial deficits rather than the inability to access or retrieve 'mental maps'. This ability to 'mental map' has been associated with the activity of the hippocampus (Mendez & Cherrier, 2003; Aguirre & D'Esposito, 1999; Maguire et al., 1996).

Brain injury and Wayfinding

The hippocampus is particularly vulnerable to injury (Kotapka et al. 1992; Bigler et al., 1997) and given its association with spatial ability, may be significant in the development of spatial deficits after TBI. Such deficits have been classified in a variety of ways, but there is inconsistency in both the use and meaning of the terminology surrounding spatial deficits. Topographic disorientation has sometimes been described as having a double aspect of recall and recognition (Paterson & Zangwill, 1944) such that associated deficits can be viewed as either amnesic or agnosic. Grüsser & Landis (1991) suggest that humans navigate by relying on 'unconsciously acquired topographic familiarity' (p.416) that, when disrupted, leads to topographic agnosia. However, some researchers (Barrash, 1998; Maguire, 1996) suggest that this may be an over-simplification. In any case, it is clear that although brain injury can lead to spatial deficits, the role of such deficits after TBI is not well understood and that a potentially sensitive marker of brain injury may result from further research into spatial deficits and compensatory strategies (Grusser & Landis, 1991) adopted by brain injured individuals including TBI survivors. Unfortunately, current assessment measures would seem to be inadequate to the task of capturing spatial deficits and strategy use after TBI.

Spatial testing

Traditional spatial test measures often include two dimensional, paper and pencil style neuropsychological tests (see examples in Lezak, 1995; Spreen & Strauss, 1998) that do not address the question of three-dimensional, real world wayfinding. An exception to this rule is the Route Learning Test (Barrash, 1998) that requires TBI patients to navigate a route in a large medical building with immediate non-verbal

corrective feedback. This real world test has been found to be sensitive to subtle impairments in route learning ability (Barrash, 1994). There are also rehabilitation tasks that do require some real world wayfinding, but are mainly limited to simple stimulus-response type measures of spatial ability (Brooks et al., 1999; Sohlberg & Mateer, 1989). In order to improve upon this situation it will be important to establish which specific cognitive mechanisms are impaired and/or spared by TBI and to employ methods that closely mimic real world wayfinding while focusing on the mechanisms involved. To this end, it may help to first clarify some basic definitions that will be applied throughout the proposed research.

Theory and Definitions

Figure 1 shows the relationship of the terms that provided the foundation for the current research. The definitions of the terms included are based upon the current state of knowledge about wayfinding from both the empirical and theoretical standpoints. For understanding, real world examples are given where appropriate.

Landmark. A landmark is a single salient cue that can be associated with a target location during wayfinding. It can be an interim cue that informs the wayfinder that they are on the right path to the target, or a large cue visible from start and finish (like mountains or a body of water) that can be used for orientation along the journey. Landmark stimuli may be configural (composed of different parts that change appearance from different viewpoints) or may be elements of a configuration (a set of stimuli that are not visible as a unit but which have spatial relations to the wayfinder). Jacobs & Schenk (2003) have further categorized landmarks as being directional (distal cues that do not mark a specific location) or positional (proximal cues that when combined provide a

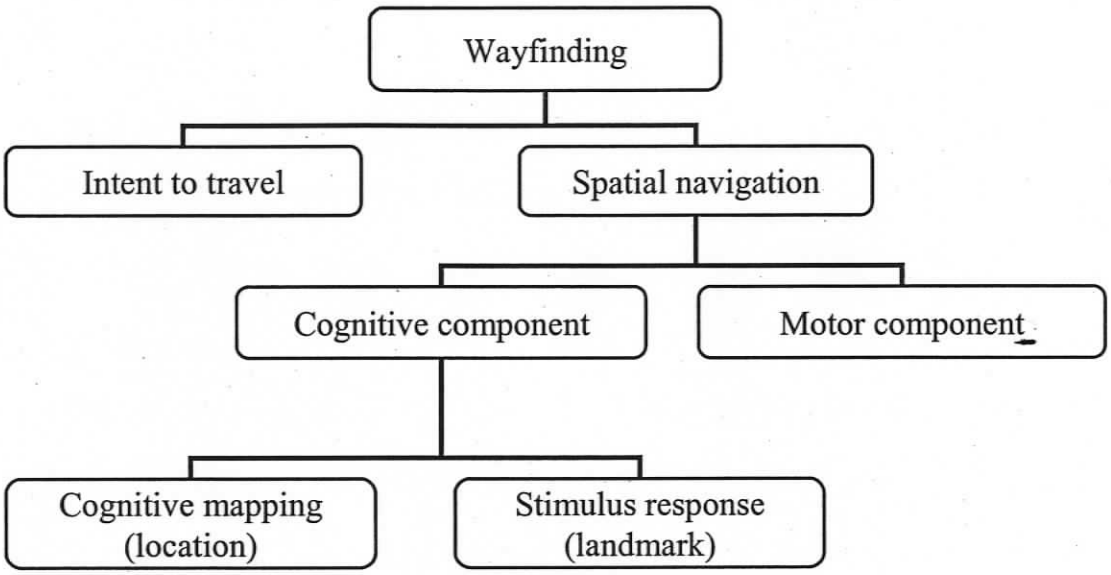


Figure 1. Structure of the terminology used to define wayfinding and its components. Note that spatial navigation has two components (cognitive and motor) and that the cognitive component is further subdivided into two mechanisms (cognitive mapping and stimulus-response).

configuration that indicates a location). For the current study, an additional category of landmark, the 'locational landmark' is defined as a single salient cue that marks a location.

Wayfinding: Intention & Spatial Navigation. Wayfinding refers to finding one's way from one location to another in both familiar and unfamiliar environments in the real world (Aguirre & D'Esposito, 1999). It is a complex behaviour that encompasses decision-making about navigational goals, the formation and maintenance of intent to travel, and spatial navigation. A typical example of wayfinding is the entire process of going from one's home to a shopping mall several kilometers away. The process would include the decision to go to the mall (and not some other destination), navigation toward the mall and arrival at the mall as planned.

Spatial Navigation: Cognitive and Motor Components. Spatial navigation can be viewed as a) the coordination of movement through space via mechanisms for identifying environmental information to guide navigation and b) a process for selecting appropriate strategies. While navigating to the mall, then, a person is able to coordinate movement toward the mall destination using a variety of cognitive approaches, for example, following instructions given on a map, using landmarks or even following the direction of the sun. The person is able to select the best strategy (perhaps a map if he/she is new to the city) and abandon others (for example, choosing not to navigate by the sun on a foggy day).

Spatial Cognition: Cognitive mapping (allocentric) vs. Stimulus Response (egocentric). For the purposes of the proposed research, the cognitive mechanisms underlying spatial navigation were investigated according to previous work

demonstrating a dissociation among allocentric and egocentric spatial systems (see reviews, Aguirre & D'Esposito, 1999; Nadel & Hardt, 2004). First, allocentric processing refers to processing spatial information from an imagined perspective (e.g., a bird's-eye view) and consists of responses to stimuli that could well be remembered rather than perceived. One theory important in this context is the 'cognitive map' theory proposed by O'Keefe & Nadel (1978). Like rats, humans may form a map-like internal representation of the environment and this representation may form the basis for superior wayfinding ability based on the idea that a cognitive map would allow humans (and rats) to develop novel trajectories between locations (Bohbot et al., 2004).

Second, egocentric processing refers to the processing of spatial information from the person's perspective and consists of responses to perceived stimuli. In egocentric processing, the organism has a vantage point (Nadel & Hardt, 2004) and in humans this is mediated in part by parietal lobe activity (Burgess, 2002). O'Keefe & Nadel (1978) described, for example, an organism centered 'taxon system' in which hypotheses about guidance and orientation mediate navigation. Guidance refers to approaching/avoiding an environmental cue due to its valence whereas orientation is the behaviour (pattern of movement) executed in the presence of a cue. Stimulus-response systems in the rat are described by White & McDonald (2002) as being associated with the striatum (caudate and putamen). Evidence from human imaging studies of wayfinding indicates that the caudate is activated while participants engage in non-spatial landmark (stimulus response) strategies (Bohbot et al., 2004), but is not activated when spatial strategies are employed. Both Nadel & Hardt (2004) and Bohbot et al., (2004) conclude that the

combined and efficient use of allocentric and egocentric systems would presumably lead to greater wayfinding success.

Strategies

The success of wayfinding may depend upon an individual's ability to identify information relevant to both allocentric and egocentric processes and to properly select which strategy to follow. It is crucial to wayfinding outcomes that strategies are internally available and appropriately selected (Bohbot et al., 2004; Iaria, Petrides, Dagher, Pike, & Bohbot, 2003; Morrow & Ratcliff, 1988). Since strategies reflect the availability of particular cognitive mechanisms, it is possible to infer that strategies employ either allocentric (spatial) or egocentric (non-spatial) systems (Iaria et al, 2003; Bohbot et al., 2004; Nadel & Hardt, 2004). Wayfinding, then, can be accomplished by combining spatial and non-spatial strategies. Further, on-going wayfinding involves spontaneous strategy selection (Iaria et al., 2003) that is fluid and dynamic, while being based on specific cognitive mechanisms (Bohbot et al., 2004).

Deficits in Cognitive Mechanisms

After TBI, wayfinding deficits could result from impairments in several different cognitive processes:

1. The ability to maintain the intent to reach a particular destination.
2. The ability to form or use a cognitive map or routes and places.
3. The ability to use landmarks to guide wayfinding actions (e.g. turning or travel).
4. The ability to discern appropriate wayfinding strategies.
5. The flexibility to alter strategy to suit environmental demands.

The underlying assumption here is that TBI selectively impairs spatial strategy use via the impairment of specific cognitive mechanisms and also that these mechanisms have anatomical bases. It is important, then, to investigate the underlying mechanisms of wayfinding in order to assess wayfinding deficits.

According to the definitions given above, one framework for the study of wayfinding deficits is a model of wayfinding recently developed in Dr. Skelton's lab (see Appendix A). The model describes wayfinding as incorporating intention, spatial navigation and interim assessments in a cyclic process, which continues until a specified goal is reached. Spatial navigation is comprised of both cognitive and motor components, such that movement is necessary for navigation and cognitive mechanisms mediate this movement. Spatial cognition further consists of both allocentric (cognitive mapping) and egocentric (stimulus response) systems, which determine the next step at any given point in time. At the heart of these systems is a process for determining whether an allocentric or egocentric strategy will be engaged. It is the activation (or not) of these strategies that is the focus of the current research.

Summary

The following statements summarize the logic utilized to design the current study:

1. Wayfinding is accomplished by combining spatial and non-spatial strategies.
2. Strategy selection during on-going wayfinding is fluid and dynamic and reflects specific cognitive mechanisms.
3. Different wayfinding processes have different anatomical bases.
4. TBI selectively impairs spatial strategy use via the impairment of specific cognitive mechanisms.

The purpose of this research, then, was to investigate the pattern of preserved and impaired cognitive mechanisms of wayfinding among survivors of TBI. Table 1 illustrates the general hypotheses with respect to TBI and the cognitive component of navigation. The specific hypotheses tested were as follows:

1. Survivors of TBI will perform poorly in a maze that requires spatial navigation/cognition compared to controls.
2. Survivors of TBI will perform well in a maze that can be solved by associating a single object with a target platform.
3. Both survivors of TBI and controls will perform well in a maze that can be solved using either spatial or non-spatial strategies. Most will solve the maze by using an appropriate landmark that must be discerned from an array.

Methods

The Use of Virtual Environments

Virtual reality (VR) is a technology which allows a user to interact with a computer-simulated environment (http://en.wikipedia.org/wiki/Virtual_reality, 2006). According to this source, VR systems such as ours that use desktop monitors to display the virtual environment (VE) are termed "non-immersive". Rizzo, Schultheis, Kerns, & Mateer (2004) describe VEs as simulations that can range from sets of simple stimuli to complex reproductions of real world space. VEs (virtual spaces) are constructed and presented via VR systems that may incorporate virtual reality technology including head mount systems or desktop computer displays.

The main concern with the use of virtual reality in rehabilitation has been

Table 1

General and specific hypotheses tested

General hypotheses (relative to comparison participants)	Specific hypotheses (relative to comparison participants)
1. TBI survivors are **impaired** at navigating using cognitive maps.	1. TBI survivors will perform poorly in a spatial maze.
2. TBI survivors are **not impaired** at navigating using simple cues.	2. TBI survivors will perform well in a single cue maze.
	3. TBI survivors will perform well in a multi-cue/spatial maze.

transferability from virtual to real performance. However, VEs have demonstrated ecological validity in that learning in virtual space can be shown to transfer to a variety of real world situations (for a review, see Rose, Attree, Brooks, & Johnson, 1998). Work in Dr. Skelton's lab has demonstrated that learning in a virtual version of a campus 'quadrangle' transferred to performance in the real space (Ross, Skelton & Mueller, in press). Apart from ecological validity, there are numerous additional advantages to testing in virtual space. First, the environment is the same from one lab to another, free from distractions like the weather or pedestrian or vehicular traffic and safe for the participant. Second, the environment can have stimuli and contingencies difficult to find in real world situations, thus providing exacting control over features of the environment, from the geometry of the space to the size and location of objects and features within it. These features make it possible to systematically vary spatial stimuli and environmental contingencies and thereby improve the analysis of spatial cognition (Rizzo, Schultheis, Kerns& Mateer, 2004). Third, desktop VR systems are relatively portable and can therefore be transported to hospital, rehabilitation or even home settings. Fourth and perhaps most importantly, VEs provide a means to engage anatomical structures underlying spatial cognition while participants are in an fMRI scanner. Although this approach has been used successfully with uninjured participants (Bohbot et al., 2004; E. Maguire, Frith, Burgess, Donnett, & O'Keefe, 1998) and temporal lobectomy patients (Bohbot et al., 2004), there have only been preliminary (though encouraging) results imaging people with TBI during virtual navigation (Skelton et al., 2000a).

The Morris Water Maze

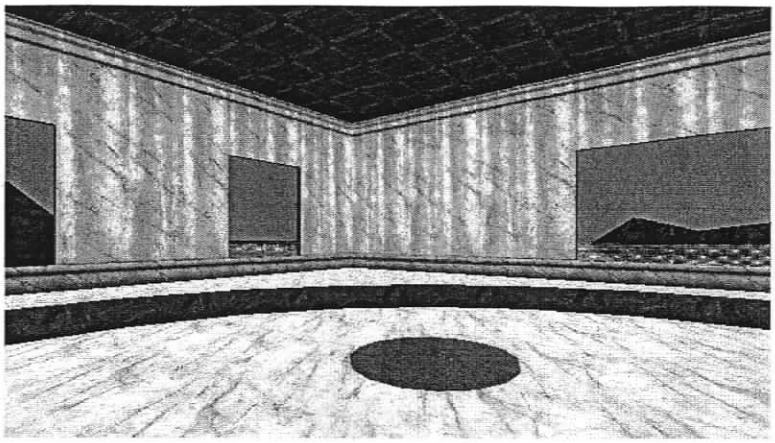
One of the most important methodological developments in the study of spatial

cognition is the MWM (Morris, 1981, 1984), because of its ability to distinguish performance based on spatial learning and memory (i.e., allocentric navigation requiring the hippocampus) from performance based on simple cues or egocentric response patterns (Eichenbaum, Stewart, & Morris, 1990; Morris, 1984; R. W. Skelton, 1998). The maze consists of a large, round featureless pool filled with cool opaque water, and requires laboratory animals to find and escape onto a 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 of a constellation of distal extra-maze cues. 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) (Kolb, Sutherland, & Whishaw, 1983; Morris, Garrud, Rawlins, & O'Keefe, 1982).

Arena Maze

This maze is an analogue of the MWM designed to test participants for the ability to use spatial (allocentric) strategies during wayfinding (Skelton et al., 2000b). The maze (for illustrations of all mazes used in the experiment, see Figure 2) consists of a large round arena contained within a room that has large windows giving a panoramic view of a realistic world outside. The maze is navigated by exploration of the room including looking out the windows to the mountains, hills, and a large body of water. Task training includes navigation to a round platform visible on the floor of the arena. In the Arena Maze, like the MWM, participants must find and then return to the fixed location of a

A.



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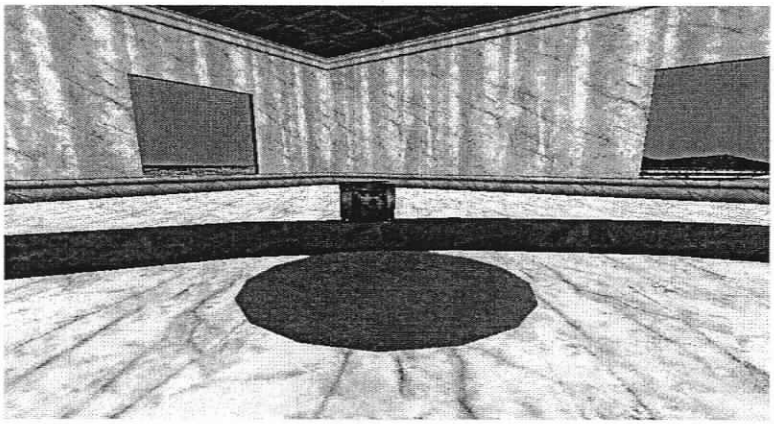

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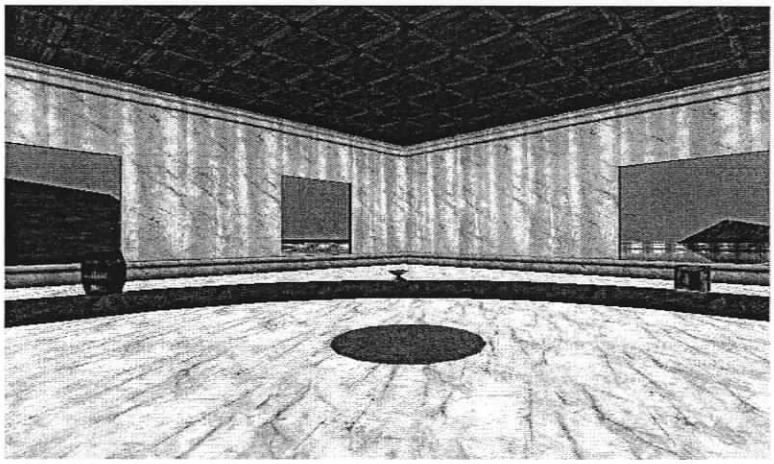


Figure 2. Three virtual maze environments given in the order they were presented to the participants. The green spot illustrates the platform locations. Note that all platforms were the same size and were invisible until they were found. **A.** The Arena Maze. **B.** The Single Object Maze. **C.** The Ambiguous Maze.

platform. This round platform is positioned out of sight just beneath the surface of the floor in order to copy the positioning of the platform just under the surface of the milky water in the MWM. The task is considered spatial because there is no single or proximal cue to indicate the location of the platform, and the platform must be located from a variety of starting points in the arena. The maze can be solved using non-spatial strategies but only slowly and by using circuitous routes.

Single Object Maze

The Single Object Maze is designed to test for the ability of participants to simply associate a target platform with a single locational landmark object. The platform is invisible and varies in position. However, the platform is located near the edge of the arena with its position indicated by an object (a large steel box) perched on the arena wall, leading to a simple non-spatial solution (Kolb & Walkey, 1987).

