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Cognitive and gender factors influencing navigation in a virtual environment

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Virtual environments (VEs) are becoming popular as media for training, modelling and entertainment. Little is known, however, about the factors that affect efficient and rapid acquisition of knowledge using this technology. Five experiments examined the influence of gender, passive/active navigation, cognitive style, hemispheric activation measured by electroencephalography and display information on the acquisition of two types of navigational knowledge using a VE: route and survey knowledge. Males acquired route knowledge from landmarks faster than females. In situations where survey knowledge must be used, proficiency in visual-spatial cognition is associated with better performance. The right cerebral hemisphere appears to be more activated than the left during navigational learning in a VE. In identifying cognitive factors that influence VE navigation, these results have a number of implications in the use of VEs for training purposes and may assist in linking processes involved in navigation to a more general framework of visual-spatial processing and mental imagery.

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1. Introduction

There has been a rapid increase in interest and use of virtual environment (VE) software for both work and leisure with the advent of powerful desktop personal computers. In most cases, a VE is a simplification of the real visual world and involves interacting with a display in which human spatial perception is required for effective use (Wann & Mon-Williams, 1996). It may also entail a degree of "immersion". Immersion, in this sense, refers to a viewer-centred perspective (Moffat, Hampson & Hatzipantelis, 1998) which results in the sensation of being situated within an environment as opposed to viewing it on a map or other such abstract representations. For example, a VE for architectural use could permit designers and clients to obtain an immersed view of a building by permitting the user to "move" through the proposed construction. Training uses have also been developed (Bliss, Tidwell & Guest, 1997) and a number of video games have been sold commercially, one of the more popular being Doom®. Witmer, Bailey and Knerr (1996) point out that VE surrogates for real environments will find their uses in cases where the real environment cannot be easily explored for practical reasons such as safety or cost.

There are several cognitive and other factors that may be important in using VEs. These include individual differences that may affect efficient use of VEs, the effectiveness

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of passive exploration of a VE as opposed to active exploration, the kinds of features or cues within a VE that facilitate tracking one's position during movement through the VE (i.e. navigation) and adverse sensory factors associated with immersion. In the latter case, a binocular head-mounted display of a VE can lead to sore eyes, headaches and motion sickness (Regan & Ramsey, 1996; Wann & Mon-Williams, 1997). In contrast, viewing the world projected on a two-dimensional (2D) screen (desktop VE system) does not appear to elicit these adverse side effects. The goal of this paper was to investigate cognitive factors that can affect virtual navigation performance using a desktop VE system.

1.1. FROM PERCEPTUAL CUES TO COGNITIVE REPRESENTATIONS

The term navigation refers to a process of tracking one's position in a physical environment to arrive at a desired destination. A route though the environment consists of either a series of locations or a continuous movement along a path. Navigation becomes problematic when the whole path cannot be viewed at once but is largely occluded by objects in the environment. These may include internal walls or large environmental features such as trees, hills or buildings. Under these conditions, one cannot simply plot a direct visual course from the start to finish locations. Rather, a knowledge of the layout of the space is required. Maps or other descriptive information may provide this knowledge. However, in this paper the concern is with the cues that are available with direct exposure during navigation that allow the viewer to develop a cognitive representation of the space. The nature of these cues is reviewed next followed by consideration of the kind of cognitive representation that can be constructed from this perceptual information.

At the lowest level there exist position, velocity and acceleration data (Loomis, Klatzky, Golledge, Cicinelli, Pellegrino & Fry, 1993) yielding location cues, depth cues and motion cues. Location information comes from landmarks, landscape features, or distant fixed cues, and is mediated by positional data. Navigation on the basis of such positional data is referred to as "piloting" (Etienne, 1992; Mizumori, 1994). Examples of landmarks include street signs, and other recognizable objects such as a particular store, pond or tree. A network of landmark information which provides the relative distance and orientation among them is the basis of a representation of the environment which can permit effective navigation. In addition, standard visual cues such as relative size of objects in view, occlusion, binocular disparity, shading, perspective lines and texture gradients carry depth information and provide 3D structure to landmark information.