Ambiguous Maze

The Ambiguous Maze is a variant of the Arena Maze and is designed to test for the ability of participants to find a hidden platform when given the choice to utilize either spatial (allocentric) or non-spatial (egocentric) strategies. The possibility exists for both spatial and non-spatial solutions. As in the Arena Maze, trials start from a variety of positions and the platform is in a constant location identical to its location in the Arena Maze. An object perched on the arena wall indicates the platform position. This locational landmark object is one of an array of eight objects spread evenly around the circumference of the arena. Because the maze can be solved both spatially and non-

spatially, participants were polled as to whether they found the platform spatially using directional room cues, or non-spatially using the locational landmark object.

Participants

Fourteen adult participants (11 men, three women) between the ages of 22 and 55 and with a history of brain injury were recruited from the Vancouver Island Head Injury Society and by the placement of a poster advertisement at the Gorge Hospital in Victoria, British Columbia. After testing, three brain injury survivors were excluded from the study, the first because she had serious motor difficulties and absence seizures that made the use of a game controller quite difficult, and two more because their injuries were not TBI but rather were due to strokes, and strokes would be expected to have different neurological features than TBI (Lezak, 1995, p. 186 & 197). The final sample of 11TBI survivors (9 men, 2 women) were community living (i.e. not institutionalized) and none had any documented history of neurological disorders prior to their injury. Time since injury ranged from 9 months to 29 years with a mean time of 10.4 years. All TBI survivors in this study were either moderately (n = 3) or severely (n = 8) injured based upon the degree of post traumatic amnesia reported and their injuries were caused by motor vehicle accidents (n = 6), violence (n = 3) and falls (n = 2).

Fourteen adult participants (12 men, 2 women) between the ages of 20 and 50 and with no reported history of TBI or neurological disorders were recruited through an advertisement placed in local newspapers. These comparison participants were matched to the TBI sample by age, education and gender. After the initial demographic interview two participants were excluded from the sample, one because upon arrival it became obvious that he had a motor disorder and one because it was suspected that he may have

suffered from TBI in his teens. The final sample of 12 comparison participants (10 men, 2 women) completed the study in exactly the same manner as the TBI survivors.

All participants were paid an honorarium of $30 for their time and for travelling to the university. The University of Victoria Human Research Ethics Committee approved the research.

Computer presentation

All VE tasks were presented using a VR system that included a desktop personal computer with a 19 inch monitor using an 800 x 600 resolution and a gamepad (Thrustmaster®) that allowed the participant to move forward, turn left or right, but did not allow them to back up. The VEs were designed using the Unreal® game engine (Epic Megagames).

Apparatus

The three mazes described above were administered according to the following sequences of trials:

1. The Arena Maze consisted of 1 exploration trial, 4 trials where the platform was visible, 10 trials where the platform was invisible and 1 probe trial in which the platform was absent.
2. The Single Object Maze consisted of 5 trials in which the platform was invisible and varied in position.
3. The Ambiguous Maze consisted of 1 exploration trial with objects around the arena, 10 invisible trials where the platform was invisible, and 1 probe trial in which the platform was absent.

The sequencing and numbers of trials were determined through past research conducted in Dr. Skelton's labs and based on both rat research (Skelton, 1998) and previous studies with humans in the Arena Maze (Skelton et al., 2000b, Skelton et al., 2006).

Detailed Procedures

A detailed script of all experimental procedures is provided in Appendix B. Participants first gave their informed consent (Appendix C) and then completed a Background Information Questionnaire (Appendix D) that provided details such as age, gender, education, and nature of injury and an estimate of post-traumatic amnesia. Participants then completed the three maze tasks in following order: Arena Maze, Single Object Maze, and Ambiguous Maze. Following completion of the mazes, several maze related post-tests were conducted as follows:

1. Where's the Door Test (Appendix E)

   The participant was asked to indicate the location of the door in the virtual room after completing the last trial of the Ambiguous Maze and being positioned in front of the golden urn. This tested the participant's understanding of the three dimensional nature of the virtual room.

2. Strategy Questions (Appendix F)

   Participants were asked for explicit information about how they solved the Ambiguous Maze.

3. Object Recognition (Appendix G)

   Participants were asked to identify which objects were present in the array of objects presented in the Ambiguous Maze. This required the selection of

objects from a sheet that had distracter objects as well. Hits, misses and false positives were recorded.

4. Room Reconstruction (Appendix H)

   Using images of the walls, floor, arena and platform, participants were asked to reconstruct the virtual room by placing the four walls and the platform in the correct relations to each other.

The completion of the previous steps signalled the end of the first session of the study. The second session was then conducted after a short break or at a later date if the participant so wished. The second session consisted of:

1. Rivermead Behavioural Memory Test (RBMT)

   This is a standardized neuropsychological test of memory for objects, faces, a spoken verbal passage and a physical route. Several delayed memory tasks are included.

2. Clock drawing task (Appendix I)

   This is another standardized test used to screen for spatial hemi-neglect and for executive function difficulties (Spreen & Strauss, 1998) that might interfere with the performance of the maze tasks.

3. Bells Test

   This is a cancellation task for the evaluation of visual neglect (Gauthier et al., 1989). The authors suggest that this task is useful for detecting milder cases of neglect that may remain after visual neglect appears to have resolved. Mild neglect could possibly interfere with performance of maze tasks. The Bells

Test was introduced part way through data collection as an extra test for spatial neglect.

4. Everyday Spatial Questionnaire (ESQ) (Appendix J).

   This questionnaire assesses the participant's perception of his/her own navigational ability. Questions are divided into two subscales, one concerning spatial ability and the other concerning object memory.

After completing the second session, participants were debriefed and paid an honorarium. The estimated time for completion of the study ranged from 90 to 120 minutes.

Virtual Environment Variables

For the purposes of this experiment, three conventional measures were adopted from the MWM paradigm. These are latency (time to reach the platform), distance (distanced travelled to the platform) and dwell time. Latency was measured in seconds and distance was measured in arbitrary units established by the x and y coordinates used in the virtual mazes. Dwell time was measured on the probe trial and indicates the percentage of time spent searching in the correct quadrant of the arena, that is, the quadrant in which the platform is normally located.

Additional Variables

In addition to the maze variables, there were several other variables of interest in this study. These fell into three general categories:

1. Demographic variables such as age, gender and education level
2. Test variables such as object recognition, room reconstruction ability, and everyday spatial performance, memory and video game experience

3. 'Screening' variables such as results of the Clock Drawing and Where's the Door tests

Demographic variables were used to match participants and test variables were correlated with maze performance. Finally, duration of hospital stay, duration of coma and an estimate of post-traumatic amnesia established the criteria for brain injury.

Analysis

Computer Note. Data from the Arena Maze were analyzed from "Demo" files recorded by the UnReal® engine while the participants navigated the virtual environment. TRAM® (software written by Ludek Nerad) was used to derive latency, distance and dwell time data.

Statistics. Statistical analyses consisted of comparisons of the two groups (TBI survivors and comparison participants). The outline of statistical procedures is presented in Table 2. A total of 12 t-tests were conducted and interpreted using the Hochberg adaptation of the Bonferroni procedure (Hochberg, 1988).

Power Analysis. Adopting a critical p value of .004 (as determined by the adaptation of the Bonferroni procedure), a power value of .8 and an effect size of 1.5 in the ArenaMaze, the necessary minimum sample size for this research project would be 30. The effect size value selected here was based upon recent work with the Arena Maze (Skelton, Ross, Nerad & Livingstone, 2006) where effect sizes for distance and latency variables ranged from 1.48 to 2.25. Calculations were made using the GPower analysis program (Erdfelder et al., 1996). Although this analysis predicted that the necessary sample size for this research was 30, only 23 were studied for several reasons. First, because it was difficult to recruit TBI survivors without co-morbid conditions that could

Table 2

A Summary of the Main Statistical Analysis for Demographic Variables, Maze Test Variables and Screening Variables

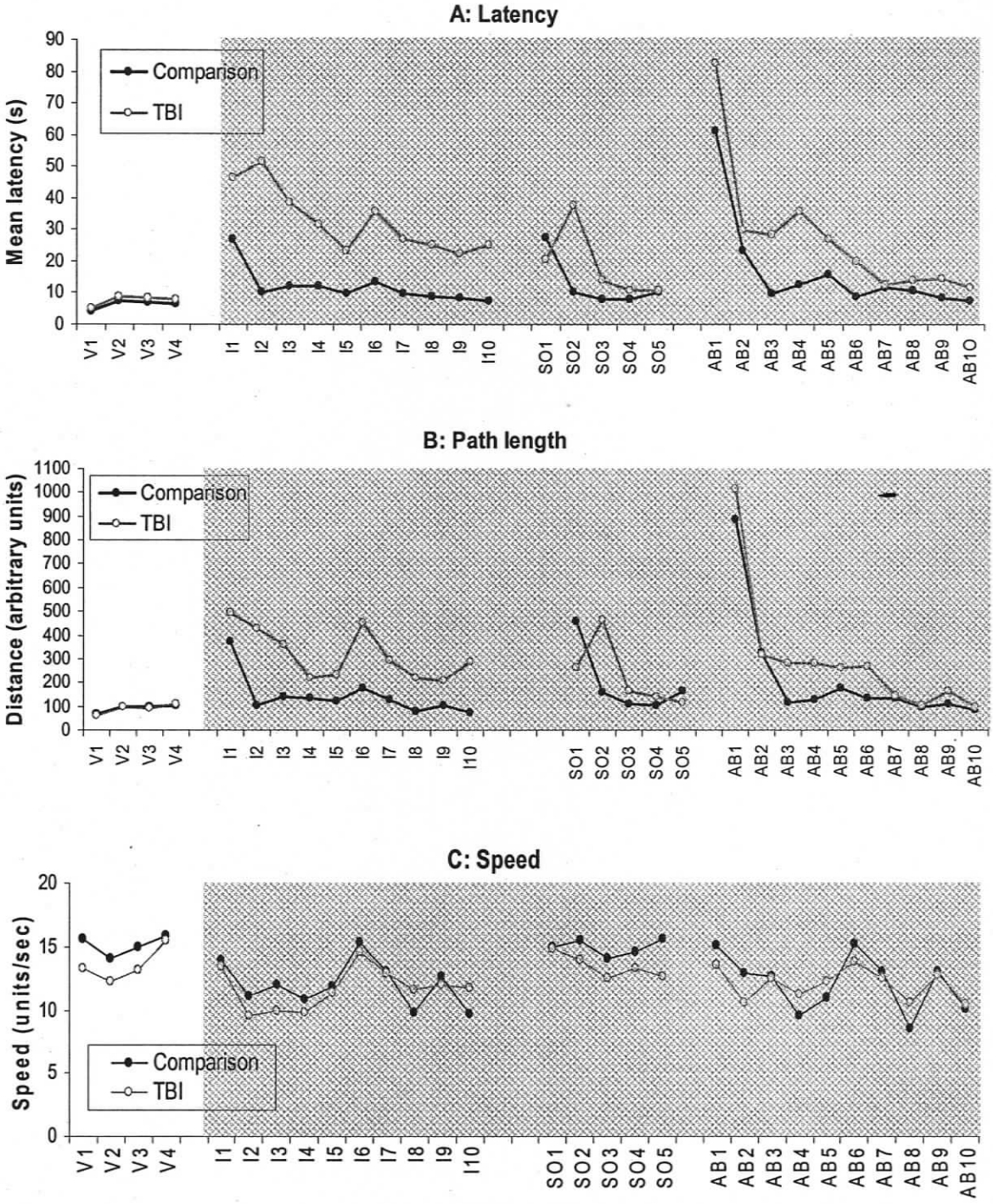
Descriptive Statistics (Means and standard deviations)	
Demographic variables	Age, education and sex
Maze test variables	Latency, distance, speed and probe dwell time and room reconstruction
Screening variables	Video game experience, ESQ, RBMT, Clock drawing task and Where's the Door task
Inferential tests (maze variables)	
Between groups t-tests (latency, distance and speed)	Arena Maze visible trials (trials 1 to 4)
	Arena Maze invisible trials (trials 2 to 10)
	Single Object Maze (trials 1 to 5)
	Ambiguous Maze invisible trials (2 to 10)
Between groups t-tests (dwell times)	Arena Maze and Ambiguous Maze probe trials
Between groups t-tests (spatial scores)	Arena Maze and Ambiguous Maze
Repeated Measures ANOVA (2 x 2 x 2)	First half (trials 2 to 5) and second half (trials 7-10) in Arena Maze and Ambiguous Maze

affect test results. Second, it was difficult to recruit community living comparison participants matching in age, education and gender. Third, the effect size proved to be larger than predicted and so fewer participants were required. For this study, p-values are reported along with their adjustments according to the Hochberg (1988) method that calculates a unique p-value for each comparison.

Results

Spatial learning in the Arena Maze

Visible platform trials. Overall, participants were able to use the game controller successfully and were capable of following instructions in a manner necessary for performance in the virtual mazes. On visible platform trials, the performance of TBI survivors was almost indistinguishable from that of comparison participants. TBI survivors were able to navigate to a visible platform in the arena, as directly and almost as quickly as comparison participants. The TBI survivor group (M = 7.4s, SEM = .55) and the comparison participant group (M = 6.2s, SEM = .14) had different trial latencies $t(20) = 2.15$, $p = .04$(two-tailed), $d = .95$, but the difference was small (see Figure 3) and after correction for experiment-wise error using the Hochberg method (Hochberg, 1988) was not statistically significant (see Appendix K for a table of error calculations for all t-test comparisons). The ranges of mean latencies for the trials were 5.5 to 7 seconds for the comparison participants and 5.25 to 11 seconds for the TBI survivors. It seems unlikely that the average difference of 1.2 s is meaningful. There was no significant difference between the path lengths of the comparison group (M = 91.5 units, SEM = 2.67) and the TBI survivor group (M = 90.6 units, SEM = 2.52), $t(21) = .26$, $p = .8$ (two-tailed), $d = .1$ (see Figure 3). The difference in latency but not path length suggests



Maze trials: V=visible trials, I=invisible trials, SO=single object trials, AMB=ambiguous invisible trials

Figure 3. Average latencies, path lengths and speeds for two groups in all phases ~~of~~ the experiment (visible trials of the Arena Maze are shown in the white panels). A. TBI survivors took slightly longer to reach the platform but the mean latencies of the two groups were within 1.5 s of each other. B. Mean distances travelled by the two groups were nearly identical. C. Mean speeds of TBI survivors were slightly less than those of comparison participants. TBI survivors stopped a little more often than did comparison participants.

that there might have been a difference in speed. TBI survivors (M = 14 units/s, SEM = .78) did have a tendency to stop and look around more often than the comparison participants and therefore had slower speeds than did comparison participants (M = 15 units/s, SEM = .61) but this difference was not significant, t = 1.59, p = .13(two-tailed), d = .64 (see Figure 3). In the mazes, participants move at a constant velocity fixed by the game controller so that 'speed' (seconds per path length unit) simply reflects the amount of stopping between sporadic periods of travel.

Invisible platform trials. TBI survivors tended to take more time to find the platform, taking longer and more circuitous routes. Patterns of individual trial paths illustrate this tendency. In Figure 4 for example, even on the 6th invisible platform trial, the survivor participant SM14 took a very long and circuitous route. In general his paths to the platform were circular rather than the more direct paths of comparison participant CM28. TBI survivors did not travel to the invisible platform as quickly as comparison participants. There was a significant difference in the latency scores between the TBI survivor group (M = 31 s, SEM = 5.14) and the comparison group (M = 10 s, SEM = 1.06), t(21) = 3.51, p = .002 (two-tailed), d = 1.68 (see Figure 5). Note that for all comparisons the appropriate adjustments were made when Levene's test indicated that the assumption of homogeneity of variance had been violated. Mean latency scores were calculated for trials 2 to 10 for both the control and TBI survivor groups. Scores for trial 1 were not included in the calculations because this trial is considered a 'search' trial. Throughout the duration of the search trial participants are unaware of the location of the invisible platform and only acquire this knowledge at the endpoint of the trial, when they