Motion cues are provided by velocity and acceleration data. These provide a basis for interpreting mobility and relative scale during navigation. The optical flow field is a global visual stimulus consisting of a set of elements that appear to expand from a point in the direction of movement (Gibson, 1950). The optical flow field can provide human navigators with primary cues for judging heading and detecting turning (Warren, Mestre, Blackwell & Morris, 1992; Dyre & Andersen, 1997; te Pas, Kappers & Koenderink, 1998; Warren & Hannon, 1988). This may permit navigation by "dead reckoning" where continuous integration of translational and angular components allows for estimation of direction and distance from a point of origin (Schiesser, 1986; Loomis *et al.*, 1993). Motion cues also provide parallax cues which can be used for making in-depth judgments.

Effective navigation of a familiar environment depends upon a number of cognitive factors. These include working memory for recent information, attention to important cues for location, bearing and motion, and finally, a cognitive representation of the environment which becomes part of a long-term memory, a "cognitive map" (Tolman, 1948). This representation is what permits the local perceptual cues to be of use in tracking or maintaining a sense of "knowing where one is". The representation also permits generation of expectancies for encountering future landmarks and (if it is veridical) the confirmation of one's location and progress through the environment which may include estimates of arrival time, energy consumption and so forth.

Environmental psychologists were among the first to investigate human spatial navigation. They noted that a cognitive map makes some aspects or attributes of the world explicit, while permitting other aspects to be computed or approximated as needed (i.e. they are implicit). Early studies were conducted in relatively uncontrolled environmental conditions, relying on participants' past experience with their environment (Appleyard, 1970; Canter, 1977). However, some consistent results emerged, the most interesting being behavioural evidence of a cognitive map (Evans, 1980). This construct has received considerable attention over the past 20 years and is still a contentious object of research (Chown, Kaplan & Kortenkamp, 1995). With prolonged exposure to an environment, people acquire the ability to draw maps, to point to unseen locations and to orient themselves in it correctly.

Building on this early work, Thorndyke (1980) and Thorndyke and Hayes-Roth (1982) attempted to study, in a more controlled way, factors that influence mental representations of the environment. They compared two groups of participants, each exposed to one or two types of information sources (immersed navigation or maps) about a large building. Results showed that navigation experience led to relatively better estimates of route distances than Euclidean, or straight-line, distances. With continued navigation these participants' results were very similar to participants who only learned about the environment by studying a map. More generally, it was concluded that map learning results in an orientation-specific representation but navigation leads to an orientation-free representation. Similar conclusions were drawn by Presson, DeLange and Hazelrigg (1989). More recently, Ruddle, Payne and Jones (1997) and Wickens (1992) have proposed that an internal representation of the environment develops through three stages: (1) landmark knowledge, (2) route knowledge and (3) survey knowledge. Route knowledge consists of a representation of a path that is marked by sequence of landmarks such that one can navigate between start and finish locations. Survey knowledge is essentially equivalent to the cognitive map plus procedures for doing computations on this map. Thus, the end-product of prolonged navigation experience is a map-like representation which can be rotated, re-scaled and used to estimate distances.

1.2. NAVIGATION IN VIRTUAL ENVIRONMENTS

While the above studies have begun to describe some of the main elements involved in human navigation, they are limited by factors inherent in trying to study human behaviour in large open spaces. For example, in studying human behaviour in natural settings such as a work environment (e.g. Thorndyke & Hayes-Roth, 1982) the participants' prior knowledge and exposure to information sources is largely unknown. For

example, it cannot be assumed that participants have not seen a map (e.g. floor plan or someone else's rough hand drawing) of the environment which is under study, or that they have not discussed with other workers routes or locations in the environment. Contamination by one of these information sources may also be confounded with length of exposure to the environment. Thus, interpretation of any group differences is problematic. On the other hand, expedients such as using simple paper and pencil maze tests or using mental imagery for an environment are confounded by excluding important cues or including additional cognitive processes.