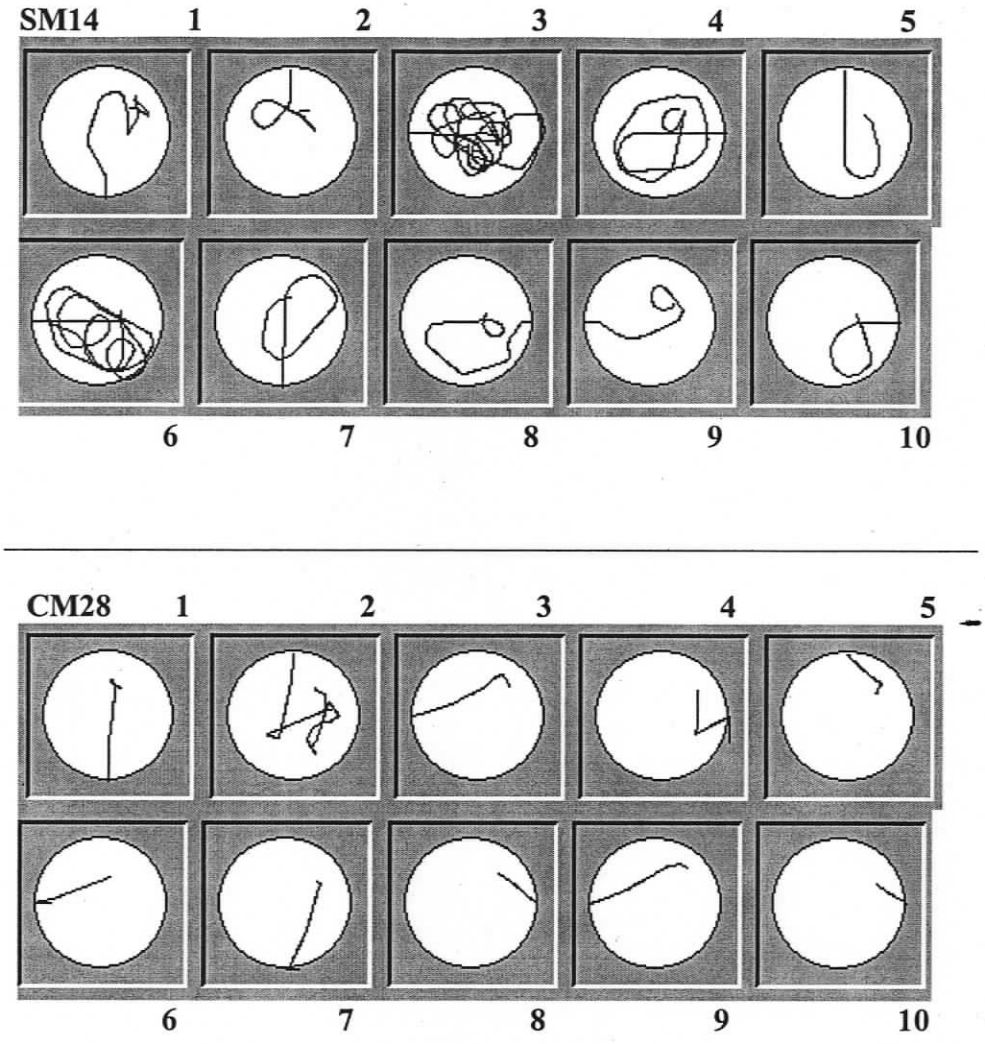
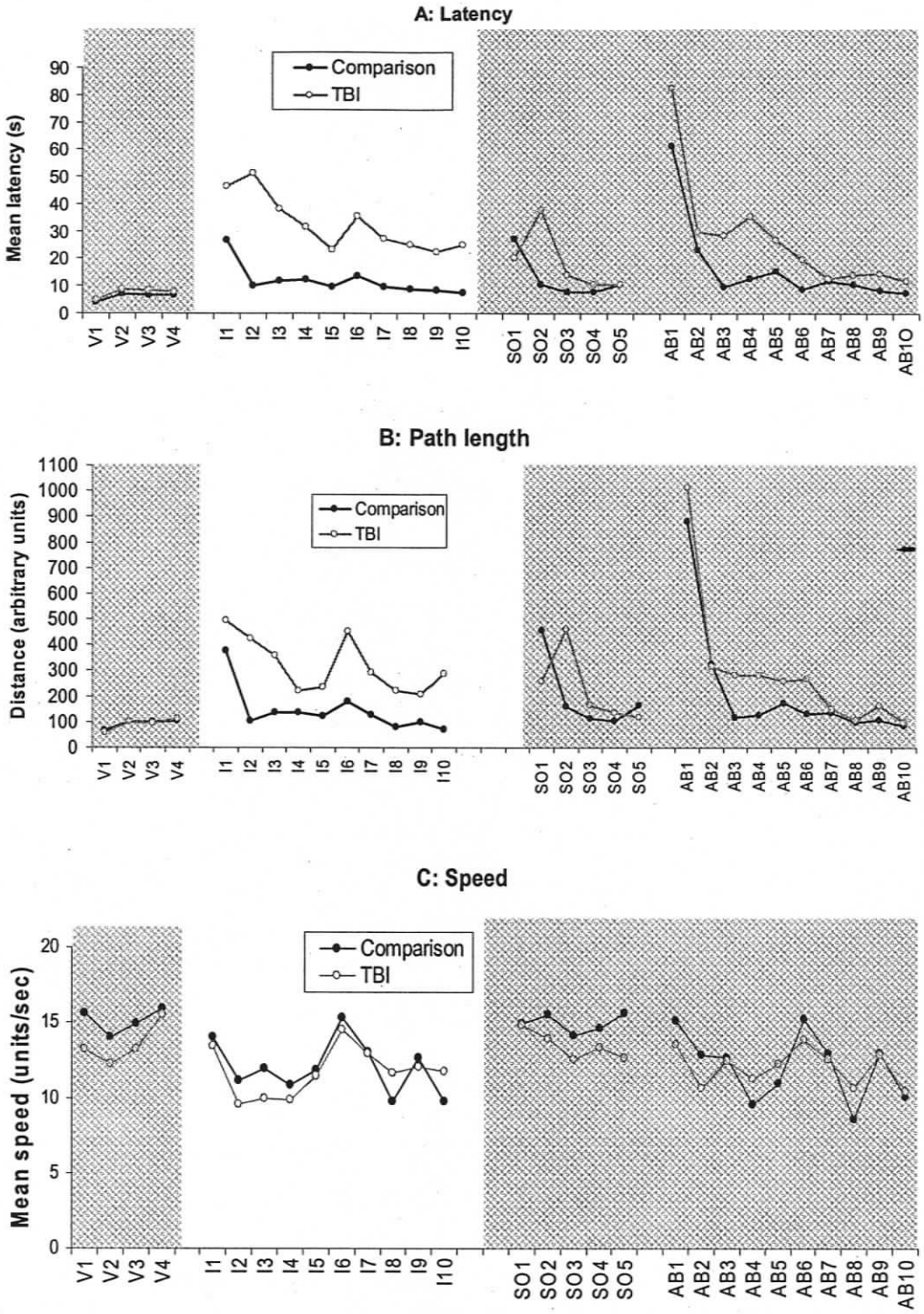


Figure 4: Sample trajectories showing the performance of one comparison participant and one TBI survivor both having individual mean latency scores close to group means. Numbers indicate invisible trials 1 to 10 of the Arena Maze. The target platform location is in the upper right quadrant.



Maze Trials: v=visible trials, I=invisible trials, SO=single object trials, AB=invisible ambiguous trials

Figure 5: Average latencies, path lengths and speeds for two groups in all phases of the experiment (invisible trials of the Arena Maze are shown in the white panels). **A:** In every trial, TBI survivors took more time to reach the invisible platform than did comparison participants. **B:** In every trial TBI survivors took longer paths to reach the invisible platform than did comparison participants. **C:** Note that there were similar speeds (and therefore equivalent amounts of stopping) for TBI survivors and comparison participants.

'step' on the platform's location. Thus, trial 1 does not provide data regarding spatial learning or spatial memory comparable to that provided by invisible trials 2-10. It is important to note that TBI survivors had longer latencies than comparison survivors throughout the entire invisible trial phase and that by invisible trial 10 there was still a mean difference score of 18 s between the two groups. However, TBI survivors did exhibit some learning in the invisible trial phase, as shown by a steady reduction in latency scores from trials 2 to 5 (see Figure 5).

The impaired ability of TBI survivors to locate the platform manifested not only in their latency to find the platform, but also in the path length, or distance they traveled in order to reach it. There was a difference in mean path lengths for trials 2 to 10 between the TBI survivor group (M = 301 units, SEM= 65.22) and control group (M = 118 units, SEM = 13.41) groups, $t(21) = 2.55$, $p = .02$. (two-tailed), $d = 1.1$ (see Figure 5). However, after correction for experiment-wise error using the Hochberg (1988) method the difference was not statistically significant.

The performance of TBI survivors and comparison participants in the invisible trials was very similar in terms of speed (the ratio of latency to distance). Mean speeds of the TBI survivors (M = 11 s, SEM = .88, range = 5 to 14) did not differ significantly from those of comparison participants (M = 12 s, SEM = .59, range = 8 to 14), $t(21) = .76$, $p = .46$(two-tailed), $d = .11$. Figure 5 illustrates the consistency of mean speed scores for the two groups.

Arena Maze probe trials. TBI survivors appeared less certain of the location of the platform as indicated by the percentage of time spent searching in the correct quadrant on the Arena Maze probe trial (see Figure 6). There were differences in dwell times in the

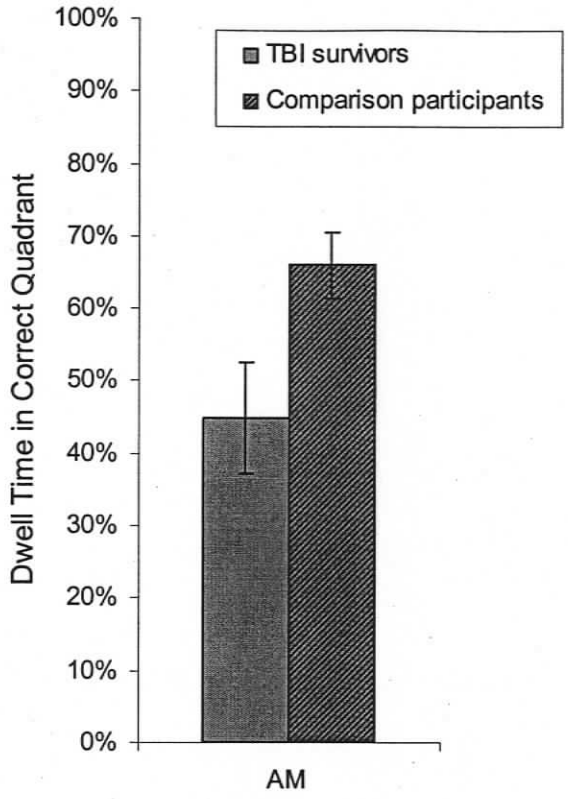
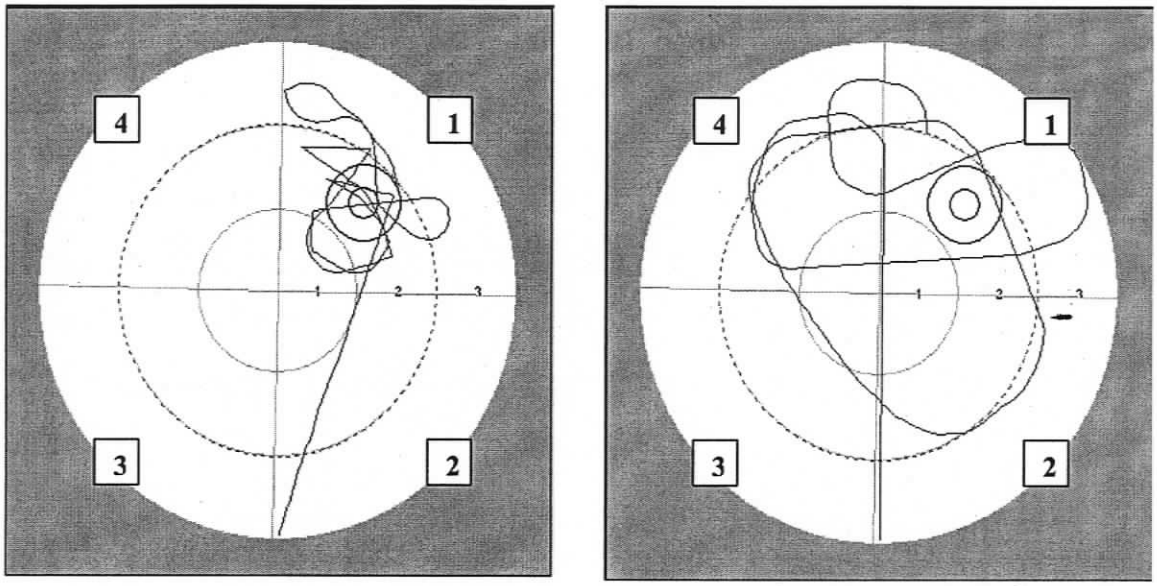


Figure 6: Average percentage dwell times in the correct quadrant for the two groups in Arena Maze probe trials. Note the difference in performance between TBI survivors and comparison participants, although the difference was not statistically significant. Bars indicate standard error of the mean.

correct quadrant recorded from the comparison (M = 66%, SEM = 5%) and TBI survivor (M = 45%, SEM = 8%) groups, $t(21) = 2.25$, $p = .04$(two-tailed), $d = .95$. However, after correction for experiment-wise error using the Hochberg (1988) method the difference was not statistically significant.

Probe trial performance was more variable for the TBI survivors than for the comparison participants. Sample trajectories for two participants with individual dwell times close to group mean dwell times are shown in Figure 7. Overall, the range of dwell time scores for comparison participants was from 46% to 88%, indicating that all spent a minimum of approximately half of their search time in the correct quadrant. For TBI survivors, four participants did not even reach dwell times of 25% (as would be expected by chance) in the correct quadrant and the range of dwell time scores was from 12% to 85%. Individual probe trials of comparison participants all exceeded a value of 25% dwell time in the correct quadrant.

Spatial Scores. Recently, Skelton et al. (2006) developed a spatial score to further assess performance in the virtual mazes. This was in response to the observation that some brain injury survivors showed poor performance in invisible trials 2-10 and passable performance in probe trials while others showed the opposite, that is, poor performance in probe trials and passable performance in invisible trials 2-10. The same is true in the current study, particularly in late trials. The spatial score incorporated measures of latency, distance and probe trial dwell time and was calculated by converting individual scores on each of the three measures to z-scores, using the mean and standard deviation for the comparison group in the calculation. The scores were then combined in



CM27 **SM14**

Figure 7: Sample trajectories of one comparison participant and one TBI survivor in the Arena Maze probe trial. The arena is divided into 4 quadrants and 3 radial annuli as shown. The comparison participant demonstrates more accurately focused searching in the platform location (double circle in quadrant 1) than the TBI survivor, whose search was distributed over two thirds of the arena.

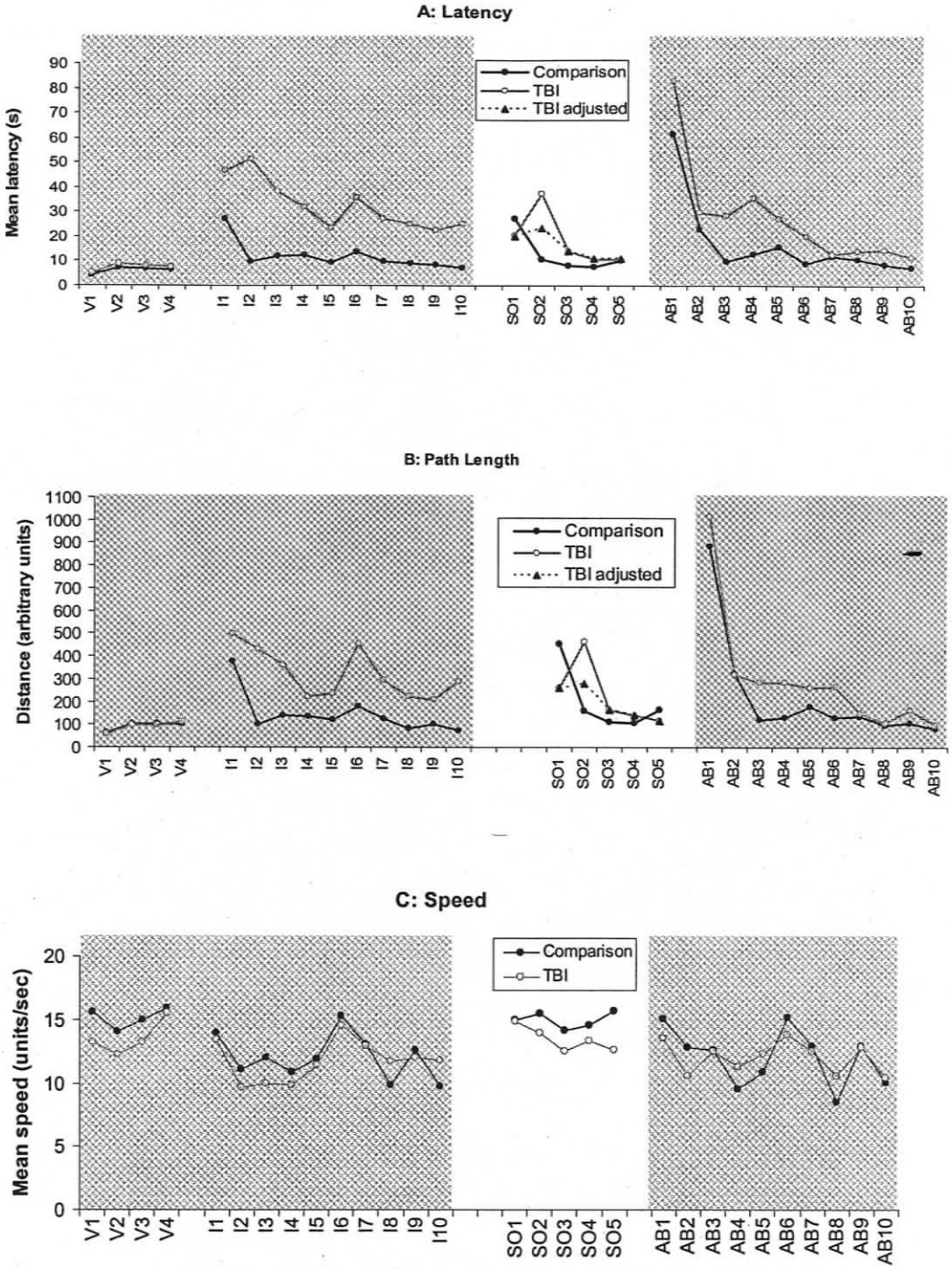
a weighted average equally representing invisible platform trials and probe trials and accounting for the fact that for invisible trials, lower distance and latency scores indicate better performance and for probe trials higher scores indicate better performance. The resulting formula is as follows:

Spatial Score = (.5 x probe z-score) – (.25 x latency z-score + .25 x path length z-score)

When spatial scores were calculated for the current study there was a significant difference between the comparison (M = .00, SEM = .23) and TBI survivor (M = -3.07, SEM = .89) groups, $t(21) = 3.47$, $p = .002$ (two-tailed), $d = 1.4$. Note that the effect size of the spatial score incorporating all three dependent variables (latency distance, probe dwell time) was 1.4 (where 1.0 is a "large" effect). Although this effect was smaller than for latency (with an effect size of 1.68), the spatial score showed that the difference between TBI survivors and control participants was not limited to a single dependent variable, but rather reflected a consistent difference across all three measures.

Training in the Single Object Maze

The 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. After the first two trials, TBI survivors were able to locate the platform as quickly as comparison participants (see Figure 8). Over all trials, there were no differences in latency scores between comparison (M = 11 s, SEM = 1.16) and TBI survivor (M = 18 s, SEM = 3.69) groups, $t(21) = 1.33$, $p = .20$ (two-tailed), $d = .63$. Also, the pattern of learning for TBI survivors closely approximated that of the comparison participants with the exception of the second trial in which one TBI survivor became confused and had a single lengthy



Maze Trials: v=visible trials, I=invisible trials, SO=single object trials, AB=invisible ambiguous trials

Figure 8: Average latencies, path lengths and speeds of the two groups in all phases of the experiment with Single Object trials shown in the white panels. **A:** Mean latencies in Single Object trials are similar for the two groups after the first trial. The dotted line shows results as they would be with the TBI trial 2 mean adjusted to account for a lengthy trial by one participant. **B:** Mean path lengths in Single Object trials are similar for the two groups after the first trial. As for latency, the dotted line shows results as they would be with the TBI trial 2 mean adjusted to account for a lengthy trial by one participant. **C:** Mean speeds after the first Single Object trial differ but only slightly, with TBI survivors being slower (stopping more frequently).

trial. It should be noted that by the third single object trial, 8 of 11 TBI survivors had achieved latencies below 15s, a time that is approximately half of the mean latency achieved on Arena Maze invisible trials. Both TBI survivors and comparison participants traveled directly to the platform in single object trials (see Figure 8) and path lengths of comparison participants (M = 120 units, SEM = 14.25) and TBI survivors (M = 221 units, SEM = 51.32) did not differ significantly, $t(20) = 1.85$, $p = .08$ (two-tailed), $d = .68$. The pattern of performance matched that of latency with performance of the two groups being very similar in the last three trials.

TBI survivors (M = 13 units/s, SEM = .88) had slightly reduced speeds in the Arena maze invisible trials with respect to the performance of the comparison participants (M = 15 units/s, SEM = .59). However this difference in speed was not statistically significant, $t = 1.64$, $p = .12$(two-tailed), $d = .67$. Figure 8 illustrates the consistent but insignificant difference.

Learning in the Ambiguous Maze

Invisible trials. Performance in the Ambiguous maze appeared to involve three stages: first trial, early trials and late trials. In the first trial both TBI survivors and comparison participants spent considerable time (and distance) either examining the eight objects or looking for the platform position in front of the objects as it was in the Single Object Maze. Figure 9 shows two typical search patterns. On the early trials (2-5), TBI survivors were able to go to the platform almost as quickly as comparison participants (Latency = 30 s +/- 6.77 s [SEM] and 15 s +/- 3.37, TBI survivor and comparison groups respectively) (see Figure 10) and there were no significant differences in latency,

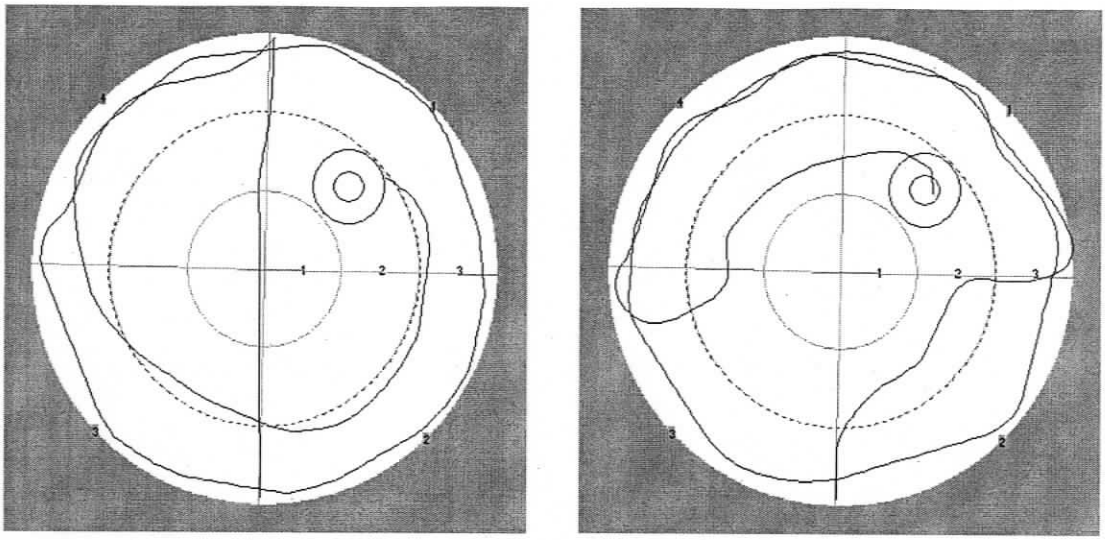
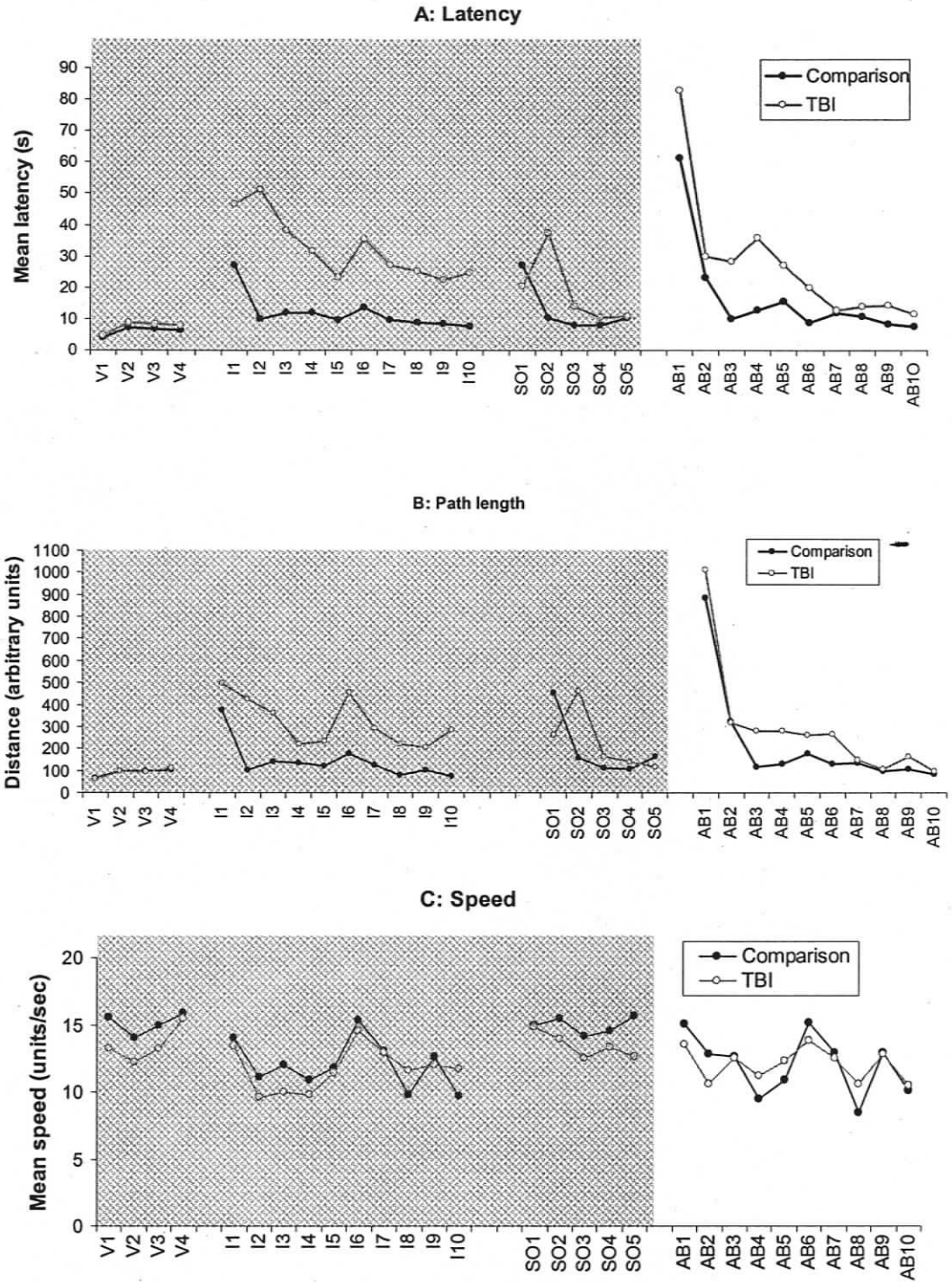


Figure 9: Sample trajectories for two participants in Ambiguous Maze trial 1. The two participants had latency scores approximately equal to the mean group scores. Like most of the participants in both groups, these two individuals circled the arena, going to each object in turn before locating the platform in the northeast quadrant.



Maze Trials: v=visible trials, I=invisible trials, SO=single object trials, AB=invisible ambiguous trials

Figure 10: Average latencies, path lengths and speeds of the two groups in all phases of the experiment with Ambiguous Maze trials shown in the white panels. **A:** Mean latencies in Ambiguous trials are similar for the two groups. **B:** Mean path lengths in Ambiguous Maze trials are similar for the two groups. **C:** Mean speeds in Ambiguous Maze trials are similar for the two groups.

t(21) =1.93, p = .07(two-tailed), d = .79. For comparisons of performance within the Ambiguous Maze, only latency will be reported. However, by late trials (7-10) the difference between TBI survivors and comparison participants was much smaller (Latency = 13 s, +/- SEM = 1.73 and 10 s, +/- SEM = 1.25, TBI survivor and comparison groups respectively) (see Figure 10), and there were no significant differences between the groups (Latency t(21) = 1.69, p = .11(two-tailed), d = .68 .

The group similarities in distance and latency in the Ambiguous Maze were reflected in the speed of travel (Distance/Latency) which was very similar across trials for both TBI survivors and comparison participants. There was no significant difference overall, t(21) = .12, p = .9(two-tailed), between the speeds of TBI survivors (M=12, SEM = .9) and comparison participants (M=12, SEM = .6). The consistency of mean speeds is shown in Figure 10.

Ambiguous Maze Probe Trials. On the Ambiguous Maze probe trial TBI survivors appeared relatively certain of the location of the platform as indicated by their spending 56% of the time in the correct quadrant (see Figure 11, right-hand bars) and were not significantly different from comparison participants (M = 68 +/- 5% versus TBI survivor (M = 56 +/- 6%) groups, t(21) = 1.63, p = .12(two-tailed), d = .63. Sample trajectories for two participants with individual dwell times close to group mean dwell times are shown in Figure 12.

Difference between performances in three mazes

Overall differences. The overall performance of comparison participants in the three mazes was very similar with respect to latency with mean scores of 10, 11 and 12 s

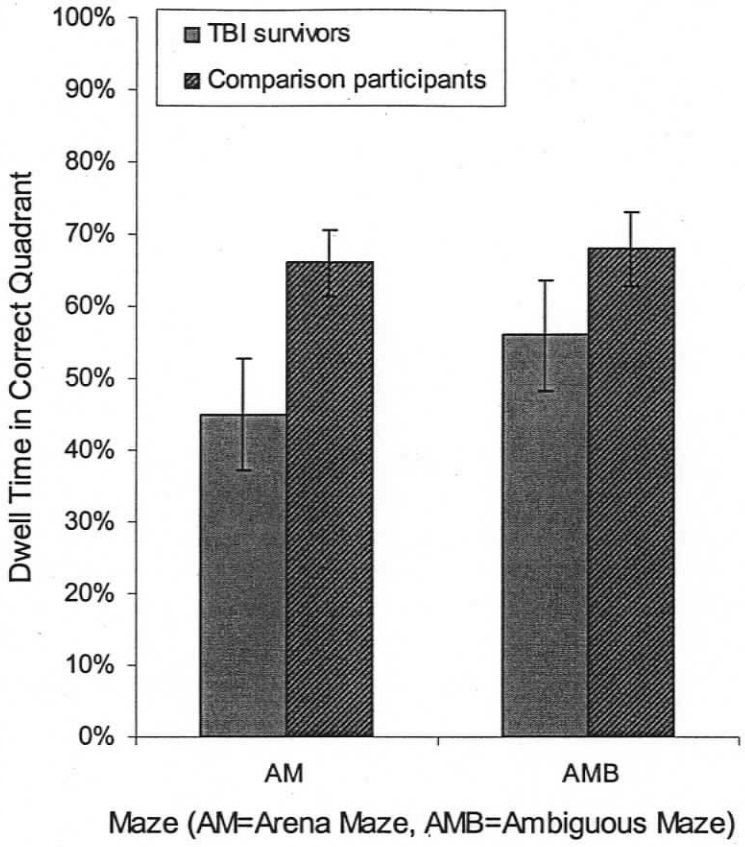
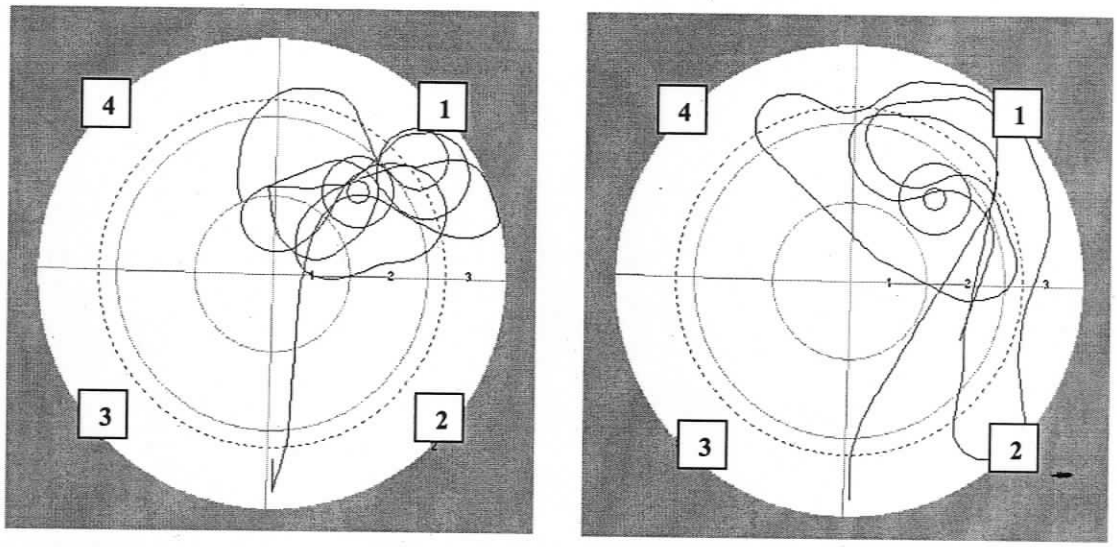


Figure 11: Average percentage dwell times in the correct quadrant for the two groups in Arena Maze probe trials and Ambiguous Maze probe trials. Note the difference in performance of the two groups in the two sets of probe trials becomes smaller after the Ambiguous Maze. Bars indicate standard error of the mean.



CM31 **SM03**

Figure 12: Sample trajectories of one comparison participant and one TBI survivor in the Ambiguous Maze probe trial. The arena is divided into 4 quadrants and 3 radial annuli as shown. The TBI survivor spent nearly as much time in the correct quadrant as did the comparison participant

in the Arena Maze invisible trials, Single Object trials and Ambiguous trials, respectively. However, TBI survivors took less time to reach the platform in the Single Object and Ambiguous trials in comparison to the Arena Maze invisible trials (see Figure 13). Overall in the Ambiguous trials, there was a difference (but not significant after applying the Hochberg method) in latency between the comparison group (M = 12, SEM = 1.98) and TBI survivors (M = 22, SEM = 3.39), t(21) = 2.37, p = .03(two-tailed), d = .99 and no significant difference in path lengths of TBI survivors (Mean =214, SEM = 34.29) and comparison participants (Mean=145, SEM = 23.18), t(21) = 1.66, p=.11(two-tailed), d = .68.

Comparisons of early and late maze performance (using latency as the measure)

One of the important differences between the Arena and Ambiguous mazes (between navigation with and without landmarks) is whether the learning rate was different between these two conditions. This was examined by comparing performance in the early phase of the maze testing (4 trials, 2-5) versus the late phase (4 trials, 7-10) Both TBI survivors and comparison participants were quicker to reach the platform in the late phase than the earlier phase in both the Arena Maze and the Ambiguous Maze (see Figures 3 and 8, respectively). However, for TBI survivors, this difference is more marked in the Ambiguous Maze than in the Arena Maze (see Figure 14). Further, mean scores were similar in late trials of the Ambiguous Maze for both groups.

A 2 x 2 x 2 repeated measures ANOVA was conducted to compare mean performances in the early and late phases of both the Arena Maze and the Ambiguous Maze. There was no main effect of the type of maze (Arena Maze vs. Ambiguous Maze) on latency to the platform. However, there was a significant interaction between maze type

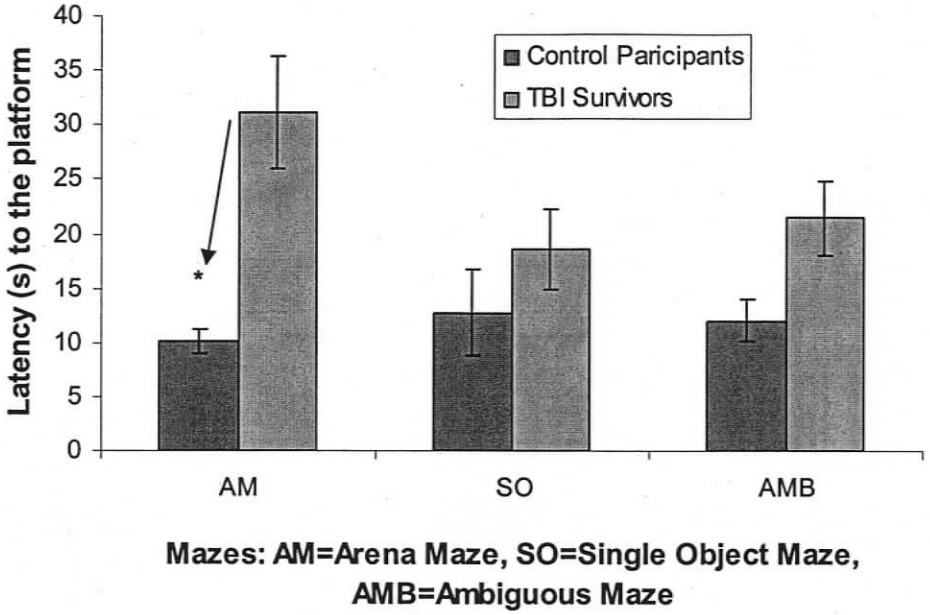


Figure 13: Comparison of performance in the three mazes between the comparison and TBI survivor groups. TBI survivors improve their performance in the both SO and AMB mazes in comparison to the Arena Maze. Control performance is consistent across all three mazes. The asterisk refers to a significant difference.

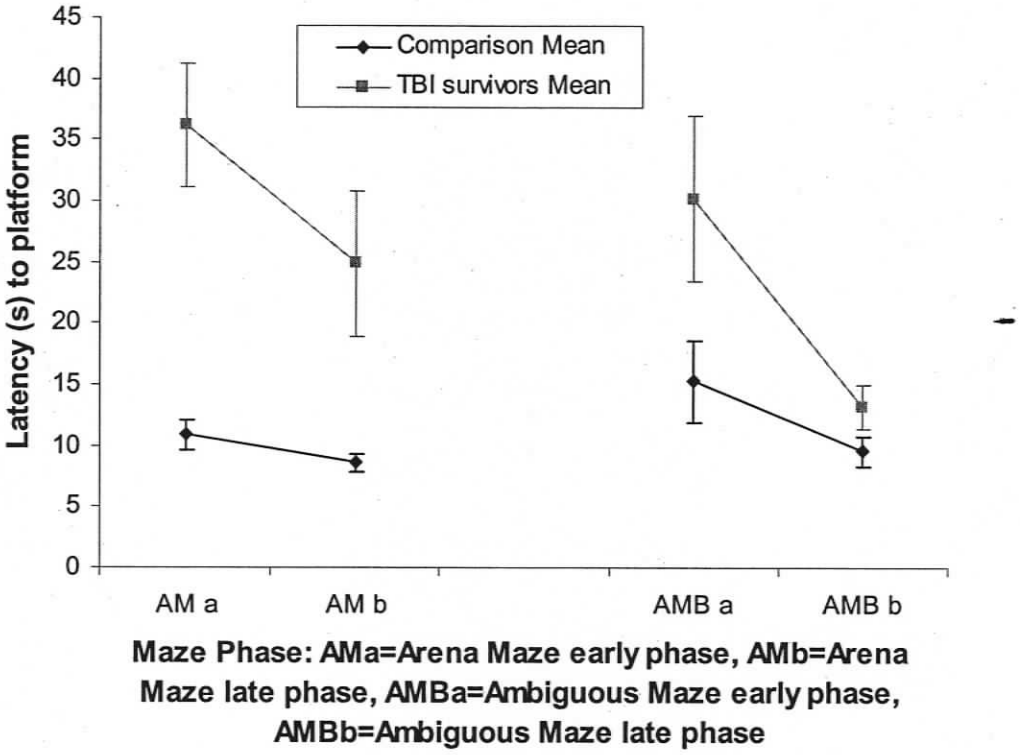


Figure 14: Comparison of mean latency scores in early and late phases of two mazes. Early phase = trials 2 to 5, Late phase = trials 7 to 10. In the second half of the Ambiguous Maze TBI survivors and comparison participants have similar mean latency scores. Bars indicate standard error.

and whether or not the participant had a brain injury, $F(1,21) = 6.97$, $p = .015$ such that for TBI survivors, performance was better in the Ambiguous Maze than in the Arena Maze and for comparison participants performance did not differ appreciably between the two mazes . There was a significant effect of maze phase such that overall, latencies in the later trials of the mazes were lower than latencies in earlier trials, $F(1,21) = 21.29$, $p = .001$, as would be expected if learning has taken place. Finally, there was a significant interaction between phase and whether or not the participant had a brain injury, $F(1,21) = 6.65$, $p = .017$, such that TBI survivors improved their latency scores from the first to second half of both the Arena Maze and the Ambiguous Maze, while comparison participants did not. The ANOVA results demonstrate that there was a floor effect in the comparison group for performance in the mazes and that in the late phase of the Ambiguous Maze, TBI survivors reached this level of performance. For TBI survivors, the rate of learning (as reflected by latency to find the platform) in the Ambiguous Maze was greater than the rate of learning in the Arena Maze whereas the learning rate was stable across the two mazes for comparison participants (see Figures 11 and 12).

Non-maze variables

'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. Eleven comparison participants (92%) and 7 TBI survivors (64%) scored perfect scores of 3 by pointing to a door position behind themselves (see Figure 15). Four TBI survivors and one comparison participant) pointed either to the side or just in front of their bodies (scoring a 2) . No participants scored 0 or 1, (as if the virtual room

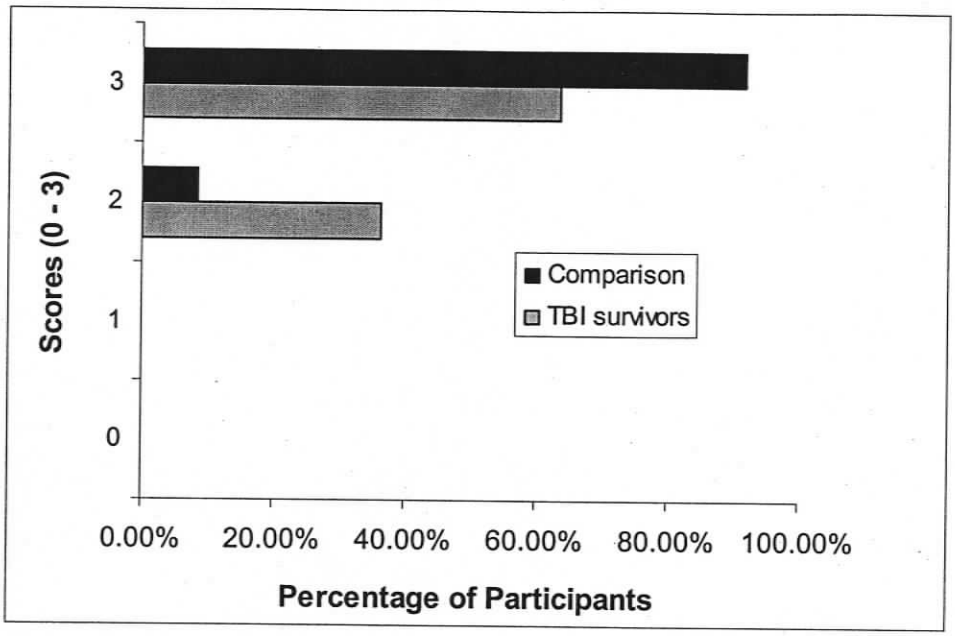


Figure 15: Results of 'Where's the door' task showing that the majority of both comparison participants and TBI survivors pointed behind (score of 3) or beside(score of 2) themselves when asked to indicate the location of the door in the virtual space. No participants pointed at the computer screen (score of 1) or did not know the location of the door (score of 0).

was inside the display screen) indicating that they all felt as if they were inside a 3 dimensional virtual room.

Room reconstruction task. The results of the Room Reconstruction test were surprising. All comparison participants were expected to achieve perfect (or near-perfect) scores on this test, and yet only 58% of comparison participants were able to position all four walls and the platform correctly (see Figure 16). An additional 33% were able to correctly align the four room walls without judging the platform properly. This suggests that the room configuration was learned but that the platform position was not as strongly connected to it as previously observed for the Arena Maze (Skelton et al., 2000b). When tested after the Ambiguous Maze, only 36% of TBI survivors were able to reconstruct the virtual room and platform location correctly, while an additional 45% of TBI survivors correctly aligned the room walls. Two TBI survivors (18%) and one comparison participant (8%) demonstrated poor knowledge of the configuration of the virtual room, scoring 0 on the task.

Performance on the room reconstruction task was correlated with performance in the Arena Maze probe trial ($r = .44$, $p < .05$) but not with other tests where spatial cognitive ability might be a factor (for example the Everyday Spatial Questionnaire and self report of computer game experience). Also, the correlation of room reconstruction scores and route scores on the RBMT approached significance ($r = .40$, $p = .06$), suggesting that the ability to recall the configuration of the virtual space is related to the ability to learn short routes in real space. However, because of the large number of correlations conducted, no firm conclusions can be drawn about the relationship of the Room Reconstruction task to spatial ability.

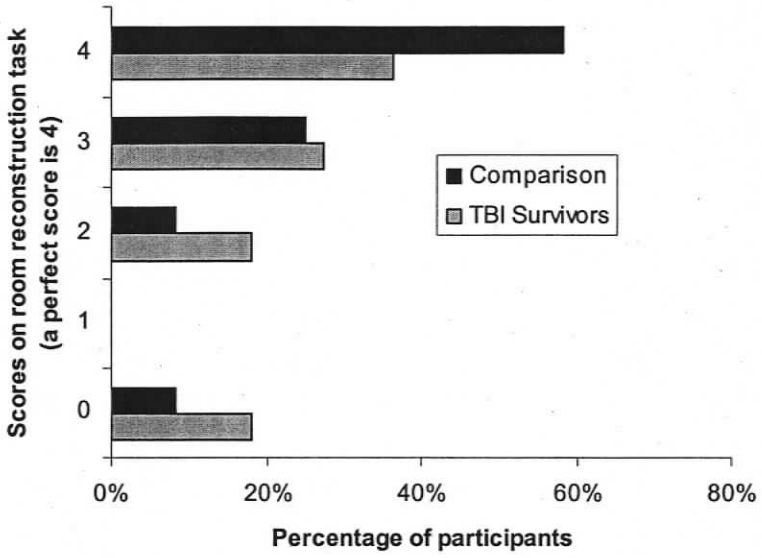


Figure 16: Comparison of scores for two groups on the room reconstruction task. A higher percentage of comparison participants (compared to TBI survivors) were able to recall the relative locations of the walls and the location of the platform in the correct hemisphere of the arena (score of 3) or in the correct quadrant (score of 4). Scores of 0, 1 or 2 indicate no knowledge of the platform location and limited knowledge of the configuration of the room based on recalling relative locations of either 2 or 4 walls.

Object Recognition task. TBI survivors and comparison participants were equally able to recognize objects from the Ambiguous Maze when asked within 15 minutes of completing the task (see Figure 17). Signal detection analysis was applied and indicated hit rates of .53 for TBI survivors and .62 for comparison participants, showing that around half of the objects present in the Ambiguous Maze could be recognized by either group after completion of the task. False alarm rates for both groups were low (TBI rate = .15, comparison rate = .08) and sensitivity was good for both groups (TBI d' = 1.1, Comparison d' = 1.7), suggesting that both groups were able to discriminate between target objects that were either present or absent from the virtual room. These results imply that there were no deficits in object memory for either experimental group.

Further analysis of the recognition of objects considered relevant to the solution of the Ambiguous Maze indicated that 90% of both TBI survivors and comparison participants recognized the cue object (golden urn) which was the one closest to the platform location (see Figure 18) 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. Only one TBI participant was unable to recognize any of the objects in the vicinity of the platform. Results indicate no impairment in object memory and recognition of salient objects that could have contributed to maze performance in this study.

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. However, TBI survivors (M = 54.02,

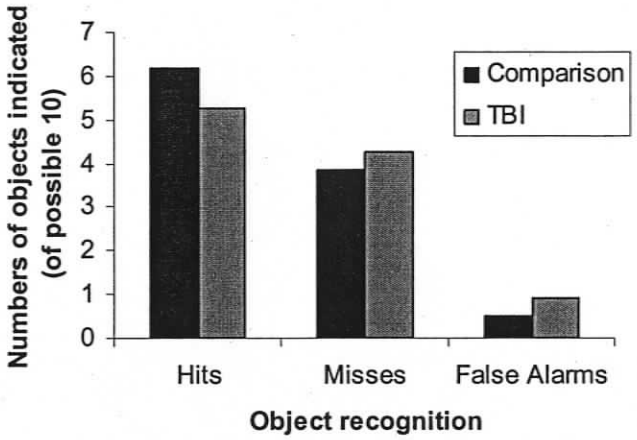


Figure 17: Comparison of performance in the object recognition task following the Ambiguous Maze. Both groups had roughly equal mean numbers of objects correctly identified (hits), objects not identified (misses) and objects incorrectly identified (false alarms).

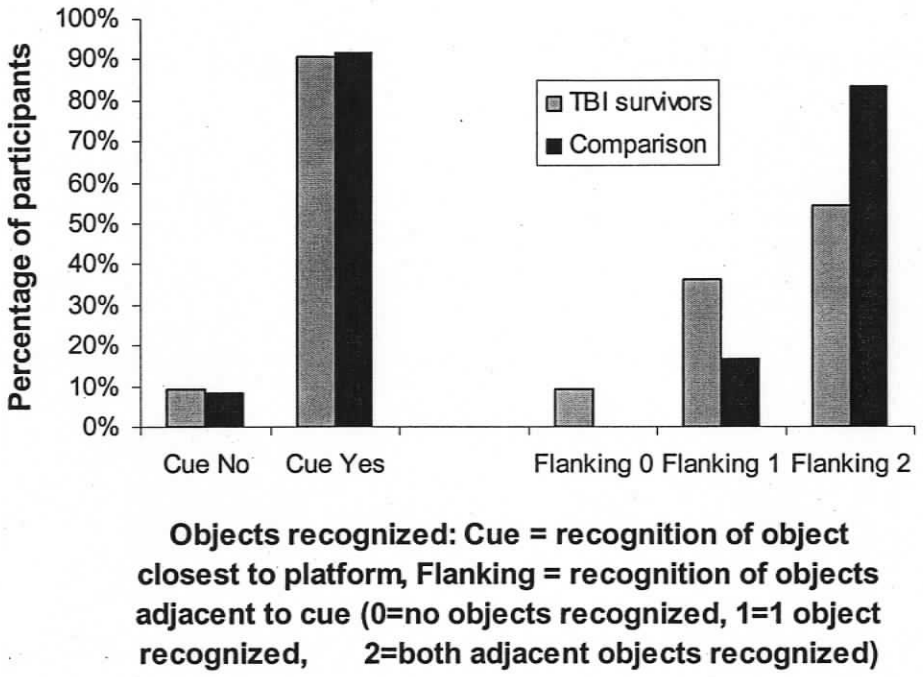


Figure 18: Objects recognized after completion of the Ambiguous Maze task. 90% of participants in both groups identified the most proximal cue object ('golden urn'). More than half of participants in both groups were able to identify the two objects on either side of the salient cue object.

SEM =8.0) and comparison participants (M = 42.6, SEM = 4.2) did not have significantly different scores on either the overall spatial questionnaire or the two sections pertaining to object location and navigation. The largest differences between the groups were in response to questions 9 (routes and shortcuts) and 11 (losing car in parking lot). Comparison participants (M = 7.54, SEM = .64) reported more frequent use of shortcuts and new routes than did TBI survivors (M = 5.77, SEM = .82) and comparison participants (M = 2.05, SEM = .82) reported losing their cars in parking lots less frequently than did TBI survivors (M = 4.38, SEM = 1.14). Three TBI participants do not drive but of the remaining eight, half reported losing their cars very frequently (more than 50% of the time). For comparison participants, only two of twelve individuals reported losing their cars more than 50% of the time.

Neuropsychological Tests

Rivermead Behavioural Memory Test. There was a significant difference in scores obtained on the RBMT by the TBI survivors (M = 15.0 , SEM = 1.6) and comparison participants(M = 19.4, SEM = 1.0), $t(21) = 2.33$, $p = .03$. Compared to test norms, the profile score of 19.4 for the comparison group in this study, was slightly lower than the mean score of 22.2 for the norm group. For TBI survivors the score of 15.09 was higher than the score of 12.89 drawn from a sample of patients with uniformly severe closed head injuries (coma > 48 hours).

Clock Drawing Task. TBI survivors scored almost as well as comparison participants on the clock drawing task (9.5 vs. 10 out of 10). Specifically, seven scored 10, two scored 9 (for slight misplacement of hands on the clock face) and two scored 8 (for misplacing one of the hands or for a gap in number placement). The difference in

performance between the two groups was not significant and there were no apparent visuo-spatial deficits that could have interfered with maze performance.

The Bells Test. This test was implemented only after the majority of data from the TBI survivors had already been collected and provide further (but limited) indication that spatial deficits (especially hemi-neglect) did not influence the results of the study. TBI survivors (n = 3) who completed the test had scores of 31, 31 and 33 (from a total possible of 35). The mean score of comparison participants (n = 10) was 31.2. Because these results are preliminary, no further interpretations were made.

Strategy selection

Comparison participants more frequently reported using room cues and finding the platform by its location in the room than did TBI participants (see Figure 19). Participants were asked specific questions with regard to the objects they used to find the platform in the Ambiguous Maze and also what aspects of the room they may have used. Any additional comments were recorded and participants were encouraged to give a full explanation of how they found the platform. Both TBI survivors (64% or n = 7 individuals) and comparison participants (75% or n = 9 participants) reported use of the cue object (golden urn) to locate the platform, as well as less frequent use of adjacent objects. Only 27% (3 individuals) of TBI survivors reported using any aspect of the room or the outer world to locate the platform but 50% (6 individuals) of comparison participants reported using room cues (with 3 comparison participants reporting multiple use of these cues). Also, no TBI survivors reported finding the platform "by the location of the platform in the room" but 50% of comparison participants reported doing so.

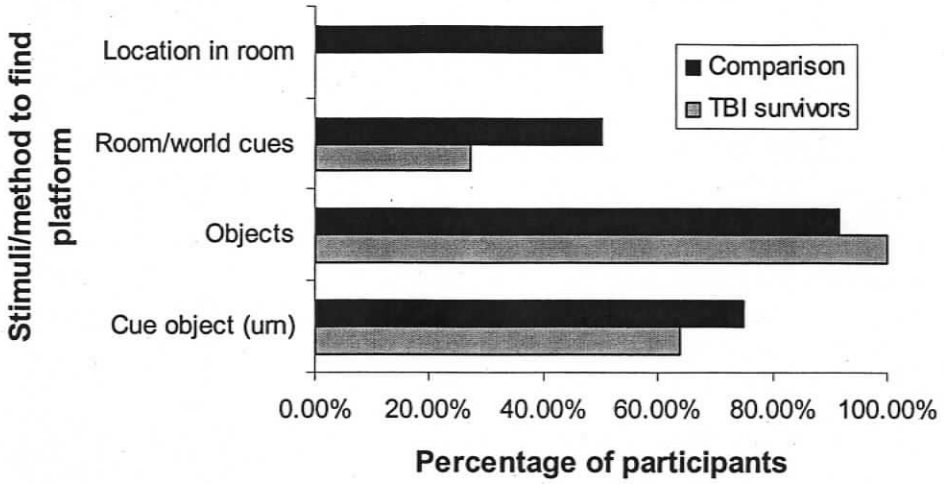


Figure 19: The use of locational landmarks or room cues during the Ambiguous Maze task. Note that TBI survivors used locational landmarks and rarely reported using room cues, whereas comparison participants used both locational landmarks and room cues.

The strategy questions represent one approach to understanding the strategies that participants may use to navigate to an invisible target location when given the option of doing this via proximal or distal cues. Other behavioural tests (such as a recently developed 'Drop the Seed' trial) (unpublished test) may better reveal the strategic approach (either object use or room/outside world use) when finding the platform in the Ambiguous Maze.

Discussion

Participants with moderate to severe TBI were tested in a virtual environment and were able to learn the location of an invisible platform (target) as well as comparison participants, as long as a single locational landmark or a set of locational landmarks were made available. However, they were less able to learn the location of the target when relying on only the surrounding environment and in the absence of locational landmarks. These results were consistent with the three experimental hypotheses that:

1. TBI survivors would be less capable than comparison participants in the Arena Maze task.
2. TBI survivors would perform as well as comparison participants in the Single Object Maze task.
3. TBI survivors would perform nearly as well as comparison participants in the Ambiguous Maze task.

Summary of maze performance

In the first four trials of the Arena Maze, the target location (platform) was immediately visible to participants as they entered the room. TBI survivors performed as well as comparison participants on these trials and were able to navigate directly to the

platform taking similar times to reach it. In contrast, when the platform was made invisible TBI survivors had difficulty learning its location, even after 10 trials, while comparison participants learned its location almost immediately and were able to navigate to it more quickly and directly than TBI survivors. In the Single Object trials, TBI survivors performed as well as comparison participants on the task of locating the invisible target adjacent to a single landmark (a steel box perched on the edge of the arena wall) that is, they arrived at the platform as quickly and directly as did comparison participants. In the Ambiguous Maze invisible trials TBI survivors were able to locate the platform as quickly and directly as comparison participants and were almost indistinguishable from comparison participants in later trials (the last four).

Procedural aspects

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. Potentially, interference could have resulted from executive function problems, verbal memory problems, object recognition/memory deficits, attentional deficits, vestibular problems, fatigue or simple motor difficulties with the game controller. However, none of these factors appeared to significantly influence maze performance.

The roughly equivalent performance of the two groups in visible trials indicates that TBI survivors were able to understand, remember and execute task instructions. Procedural problems could have been expected to interfere with latency to find the platform but TBI survivors had no trouble recalling the instructions or staying on task. Further, the visible trials demonstrated that TBI survivors were able to make very basic

stimulus response associations, in this case traveling directly to an important landmark (cue) in the virtual environment.

Object recognition/memory was not detrimental to maze performance as indicated by TBI survivors being able to identify the same numbers of objects present and absent from the Ambiguous Maze as were comparison participants. Also, the identification of the most salient objects was nearly identical for the two groups. Thus it can be inferred that neither executive function deficits nor memory problems interfered with basic performance in the virtual mazes.

Another concern with the TBI population is the potential for spatial neglect ~~as~~ a result of injury (including more subtle forms of neglect) that could interfere with the ability to navigate. According to the clock drawing task, TBI survivors showed little evidence of spatial neglect that might have interfered with performance. This is important because at least one study involving TBI survivors with and without hemi-neglect, showed that neglect may adversely affect navigation in real space (Guariglia et al., 2005). The authors of the study tested their participants for neglect by having them complete a battery of neglect tests (Pizzamiglio et al., 1992) and then required them to navigate to an invisible target location in a real room from varying start points. Patients who showed signs of neglect had more difficulty with the navigation task. However, more subtle forms of neglect may not be detected by either the clock drawing task or the aforementioned neglect battery and more sensitive testing may be required to reveal such deficits. The late introduction of the Bells Test (a cancellation task)(Gauthier et al., 1989) in this study was in response to the concern about subtle neglect problems but not enough

data were collected to address the issue adequately. Future use of the Bells Test in combination with simple computer based neglect tests may resolve the issue.

Neither TBI survivors nor comparison participants experienced any serious problems with fatigue or dizziness (vestibular problems) during testing. Four participants (two from each group) reported mild visual effects when looking away from the screen and two TBI survivors reported mild fatigue during the Arena Maze trials. Participants were observed for signs of fatigue and reminded at the end of each maze task, that they had the option to take a break from testing. The use of the game controller presented no particular problems for either the TBI survivors or the comparison participants. Both reported equal experience with game controllers, joysticks and computer games prior to testing. Also, there were no motor problems with the use of the controller with the exception of one participant who has a right hemiplegia. In this case the controller was taped to the table in front of the monitor so that the participant could easily use his left hand to operate it. He reported no problems with this method and was comfortable throughout the testing session.

Finally, the lack of counterbalancing did not seem to affect the outcome of the experiment. All participants were run in the same order, that is, Arena Maze then Single Object Maze then Ambiguous Maze. This order was selected as a training type approach designed to investigate what aspects of spatial cognition remain intact for survivors of TBI. Also it was by no means clear that TBI survivors would be able to perform successfully in the Ambiguous Maze due to the complexity of the environment. An indication that the order of the mazes did not influence the outcome of the experiment is that the first few trials of the Ambiguous Maze were lengthy for both groups, suggesting

that comparison participants were not able to immediately transfer knowledge of the Arena Maze into the Ambiguous Maze trials. Further, the learning curves of the comparison participants were very similar for the two mazes.

Some limitations

Analyses and statistical power

The power to detect group differences between comparison participants and TBI survivors may have been compromised by the smaller than anticipated sample size. Post hoc analyses revealed that the power to detect effects for the main hypotheses was .71, slightly lower than the desired .80 (A sample size of 32 would be required to achieve this figure). Because the TBI sample was drawn from the Vancouver Island Head Injury Society membership and because some participant data had to be removed from the sample, the value of n was smaller than desired. Also, the study suffers from the normal limitations of group studies in that it does not provide information about the wayfinding abilities of individual TBI survivors. Such information would be useful in both assessment and rehabilitation.

Specific research implications

The group differences in latency and distance in the Arena Maze are consistent with those found in previous work (Skelton, 2000) using the Arena Maze with the TBI population. However, the mean differences reported between TBI survivors and comparison participants are less pronounced (i.e. effect sizes are smaller), perhaps due to differences in severity of injury. According to verbal report of post traumatic amnesia and coma duration, the majority of TBI survivors in this study were severely injured but some were only moderately injured. The inclusion of moderately injured participants may have

influenced the outcome and if so, this information is important for the design of future studies investigating spatial deficits. The smaller observed effect sizes also extended to the probe trial analysis, suggesting that group differences in knowledge about the virtual environment were less pronounced in this study than in earlier ones.

Wayfinding without locational landmarks

In the absence of locational landmarks, TBI survivors had difficulty locating the invisible target platform when it was repeatedly in the same position and when they had been told that it would always be in the same place in the arena/room. For example, on the last of 10 identical trials TBI survivors took a mean of 25 s to locate the invisible platform, while comparison participants had a mean latency to the platform of only 7 s. Previous studies with university undergraduates (unpublished data) and a small number of older participants (Skelton, 2000) indicate that latency scores of greater than 15 s rarely occur in the comparison population but for this experiment, TBI mean latency scores in the Arena Maze invisible trials were in excess of 20 s each. Interestingly, TBI survivors sometimes verbalized the nature of their difficulties in the Arena Maze invisible trials and some typical comments were: 1)"I lucked out finding it", 2) "I'm losing where I'm going", 3)"I forgot where I started", and 4) "I'm totally messed up because the windows are changing". Such comments were not commonly present for the comparison participants.

There were other indications that TBI survivors were impaired in their knowledge of the virtual space. For example, in the probe trial (after the invisible platform trials), TBI survivors spent less time than comparison participants searching in the correct quadrant of thearena. Also TBI survivors were less able than comparison participants to

physically reconstruct (using a paper model) the main features of the room and platform location after completion of the maze tasks. The question remains, why did TBI survivors have difficulty navigating in the Arena Maze invisible trials, that is, what is the nature of the cognitive deficit observed? To answer this question, the study used two additional tasks to test for wayfinding abilities that might be spared after TBI.

Navigation to a single locational landmark

TBI survivors were able to navigate using a single locational landmark. They were consistently able to find an invisible platform next to a single salient landmark object (a steel box perched on the arena wall) even though the landmark object changed location from trial to trial. Latencies and distances to the platform were slightly longer than for comparison participants but not significantly so. These results suggest that the deficits observed in the Arena Maze invisible trials were not due to an inability to associate a target location with a single landmark.

The Single Object Maze trained participants to use a single landmark to locate an invisible target platform very close by and thus tested the ability to associate the location of the platform with a single landmark. The single object trials (like the visible platform trials) were considered to be simple stimulus-response trials but slightly more difficult than the visible trials in that the cue is removed from the platform location and the location of the platform is initially invisible. It was by no means certain that TBI survivors would perform well in the in the single object trials but they did so with relative ease. Consequently, the single object trials can also be considered a control with respect to the later ambiguous trials that presented an array of objects in the virtual environment.

Navigation in the presence of positional landmarks

TBI survivors were able to navigate using positional landmarks even when multiple landmarks were introduced into the virtual environment. This was a surprising result given the increased complexity of the Ambiguous Maze that required TBI participants to select from among eight objects and a variety of room cues in order to locate the platform. TBI survivors exhibited latencies and distances that did not differ significantly from those of comparison participants in the Ambiguous Maze and closer examination of the results revealed some interesting points. Both groups had lengthy first trials indicating that the comparison participants saw the task as new and did not immediately apply their spatial knowledge of the Arena Maze to locate the platform. There was considerable evidence that both groups searched systematically near the objects in the first ambiguous trial and therefore were applying knowledge gained in the Single Object training trials to the solution of the Ambiguous Maze. However, comparison participants reached the platform more quickly and directly than TBI survivors on the early trials, indicating that they may have begun using their knowledge of the environment to find the platform. The most surprising result, however, was that in later trials the performance of the two groups became almost indistinguishable. This would indicate that TBI survivors had acquired sufficient knowledge of the environment to find the platform efficiently.

It was uncertain whether TBI survivors would be able to succeed at the Ambiguous Maze task, but they performed as well as comparison participants. Therefore the deficits observed in the Arena Maze invisible trials were likely not due to the complexity of the environment or to the ability of participants to navigate in the presence of both positional and directional cues. But how were TBI participants able to find their way as well as

comparison participants in the virtual Ambiguous Maze with its multiple landmarks when they could not find their way in the virtual Arena Maze, which consists of the same basic environment and contingencies (without locational landmarks)? That is, if there are no differences between the two groups in Ambiguous trials, what is the nature of the deficit observed in the Arena Maze invisible trials?

One explanation of the varying performance in the maze tasks is that some comparison participants may have used different navigational strategies based upon the specific demands of the Arena Maze and Ambiguous Maze tasks while TBI survivors may not have had the ability to do so. Some evidence for this comes from the results of the Room Reconstruction task conducted after completion of the Ambiguous Maze. The performance of the comparison participants was surprisingly poor on this task and was inconsistent with performance of this task in previous work (Skelton et al., 2000b). However, because the task was not given directly after completion of the Arena Maze (as in previous studies) it would seem that some knowledge of the virtual space might have been lost or become less important to the comparison participants during navigation of the Ambiguous Maze. In other words, the change to a task that can be solved using an egocentric navigational strategy influenced how much allocentric knowledge was retained or applied. The variable performance of the TBI survivors in the maze tasks might then be attributed to the absence of allocentric spatial knowledge. This seems to be summed up in a very revealing comment made by one TBI survivor during the Ambiguous Maze trials, "I just use my close-up world".

A deficit in cognitive mapping?

The cause of the spatial deficits apparent in the TBI group in the Arena Maze invisible and probe trials is not known, however, it is proposed that TBI survivors had difficulty constructing, remembering or using cognitive maps of large-scale space during spatial navigation. The cognitive mapping theory proposed first by Tolman (1949) was based on research with rats and on animal models of learning and memory, but later expansions of the theory by O'Keefe & Nadel (1978) have gradually led toward the conclusion that the theory has implications for the study of human spatial ability. Accordingly, cognitive maps are thought to provide for flexibility and accuracy during navigation to a goal and may therefore be an expedient mechanism for purposes of wayfinding not only in rats but perhaps in humans too. O'Keefe & Nadel (1978) asserted that cognitive maps are formed quickly and constitute 'information structures' (p.78) from which visual images of the environment can be generated. These information structures are flexible and useful as long as minimal details of the environment (say two or three cues) remain constant and map construction is mediated by a specialized locale system. Cognitive maps allow organisms to accurately predict the location of hidden targets and to form novel routes to target locations in the environment from viewpoint independent (allocentric) perspectives. Without access to a cognitive map, it would be expected that the search for a hidden target would take longer and be less direct, as seems to be true for TBI survivors.

The MWM has proven to be a useful tool for testing the cognitive mapping theory as it applies to rodents. Normal performance in the maze has provided a standard against which deficits in spatial performance can be measured. Typically, normal healthy rats

learn the location of a hidden platform in milky water after about 8 trials and navigate to it (from varying start positions) quickly and directly on successive trials (see for example Skelton, 1998). Such performance generates learning curves with steep drops in latency and distance (between the first and eighth trials) to 'floor' values that represent the quickest or most direct way in which the rat can find the target platform. Also, on probe trials, healthy rats spend significantly more time searching in the correct quadrant of the arena than would be expected by chance (Skelton, 1998). In contrast, rats with brain injuries show deficits in MWM performance, resulting in impaired learning curves where time or distance to the invisible platform does not reach control levels (see for example, Skelton, 1998; Kolb, Sutherland & Wishaw, 1983) at least in the first few weeks after injury. Similarly, in probe trials, brain injured rats do not spend more time searching for the platform in the correct quadrant of the arena than would be expected by chance (Skelton, 1998). Since the MWM is thought to test spatial learning and memory, the poor performance of the brain injured rats may be due to the inability to form, remember or use cognitive maps.

In the invisible trials of the Arena Maze, comparison participants learned the location of the hidden platform very early on (after one trial), suggesting that they quickly formed an information structure (possibly a rough cognitive map) sufficient to find the hidden location on all successive trials. The learning curve generated by comparison participants' performance mirrors that of normal rats in the MWM and on probe trials, comparison participants had a mean dwell time in the correct quadrant that was significantly different than would be expected by chance, indicating that they were able to identify the correct location of the hidden target platform. In contrast, TBI

survivors took up to 7 trials to learn the location of the platform and never found the platform as quickly and directly as comparison participants. The learning curve generated by the performance of TBI survivors is similar to curves generated by the performance of rats with experimentally induced brain injuries (for example, Skelton 1998). On probe trials, TBI survivors spent more time searching in the correct quadrant than would be expected by chance but this was due to the performance of two survivors who exceeded the mean score for comparison participants. It seems as though TBI survivors were unable to form a configuration of directional cues (i.e. features of the room and outside environment) that would allow them to construct cognitive maps or that they were unable to remember or use such configurations. On the face of things, then, it looks as though TBI survivors may have a cognitive mapping deficit.

Bennet (1996) argues that most demonstrations of short-cutting ability that purport to show cognitive mapping in rats could be due to simply going to a goal-proximal cue (dead reckoning) or cognitive mapping demonstrations can be explained by path integration which requires distance and direction information to be combined with movement while navigating. However, this latter interpretation has recently been incorporated as an essential component of cognitive mapping (Jacobs & Schenk, 2003). It may be that understanding the environment from more than an egocentric prospective provides the necessary flexibility for animals (and humans) as they move/navigate. This flexibility would allow for navigation to occur more quickly and directly and for novel approaches to wayfinding problems.

A hierarchical framework for conceptualizing spatial cognition comes from Maguire et al. (1996) who described three stages necessary for acquisition of knowledge

about the environment as follows: 1) recognition of important objects (landmarks), 2) the development of route knowledge (through the connection of landmarks) and 3) the development of a configuration (or map) from routes and landmarks. The first two stages correspond to the taxon system and are considered egocentric in that orientation toward important landmarks and the connection of these landmarks to form routes is always from the perspective of the self. The third stage corresponds to the locale system and is allocentric because the environment is interpreted from perspectives other than that of the self and because configurations (or maps) include new routes that have not yet been travelled. In the current context, TBI survivors could certainly be described as having deficits in path integration or in the ability to construct configurations of routes and landmarks but whatever the explanation the outcome is the same for these survivors in that they seem to have a wayfinding deficit. Having said this, it is important to rule out the possibility that this deficit is due simply to a deficit in the first stage of the acquisition of spatial knowledge, that is, the inability to form simple associations between stimuli (i.e. associate a target location with a single locational landmark).

Residual Abilities

TBI survivors exhibited significant wayfinding difficulties in the Arena Maze but it also true that on the vast majority of trials, they did finally locate the platform. The self report of TBI survivors in previous study (Skelton et al., 2000b)revealed some interesting non-spatial (egocentric) approaches to navigation in the Arena Maze. At this point it is important to note that the Arena Maze can be navigated using mechanisms/strategies other than cognitive mapping. These mechanisms might include, 1) a simple response (praxis) strategy of random search, circling or grid patterns where a participant selects a

simple movement pattern and executes it until coming into contact with the desired location, 2) a more complex (taxon) strategy involving intricate approaches like, for example, counting the tiles (that appear on the screen) on the ceiling of the room, 3) a view dependent response where the participant goes to the platform from a particular perspective, e.g. first going to the door and then to the platform. However, previous research (Skelton et al., 2006) suggests that the use of these strategies is likely to be reflected in poor performance in the Arena Maze invisible trials, i.e. longer latencies and meandering paths to the platform location.

Sparing of simple stimulus-response associations

In the Single Object Maze, TBI survivors had no difficulty navigating to a hidden target by using a single locational landmark and did so as well as comparison participants. It seems that TBI survivors are able to make simple stimulus response associations of locational landmarks to hidden platform locations and it is therefore proposed that TBI survivors were tapping into a system (or systems) that is not significantly disrupted by TBI. Theoretically, such systems are well described by O'Keefe & Nadel (1978) as the taxis and praxis systems (motor and sensory systems, respectively). Both are considered to be egocentric and involved in stimulus-response learning and so-called 'non-spatial' forms of navigation. Cognitive mapping theory incorporates these two egocentric systems and of course the allocentric locale system as well. The theory proposes that routes are constructed from series of stimulus-response associations (taxon system) and that organisms are guided toward relevant stimuli using an orientation response (taxis). The theory also suggests that route learning is inflexible, in that if a relevant stimulus response association is degraded or lost the route can no

longer be used to successfully reach a desired goal. Maps, then, are considered to be more flexible in that they provide for the capacity to engage multiple routes or to form novel routes. In the current study, the environment was manipualated in such a way that navigating by directional room/environment cues was detrimental to performance, i.e. a cognitive map of the environment was likely not sufficient to find the platform. TBI survivors, then, may have used the same cognitive mechanism (a stimulus response mechanism) as comparison participants when finding the target platform.

Applying the hierarchical perspective, the implication is that TBI survivors retained the ability to recognize important landmarks (e.g. in the Single Object Maze) and were able to form simple associations of a locational landmark with a target location. O'Keefe & Nadel's (1978) taxon system may be at least partially spared in TBI survivors who are able to accomplish the first stage of spatial knowledge acquisition. In short, at least one aspect of spatial cognition (basic stimulus-response association) is preserved, and could be the foundation for more complex egocentric navigation such as the formation of routes. However, the limits of the spatial cognitive ability of TBI survivors are not known and therefore the extent of the loss responsible for deficits in performance in the Arena Maze is also not known. For example, do TBI survivors really have a cognitive mapping deficit or have they simply lost the ability to cope in a complex environment?

Sparing of stimulus response associations in a complex environment

In the Ambiguous Maze task, TBI survivors demonstrated the ability to navigate in an environment that was more complex than the Single Object Maze (and arguably the Arena Maze). TBI survivors (or the comparison participants for that matter) may or may not have navigated the same way as they had previously in the Arena Maze. They could

have been using either locational landmarks (objects) or a combination of positional and/or directional landmarks (room cues). However, by self-report, not a single TBI survivor indicated the use of room cues such as windows, doors or the outside environment to locate the platform, whereas half of the comparison participants reported using directional room cues. From a review of comments made during performance of the task, it was clear that about half of the TBI survivors recognized the change in task demand in comparison to the Arena Maze and some typical comments were, "I don't need the windows", "I can use the objects", and " Why use the windows"? In general, these participants seemed relieved that locational landmarks were made available.

The use of locational landmarks by TBI survivors (and comparison participants) was also indicated by object memory tests and self report. For example, there was evidence that some survivors navigated the Ambiguous Maze by simply selecting one important locational landmark and moving toward it. In fact, the object (golden urn) closest to the platform in the Ambiguous Maze was specifically selected on this basis, being brighter, a different colour and of a more unusual shape than the other objects present in the environment. Almost all of the participants in both groups recognized this object during the object recognition task and felt that it was important for finding the platform (only one TBI survivor did not make the association). Therefore, TBI survivors might have been able to accomplish Maguire's (1996) first stage of spatial knowledge acquisition by associating the platform with a distinct landmark object, but one that was further from the target platform than in the Single Object maze. Interestingly, there was little evidence of the use of simple response strategies (circling or grid patterns) in the trajectories of any of the participants except on the first trial where some individuals

systematically searched in front of each object in a manner similar to the approach used in the Single Object Maze.

TBI survivors may also have recognized and learned configurations of objects (i.e. positional landmarks) to assist them in finding the platform. For example, they were able to recognize the objects (barrel and box) on either side of the important locational landmark (the golden urn) although slightly less frequently than comparison participants. Although simple recognition does not mean that configurations were learned, it is interesting that multiple objects in the vicinity of the platform were recognized more than other objects. Also, by verbal report, both TBI survivors and comparison participants indicated that they used locational landmarks near to the invisible platform with almost equal frequency. Although the results indicate that TBI survivors made multiple associations, it is not known if these were integrated into configurations of positional landmarks.

In summary it is proposed that TBI survivors were unable to form, remember or use the cognitive maps necessary for locating the platform efficiently in the Arena Maze but were able to activate egocentric strategies sufficient to perform well in the Ambiguous Maze after 'training' in the Single Object Maze. Nadel & Hardt (2004) have pointed out that there is general agreement about the existence of egocentric and allocentric spatial knowledge but more importantly for the current work, it is understood that different spatial systems contribute to this knowledge. As summarized earlier, these differing systems (and resulting cognitive mechanisms) likely allow for navigation to occur using either an egocentric (stimulus response) or allocentric (cognitive mapping) strategy based upon the demands of the task. The ability of TBI survivors to navigate efficiently in the

Ambiguous Maze but not the Arena Maze suggests that whatever mechanisms were utilized, they were insufficient to navigate well in a virtual environment with no locational landmarks available for guidance to the hidden target platform and that a cognitive mapping deficit is responsible for these results.

The results discussed here speak to the idea that spatial navigation is mediated by underlying cognitive mechanisms that can be selectively impaired/spared after a traumatic brain injury. In the current study, 8 of 12 TBI survivors were significantly impaired in their ability to wayfind in the Arena Maze, a figure that matches that found in previous work (Skelton et al., 2000b). The replication of this proportion of a TBI sample showing a deficit in spatial cognition suggests that further work may need to be done to assess the incidence of such deficits and what sort of effect this may have on the lives of TBI survivors.

Navigational strategies

These views of the deficits and residual abilities of TBI survivors bring up some interesting points about the types of strategies (spatial/non-spatial or allocentric/egocentric) that are used to navigate and the circumstances under which they are utilized. There are many examples of navigating in real life situations where either an egocentric or an allocentric strategy will lead to success in reaching a goal. For example, a person could locate their car in a parking lot by counting stalls (non-spatial/egocentric), by associating the location with a single locational landmark (a signpost for example, and again non-spatial), by knowing its cardinal position and its position in relation to positional landmarks (spatial/allocentric) or simply by wandering until they find it. There

are multiple strategic possibilities and it is certainly clear that uninjured humans select from available navigational strategies spontaneously (see for example, Iaria et al., 2003)

The observed tendency of humans to spontaneously select navigational strategies leads to the question of whether and when strategies can be changed or switched. Iaria et al., (2003) reported that some participants selected a strategy spontaneously and then switched strategies part way through maze trials (in a virtual radial arm maze) when a new strategy was found to be more efficient. Kallai et al., (2005) speculated that some of their participants oriented using a cognitive map and then refined their searches by using locational landmark objects, thus switching strategies in the normal course of navigation. Further, Nadel & Hardt (2004) and others (Iaria et al., 2003) have concluded that because navigation is a fluid process engaged in by a moving organism in a potentially changing environment, flexible switching from one strategy to another is essential to efficient wayfinding. The data from the current experiment are not very revealing with respect to strategy selection, however it is possible that flexible switching might have occurred in comparison participants who reported the use of both object and room cues. It is also possible that TBI survivors used inefficient strategies in early trials, but were able to switch to a more useful strategy in later trials. Further, more detailed investigations of strategy availability and selection would contribute to a greater understanding of wayfinding problems experienced by TBI survivors. To this end, new virtual maze tasks could be developed to improve understanding of strategy selection and virtual environments could be combined with other technologies such as eye-tracking devices to give a more detailed representation of the behaviours underlying strategy selection.

Anatomy and cognitive mapping

The question arises as to whether the current study provides new information about the neuro-anatomical basis of cognitive mapping. In animal models of TBI, both hippocampal and frontal lobe damage lead to deficits in performance in the MWM (Kolb et al., 1983) but clearly the hippocampus is shown to be essential for the acquisition and recall of spatial information (Driscoll & Sutherland, 2005; Nadel & Hardt, 2004). In humans, the evidence for the importance of the hippocampus in spatial processing is not quite so direct as in animal studies however, convergent studies (see for example, Maguire et al., 1996) show that damage to the medial temporal lobe is associated with memory impairment and that more specific damage to the hippocampal complex is associated with impairment in spatial information processing (for review see Nadel & Hardt, 2004) and possibly the normal construction of cognitive maps. Aguirre & D'Esposito (1999) reviewed the relationship between brain injury and the nature of the corresponding spatial deficit and found that deficits were present in humans after damage to posterior parietal cortex, the posterior cingulate, the lingual gyrus, the parrahippocampal gyrus and the hippocampus. The deficits reported differed depending upon the location of the injury and the authors concluded 1) that disruptions in the ability to learn new representations of information from the environment (or anterograde disorientation) result from parahippocampal damage, and 2) damage to the hippocampus can lead to memory deficits and deficits in the ability to form cognitive spatial maps of the environment from newly acquired representations or information structures. Ultimately, Moscovitch et al. (2005) have stated unequivocally that the hippocampus is essential for spatial learning and memory, in animals and likely humans as well.

In human TBI there is a high incidence of temporal lobe damage (Bigler, 2001) and specifically damage to the hippocampus that may contribute to the spatial deficits observed in this and other similar experiments. It is known that such damage can be long lasting (Bigler, 2001; Skelton et al, 2000) so that behavioural deficits can be expected even in survivors who are years beyond the date of their injury. This certainly seemed to be the case in the current study where the mean time since injury was 10.4 years and yet wayfinding deficits were consistently observed and reported. TBI survivors were all community living (that is, not living in institutions) and presumed to be recovered. Although the data generated here could not be correlated with information from MRI scans, it seems likely that this moderate to severely injured group had some hippocampal damage along with damage to other anatomical areas. Bigler (2001) has suggested that the only way to adequately assess long-term damage from TBI is through successive scans that would not have been available for this group of TBI survivors. However, prior work (Skelton et al., 2000a) with TBI survivors using fMRI and a virtual navigation task demonstrated that even after years of recovery the hippocampus (even when damaged) was active during virtual navigation. Further, preliminary work (Hunsaker, Livingstone, Skelton & Hopkins, 2006) with anoxic participants who have affirmed hippocampal damage indicates that they have similar wayfinding deficits to those of TBI survivors Taken together, these findings suggest that the hippocampus is a key structure involved in spatial learning and memory in humans. Future research with the TBI population should aim to clarify the relative contributions of the hippocampus and other structures (for example the frontal lobes) to wayfinding deficits. The maze tasks described in this study could be adapted as behavioural measures in the context of both EEG and MRI to further

investigate the functional anatomy underlying spatial cognition and the patterns of function that are correlated with TBI .

Relationship to real world navigation

It is important to establish that the virtual reality testing used is ecologically valid. Performance in virtual environments such as the one used here, is thought to transfer readily to real world environments and has been shown to do so in the case of route learning in uninjured (Ross, Skelton & Mueller, in press) and stroke patients (Brooks et al. 1999) . Indications of transferability are 1) that participants see themselves as embedded in the virtual space, and 2) that deficits in virtual environment wayfinding tasks are correlated with deficits in real world wayfinding. The results of the 'Where's the door?' task indicated that all participants were aware of the three dimensional aspect of the virtual space. Participants were embedded enough in the space to point over their shoulders in real space when asked to point toward the door placed behind them in virtual space. TBI survivors were less accurate in their pointing but always pointed either beside or behind themselves, indicating that they knew the door was in a three dimensional room that wrapped around them and did not think of the virtual space as just a picture on a flat computer screen.

Correlating deficits in the virtual environment wayfinding tasks with deficits in real world wayfinding presents more difficulty since good tests of real world wayfinding deficits are not readily available. For this study, the ESQ gave some indication that TBI survivors have more difficulty finding their way than do comparison participants. This apparent deficit was strongest when it came to questions regarding locating a car in a parking lot or making novel routes/shortcuts. Although differences between comparison

participants and TBI survivors on these questions were not statistically significant, it is interesting that the results of this self-report are consistent with those from a previous study (Skelton et al., 2006). Also, there were positive correlations between the spatial component (questions 1-8) of the ESQ and maze variables (latency and distance) suggesting that self report of wayfinding difficulties is correlated with poor spatial performance in virtual reality environments. These results imply that virtual environments are good candidates not only for assessing wayfinding problems but possibly for rehabilitating them as well.

Implications for rehabilitation

Along with ecological validity, 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 potential 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 participants, and 5) the tasks could be adapted as 'errorless learning' (Wilson, 2000) approaches. In the current study, participants did not become frustrated by the maze tasks and seemed to have no sense of what would constitute a good or poor latency to the platform. Wilson (2002) emphasizes the importance of errorless learning (i.e. learning with no mistakes) in the rehabilitation of memory deficits and suggests that this could apply to the rehabilitation of other cognitive deficits as well. Also, good tests of the ability to navigate would shift the assessment of wayfinding deficits from a reliance on self report to more objective tests of spatial cognition.

Conclusions

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 locational landmark and surprisingly, were also able to navigate under complex conditions and in the presence of multiple landmarks (directional and possibly positional). It remains to be seen whether TBI survivors consistently have real world wayfinding problems and if so, whether virtual reality compensatory strategies can improve their ability to navigate in real space. Nevertheless, 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.

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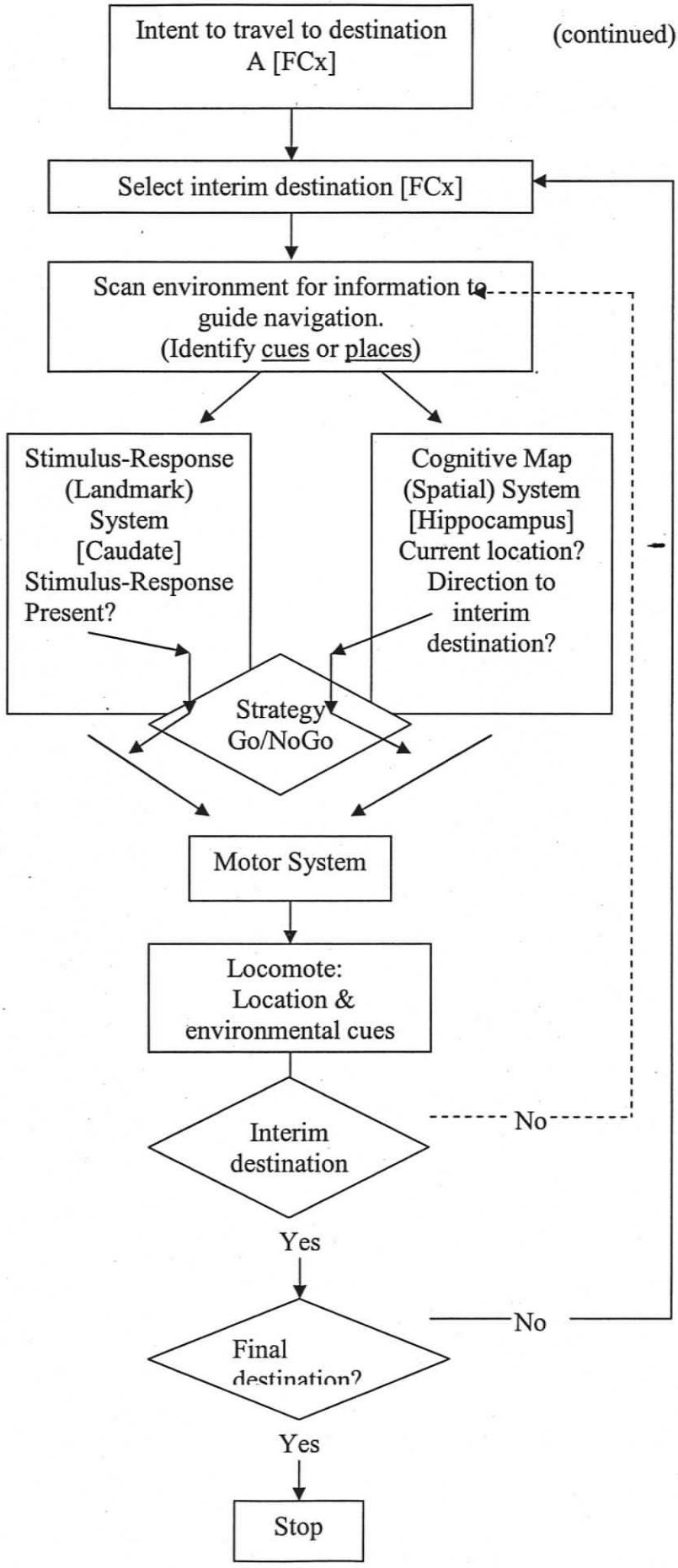
Appendix A

A Model of Wayfinding Processes (A working hypothesis, see figure below)

The intent to travel follows immediately from a decision to move to a new destination, and this intent must be maintained (by the Prefrontal Cortex) until the destination is reached. The system selects an interim goal or destination and then surveys the environment for navigational guidance information and then processes it (see Previc for anatomy). The environment will contain stimuli (cues, landmarks) already associated with a locomotor response, or configurations of stimuli sufficient to allow the cognitive map to recognize the current spatial location, or both. At that point there must be a mechanism to select which type of information to act on, and then engage either the stimulus-response system (in the caudate) or the cognitive map system (in the hippocampal formation). The selected system then activates the motor system, which moves the organism, changing its location and the environmental cues available. If the interim destination is not reached, the system lops back to rescan the environment and continue. If the interim destination is reached, but the final destination is not, the system loops back to check intent and select the next interim destination. If the final goal is reached the system, and the organism, stop.

By this model, navigation is not conducted entirely by one system or the other (S-R or spatial), but dynamically by either one, depending upon what cues and associations are available at any given time. The strategy selection stage could have degrees of flexibility such that the ability to choose one strategy over the other could be constrained by the relative functional strengths of the two systems or by predispositions to use one of the systems based on past successes and failures, or by physiological states like current stress level. All three of these factors, and their interactions, are influenced by developmental history, assuming that functional systems are strengthened by use, especially when the outcome is successful and that chronic stress or physical trauma could damage, weaken or destroy one of the systems. (Note: This system does not require awareness but operates for both real and imagined locomotion.)

Appendix A (continued)



Appendix B

Script - Arena Maze, Single Object Maze and Ambiguous Maze (2004)

(ABC ORDER)

Preparation by Experimenters

1.Set up computer

i) Open the file — **Type [Open AM04] [Enter]**
ii) Curtain down — **[~] (⇓)**

2. Put the stopwatch and data sheets near the computer ready for manual recording

3. Check all documents as per attached materials list.

Preparation of the Participtant

Seat participant at computer

Consent Form:

Exp: Hi, I'm _(name: Operator)_ and this is _(name: Recorder)_ .
We're going to go over this consent form with you.
It will give you an overview of what we will be doing today.

Go over the consent form with the participant.
Have the participant sign one copy for you and return one copy for the participant to keep.
For those with TBI, the consent form may have to be read one line at a time and care should be taken to ensure understanding of the form.

Personal Information Questionnaire (Interview)

For those with TBI, assistance may be required with interpretation of questions.

Exp: I am going to ask you some questions now.
You may skip any questions that you do not wish to complete.

Overall Introduction

Exp: Today you will be moving through several virtual rooms to complete a number of tasks.
Your task is to find a green spot, or platform, on the floor.
You will be transported into one of the rooms
If you ever feel sick or dizzy please let me know.

Appendix B (cont'd)

You may ask questions at any time. Are you ready to start?

Comp: curtain up [~] (⇑)

[Arena Maze] Exploration of the Room

Exp: This is the first practice room. Here you can practice moving around.
You also get to see what the room looks like and see the world outside.
The round area in the middle of the room is the arena.
You will be using the controller to move around.

Give the participant the controller.
Use the thumb pad on the left **(point to it)** to turn left or right.
Use the buttons on the right **(point to them)** to move forward or turn left and right.
There is no button to go backwards. You can explore this room as much as you like. When you are comfortable with the movement, please tell me.
Are you ready for the next phase? **(You may have to remind the participant not to go through the door until they have explored)**

Rec: **Use the hand-timer to record the amount of time the participant spends exploring. Start timing when the participant starts moving and stop timing when the door creaks**
(or when the participant indicates an end to exploration).
For successive trials,
start timing when the space bar is pushed to send the participant to the next room.

Part: (Explores room outside arena)
Exp: (Prompts) Please look at the world out all three sides of the room
Please don't walk through the door until I ask you to.

Exp: When you are ready you can walk through the door.
There will be a brown wooden ramp and a blue teleport box in the next room.
Please wait for the ramp to go up.
Please walk up the ramp, then wait in front of the teleport box.
Your next task begins when you walk through the teleport box.

[Arena Maze] Visible trials

Exp: On the next 4 trials, the platform will be visible.
Your task will be to walk to the platform as quickly and directly as possible.
Once you are on the platform, you can look around the room for as long as you like. Ok?
Exp: Hang on while I get the computer ready.

Appendix B (cont'd)

Comp: Start demo recording **Type [DEMOREC SC/MF/XXA] [Enter]**

Screen: Demo recording started (file #) ***see explanation end of script**

Curtain up **[~] (⇑)**

Exp: Are you ready? Ok, good. Then step into the teleport box.

Part: (goes to visible platform.)
Exp: Ok. (To inform recorder that the subject reached the platform)
Exp: (Prompts) Stay on the platform and look around the room
Please look around the room at least once.
Have you looked around the room as much as you want?

Exp: Are you ready? Ok, good.
Comp: send participant to next level. **[spacebar]**

On 2nd – 4th trials, when part. on platform
Exp: Would you like to look around the room?
Are you ready for the next trial?
(If yes)
Comp: **[spacebar]**

Exp: **If they leave the platform**
(Prompts) Please stay on the platform as you look around.
I'll move you back onto the platform.

After the 4th trial, while part still on the platform,

Exp: Good. You are finished this phase.
Curtain down **[~] (⇓)**

[Arena Maze] Invisible trials and probe trial

Exp: Are you ready for your next task?
From now on the platform will be invisible until you step on it.
When you step on it, it will rise out of the floor, making a mechanical sound.
The platform will always be in the same place.
Go to the platform as quickly and directly as possible.
You will be doing this task a number of times.
On one of the trials, the platform will be very small and hard to find.
Keep searching for it anyway. Ok? Are you ready to start?

Comp: Curtain up **[~] (⇑)**
[Spacebar]

Appendix B (cont'd)

Part: (executes 1st Arena maze trial)
When part. finds the platform
Exp: Good.

If the participant does not find the platform in 3 minutes, say
Exp: (Prompt) Ok, good. Let me guide you to the platform
(use movement based directions to rotate the participant until facing the platform, then say,
'go straight')

Exp: (If necessary, Prompt)
Do you remember the task? Have you searched enough?

When they find the platform
Exp: (Prompt) Stay on the platform and look around the room

Exp: Are you ready for the next trial?
Part: (response)
Exp: Ok, good. Remember, your task is to find the invisible platform.
Comp: **[spacebar]**

Part: (executes 2nd Arena trial.)

Trials 2 and 3
Exp: Would you like to look around the room?

Exp: Are you ready for the next trial?
Part: (response)
Ok, good.
Comp: **[spacebar]**

For the remainder of the trials, ask,
Exp: Do you want to look around? Ready?"
Comp: **[spacebar]**

Repeat to end of 10 invisible trials and probe (50 seconds)

Comp: Curtain down **[~] (⇓)** Type
[STOPDEMO] [Enter]

Type [Open
SINGLEO] **[Enter]**
[Single Object Maze]

Appendix B (cont'd)

Exp: For the next 5 trials you will be in the same room and the platform will be invisible.
The platform will be in a different place each time and your task will be to find it.
Once you are on the platform, you can look around the room for as long as you like.
Do you have any questions? Are you ready?

Exp: Hang on while I get the computer ready.

Comp: Start demo recording **Type [DEMOREC SC/MF/XXB]**

Screen: Curtain up **[~] (⇑)**

Part: (goes to invisible platform.)

Rec: **Use the hand-timer to record the amount of time from start to platform. Start when the operator says ok.**

Exp: (Prompt) Stay on the platform and look around the room

Exp: **(while participant is on the platform)**
Are you ready to go to the next room?
Remember, your task is to find the platform.

Comp: send participant to next level **[spacebar]**

On 2nd – 4th trials, when part on platform ,

Exp: Would you like to look around the room?

Exp: Are you ready for the next trial?
(If yes)

Comp: **[spacebar]**

After the 4th trial,

Exp: Good. You are finished this phase.

Part: (still on the platform)

Comp: Curtain down **[~] (⇓)** **Type[STOPDEMO]** {no spaces}

Comp: Open the next file **Type [Open AMBIG] [Enter]**

Appendix B (cont'd)

[Ambiguous Maze] Exploration trial

Exp: Now there will be another practice room. You can see what the room looks like and what the arena looks like. You will be able to walk around in the arena.

Rec: **Start timing when the participant starts moving and stop timing when the door opens (or when the participant indicates they have finished exploring). For successive ambiguous maze trials, start timing when the space bar is pushed.**

Exp: When you are finished exploring, let me know and I will jump you out of the arena. As before, you can walk through the door. There will be a brown wooden ramp and a blue teleport box in the next room. Please wait for the ramp to go up. Walk up the ramp and then wait in front of the teleport box. Your next task will begin when you walk through the teleport box.

[Ambiguous Maze] Invisible trials

Exp: Are you ready for your next task?
As before, the platform will be **invisible** until you step on it. Your task will be to find the platform. Go to the platform as **quickly and directly** as possible.
You will be doing this task **a number of times.**
On one of the trials, the platform will be very small and hard to find. Keep searching for it anyway. Ok? Are you ready to start?

Exp: Hang on while I get the computer ready.

Comp: Start demo recording: **Type [DEMOREC SC/MF/XXC] [Enter]**

Exp: Are you ready to start?

Comp: Curtain up **[~] (⇑)**

Rec: **Use the hand-timer to record the amount of time from start to platform rising. The sound of the platform indicates the stop time.**

Part: executes 1st Ambiguous trial.

Appendix B (cont'd)

When part. finds the platform

Exp: Good.

If the participant does not find the platform in 3 minutes,

Exp: (Prompt) Ok, good. Let me guide you to the platform
(use movement based directions to rotate the participant until facing the platform, then say,
'go straight')

Exp: (If necessary, Prompt)
Do you remember the task? Have you searched enough?

Exp: **When they find the platform**
(Prompt) Stay on the platform. Look around the room.

Exp: Are you ready for the next trial?
Part: (response)

Exp: Ok, good. Remember, your task is to find the invisible platform.
Comp: **[spacebar]**

Part: (executes 2nd Ambiguous trial.)

For trials 2 and 3

Exp: Are you ready for the next trial?
Part: (response)
Ok, good.
Comp: **[spacebar]**

For the remainder of the trials

Exp: Ready?

Comp: **[spacebar]**

Repeat to end of 10 invisible trials and 1 probe trial

Exp: Good. Thank you for finishing all the tasks

Comp: Curtain down **[~](⇓) Type [STOPDEMO] [Enter]**

[Follow-Up]

Room Reconstruction
Strategy Questions and Fatigue Questions

Appendix B (cont'd)

Object Recognition
Everyday Spatial Questionnaire
Rivermead Behavioural Memory Test
Clock Drawing Neglect Test

Place upright a standard unlined letter-size sheet of paper and a pencil in front of the participant

Exp: I want you to draw the face of a clock with all the numbers on it. Make it large.

After completion of the clock face

Exp: Now, draw the hands pointing at 20 to 4.

Instructions may be repeated or rephrased if the patient does not understand, but no other help should be given.

Rec: The time taken to complete the task may be noted.

Debriefing and Honorarium

Exp: Thank you very much for participating in our study today.

END SESSION

After the run, move the dem files to two safe places (one for processing, one for safe storage).
When you have a few subjects run, move the files off to a CD).

Participant code explanation: **S/C** (SURVIVOR, CONTROL)
M/F (MALE, FEMALE)
XX (NUMBER , EG. 01,02,,,)
A/B/C (ARENA MAZE, SINGLE OBJECT MAZE, AMBIGUOUS MAZE)

Appendix C

Participant Consent Form

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

You have been invited to participate in a study entitled 'Virtual environment navigation tasks and the assessment of cognitive deficits in individuals with brain injury' being conducted by Dr. Ron Skelton. Dr. Skelton is a faculty member in the department of Psychology at the University of Victoria.

Your participation in the study includes a short interview about your general personal information (e.g., age, gender) and your brain injury if you've had one and your familiarity with computer games. You will be asked about the circumstances of your injury but you may skip these questions if you like. You will be asked to complete several computer mazes using a game controller and then asked about how you did it and how you find your way in everyday life. You may also be asked to complete a couple of standard tests of memory and eye-hand co-ordination. You will be tested for 90-120 minutes, and the testing may be spread over two sessions (on different days) if you choose. Testing will be done by two qualified students, one graduate and one undergraduate, who have been trained to administer the computer mazes and other tests in the study.

The purpose of the present study is to examine some of the problems that can follow a brain injury. You have been selected to participate because you are between the ages of 19 and 60 and have received treatment for a traumatic brain injury, or because you are the family member or friend of someone with a traumatic brain injury. By participating in this study you will be adding to our understanding of the difficulties those with brain injury may have finding their way in the world. It is hoped that this research will contribute to future improvements in assessment and rehabilitation for those who survive traumatic brain injury. You may even gain insight into your ability to find your way in the world.

Your participation in this research is completely voluntary. Information about your participation and your performance will not be communicated to anyone else and so will have no effect on any services you may be receiving. You may withdraw or take a break at any time, or refuse to answer or complete any part of the study without explanation. If you withdraw from the study your data will only be used if you give the researchers permission to do so.

Some people experience mild dizziness when navigating virtual environments. If you experience this or any other discomfort, please let the researcher know right away. You are free to take a break at any time and free to discontinue your participation.

In order to protect your privacy, you will be assigned a code number and this number will be the only indication that the data came from you. Your name will be on the consent form, but this will be stored separately from the interview forms and data. Neither your

Appendix C (cont'd)

name nor identifying information will appear in any publication of the results. Obviously though, your participation will not be anonymous because the researchers who work with you will know your name and face.

All information and data collected from you will be stored under your code number, in a locked office separately from this signed consent form. Access to your data will be restricted to the researchers and the principal investigator. We are required by the American and Canadian Psychological Associations to keep data for 7 years after publication of the research findings, at which time they will be destroyed by shredding all papers and deleting all electronic files. The results of this study may be published in a scientific journal and presented at scholarly meetings or conferences. It may also form part of a thesis of the student researchers.

You will be reimbursed for transportation costs and given an honorarium of $15 per session, to compensate you for your time.

If you have any questions or concerns about this study, you may contact Sharon Livingstone at 721-7552 or by email at sal@uvic.ca, the Principal Investigator, Dr. Ron Skelton at 721-8711 or by email at skelton@uvic.ca or the Associate Vice-President, Research (250-472-4362).

Please consider the following requests with regard to future research:

1. Would you be willing to be contacted for follow-up information or would you be interested in being informed of other opportunities to participate in studies conducted by these researchers? If so, your willingness will be indicated in your data records and your name and phone number will be retrieved from this form.
Initial here if yes. _____ and add your phone number _____.

2. It is possible that the data we collect might be useful in the future in other studies of spatial navigation. These studies would be similar to the one you are participating in now. Your data will be stored anonymously and any future research will receive scientific and ethical approval before it is conducted. If you agree to let us use your data in a future study, please put your initials here. _____

3. If you choose to withdraw from the study:

Please initial here if we may have permission to use your data. _____

Please initial here if we do not have permission to use your data. _____

Your signature below indicates that you understand the above conditions of participation in this study and that you have had the opportunity to have your questions answered by the researchers.

_____	_____	_____
Name of Participant	*Signature*	*Date*
_____	_____	_____
Experimenter	*Signature*	*Date*

Appendix D

BACKGROUND INFORMATION QUESTIONNAIRE
Code#_____

1. Date of Birth (day, month, year): _____ 2. Sex: _____

3. Education: (Last Grade or Year of University Completed, please specify which)

_____

4. Handedness (Right/Left): _____

5. Do you have any problems with dizziness? (Yes/No) _____

6. Do you play Computer Games? (Yes/No) _____

If yes, which ones?

_____

If yes, are any of the games you play 3-D games? (Yes/No) _____

7. Have you ever used a joystick? (Yes/No) _____

If yes, specify how often:

Never (Ever) |----------| Every day

8. Have you ever used a game controller? (Yes/No)____If yes, specify how often:

Never (Ever) |----------| Every day

Other Information:

9. Do you suffer from any neurological disorders (eg. epilepsy, MS)? (Yes/No)

_____

If yes, which disorder? _____

Appendix D (cont'd)

10. Do you suffer from any psychiatric disorders (eg. depression, schizophrenia)?

(Yes/No)_____

If yes, which disorder? _____

11. Are you currently taking any medications? (Yes/No)_____

If yes, please specify: _____

Questions for participants with brain injury:

It is not uncommon for people who have had a brain injury to have trouble remembering what happened. I'm going to ask you a few questions about what you remember around the time of the injury and your hospital stay. Please answer them as best you can. For some people, discussing these topics may be difficult or upsetting for them. If you find our discussion upsetting, please let me know and we can move on.

12. When were you injured? (month, year) _____

13. Could you go over **how you got your brain injury**? *{Record MVA, fall, stroke etc, and a few details}*

_____

_____

_____

_____

_____

14. Were you hospitalized after your brain injury? Y / N *{If yes}* For how long?

_____

{If injury is within the past year, ask} How long have you been out of the hospital?

_____

15. Did you lose consciousness or were you in a coma after you brain injury? Y / N

Appendix D (cont'd)

16. What is the last thing that you remember before losing consciousness?

---

17. What is the first event you can remember after regaining consciousness?

---

18. After brain injuries, many people have large gaps in their memory. For example, they may have a period of a day, a week, or a month where they don't remember things that happen, things they've done or visitors they've had. This is called "Post-Traumatic Amnesia". Did you have any gaps like that? Y / N *{If yes}* When did you stop having these gaps? (How long after your injury?) ____

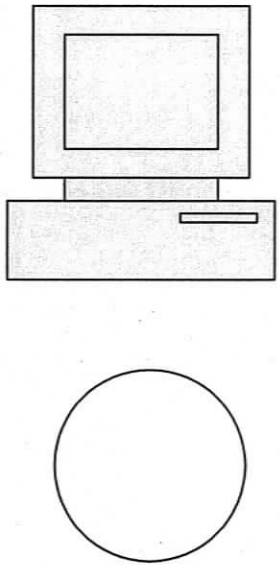
*NOTE: try to get an **estimate of Post Traumatic Amnesia** duration and circle one of the following:*

10 minutes or less	*An hour or less*	*A day or less*	*A week or less*	*1-2 weeks*	*A month or more*

Appendix E

Where's the Door Test

Instructions:
Curtain up after last trial of the ambiguous maze
Ask participant to remain on platform and face the golden urn
Then ask, "From here, where is the door? You can show me by pointing."
Record (1) Direction of pointing by drawing an arrow on the diagram below (2) Any comments by the participant with regard to whether he/she felt embedded in the space.



Comments:_____

_____

_____

_____

_____

Appendix F

STRATEGY QUESTIONS and FOLLOW UP DATA SHEET

1. In the maze with objects, how did you find the platform?
(Please check all that apply)

Early Middle Late

[ ] [ ] [ ] By using one object.
Which one? Early_____
Middle_____
Late_____

[ ] [ ] [ ] By using a combination of objects.
Which ones? Early_____
Middle_____
Late_____

[ ] [ ] [ ] By the location of the platform in the room.

[ ] [ ] [ ] By going to the same starting place each time and then to the platform.

[ ] [ ] [ ] Other (please explain)

2. Please answer the following questions by checking all that apply.

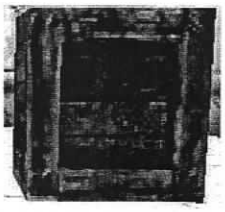
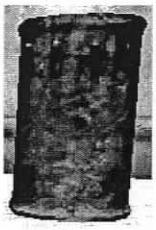
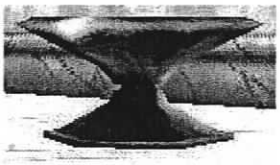
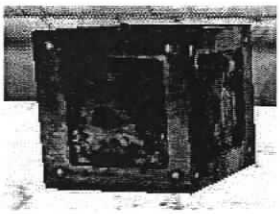
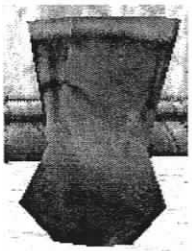
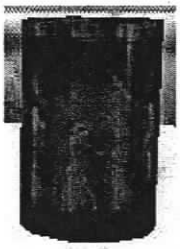
Did you get dizzy at all? Yes [ ] No [ ]

Did you feel tired when you were looking for the platform? Yes [ ] No [ ]
If yes, when did you feel tired?

Appendix G

Which of the objects below were in the room? Code_____

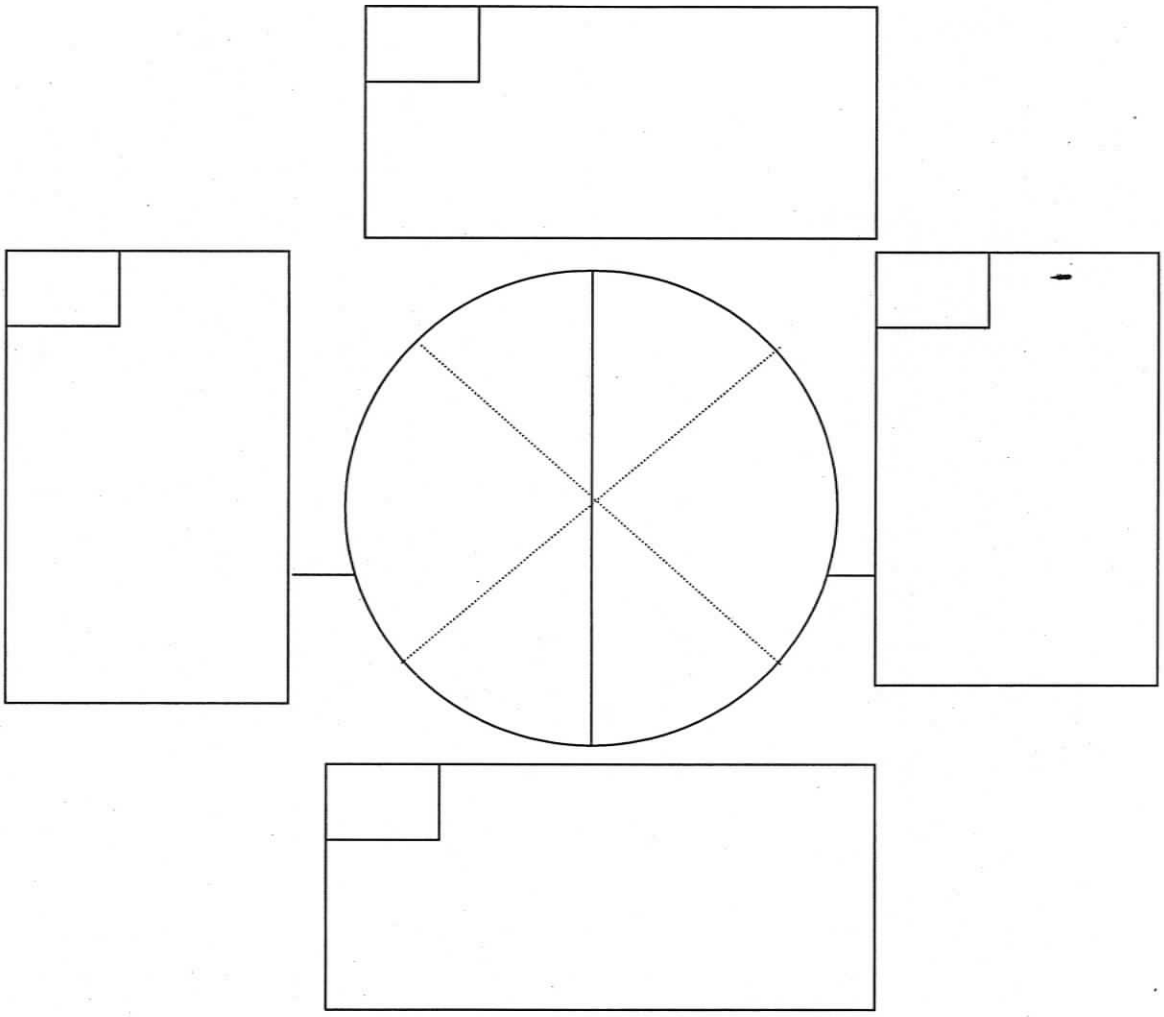
Please put check mark in ( ).

 A ( )	 B ( )	 C ( )	 D ( )
 E ( )	 F ( )	 G ( )	 H ( )
 I ( )	 J ( )	 K ( )	 L ( )
 M ( )	 N ( )	 O ( )	 P ( )

Appendix H

ROOM RECONSTRUCTION DATA SHEET

Code _____ **Room** _____



Appendix I

Clock Drawing Code #_____

In the space below, draw the face of a clock with all the numbers on it. Make it large.

----------fold bottom portion of page underneath----------

Now draw hands pointing at twenty to four.

Appendix J

EVERYDAY SPATIAL QUESTIONNAIRE Code#_____

Place a mark on the line that best describes your recent experience (e.g. in the last month)

1. Do you get lost in small familiar buildings (like a friend's house, corner store, etc.)?

Never (ever) |----------| Every time.

2. Do you get lost when you go into large buildings you've been in before (Malls, office buildings)?

Never (ever) |----------| Every time.

3. Do you get lost when you go into large buildings for the first time?

Never (ever) |----------| Every time.

4. Do you feel disoriented when you come out of an unfamiliar building?

Never (ever) |----------| Every time.

5. Do you get lost or feel lost when you are in familiar parts of town (like your own neighbourhood)?

Never (ever) |----------| Every time.

6. Do you get lost or feel lost when you are in unfamiliar parts of town?

Never (ever) |----------| Every time.

7. Do you get people to take you over a route before you'll go that way yourself?

Never (ever) |----------| Every time.

8. Do you stop and ask directions when you are on your way to someplace (or want to)?

Never (ever) |----------| Every time.

9. Do you make up shortcuts and figure out new routes from one place to another?

Never (ever) |----------| Every time.

10. Do you forget where you put things?

Never (ever) |----------| Every time.

11. Do you have trouble finding your car in a parking lot?

Never (ever) |----------| Every @#$% time!

12. Do you put things like keys and your wallet in specific locations so you can find them again?

Never (ever) |----------| Every time.

13. Is it important to you that your clothes and food cupboards are arranged in a very specific way?

Not at all |----------| Absolutely!

Appendix K

Error calculations for all t-tests according to the Hochberg method (1988)

Between group tests	Unit of measure	Obtained t	Obtained p	Hochberg p
AM 2-10	Latency	3.51	0.002	**0.006**
Spatial Score AM	no unit	3.53	0.002	**0.006**
AM 2-10	Distance	2.55	0.02	0.007
AMB 2-10	Latency	2.37	0.03	0.008
Spatial Score AMB	no unit	2.41	0.03	0.010
Probe AM	Quadrant Dwell	2.25	0.04	0.013
Visible	Latency	2.15	0.04	0.017
AMB 2-10	Distance	1.66	0.11	0.025
Probe AMB	Quadrant Dwell	1.63	0.12	0.050