Regian, Shebilske and Monk (1992) have studied learning effects using a simple screen-based VE. They showed that prior exploration of a virtual environment leads to knowledge which allowed the person to navigate between specified virtual locations in a series of test trials. Witmer *et al.* (1996) have shown that transfer of training from a VE to the real environment is possible, with performance improving with increased training exposure. Ruddle *et al.* (1997) were able to partially replicate the Thorndike and Hayes-Roth (1982) study using a VE, confirming that route knowledge is eventually acquired from navigation experience. While these few studies of the utility and viability of VE technology provide encouraging results, they leave unanswered a number of questions about what and how the participants learn in navigation tasks. In the context of human–computer interaction, it is essential to determine which variables impact on the utility of VEs for such practical applications as training and knowledge representation (e.g. database design and exploration). In addition, as Ruddle *et al.* (1997) have noted, the kinds of spatial knowledge acquired, and the rate of acquisition may be different in a VE compared to real-world experience. Thus, empirical studies are required to address these issues.

1.3. COGNITIVE FACTORS THAT MAY INFLUENCE VIRTUAL NAVIGATION PERFORMANCE

The previous sections have described the types of stimuli and navigation exposure that may be necessary in order to acquire navigation knowledge. In this section, some cognitive factors that may mediate the effects of this information are introduced. Humans have evolved to perform a variety of tasks which require visual-spatial skills. While many of these skills have been intensively investigated (Humphreys & Bruce, 1989; Humphreys, 1992), the cognitive skills used in navigating the environment have received less attention. This may in part be due to the difficulty in conducting controlled experiments in real environments. It may be argued, however, that individuals who excel at visual-spatial tasks will perform better on navigation tasks since the latter may also require recollection and manipulation of visual-spatial information.

Mizumori (1994) has argued that specific brain regions (for example, the place cells of the hippocampus) are responsible for the encoding and utilization of spatial information in a navigation tasks. Evidence from a variety of sources has indicated that visual-spatial cognitive functions are right-hemisphere lateralised, (Kolb & Wishaw, 1990; Lezak, 1995). While both cerebral hemispheres are capable of generating mental images, Kosslyn, Maljkovic, Hamilton, Horowitz and Thompson (1995) have suggested that right hemisphere imagery may better support the kinds of cognitive processes necessary for navigation of the environment. Vogenthaler (1987) has noted that lesions of the right cerebral hemisphere can result in a reduction in ability to navigate within a building,

resulting in disorientation. These findings suggest that there should be greater right hemisphere activation during virtual navigation tasks. One method for examining this is to record the electroencephalogram (EEG) and compute the asymmetry of synchronized brain wave power (Pivik, Broughton, Coppola, Davidson, Fox & Nuwer, 1993). Greater asymmetry should be evident in individuals who exert greater cognitive effort to perform a task such as navigation (Earle, 1985). The block design sub-test of the Wechsler Adult Intelligence (revised) test may also be a useful indicator of the visual-spatial skills required for navigation. This test also shows a decline in performance after right cerebral hemisphere damage (Newcombe, 1969; Black & Strub, 1976).

Previous research has identified gender differences in spatial abilities, with males performing better on tasks involving mental rotation and spatial perception (Linn & Petersen, 1985). Bryant (1982) found that facility with mental rotation was related to the ability to point to unseen spatial locations. Kimura (1992) has argued that some of these differences in spatial ability may be biologically based. In fact, Bever (1992) found that females were better than males at learning a maze when learning on each trial required travelling in the same direction. This may permit a verbal sequence to be learned to solve the maze. Using a questionnaire ("the Way-Finding Strategy Scale"), Lawton (1994) examined the hypothesis that males would show a preference for solving navigation problems by using survey knowledge-based strategies. Males indeed were more likely to report using orientation cues (such as where north is) when they navigate as opposed to females who reported relying more on route descriptions. These results are consistent with both Tapley and Bryden (1977), who showed that males generally perform better on "the Road Map Test" which assesses spatial orientation, and Crook, Youngjohn and Larrabee (1993) who used a test of topographic memory. A review of gender differences in spatial ability can be found in Voyer, Voyer and Bryden, (1995). Finally, Moffat *et al.* (1998) found that males learn a virtual maze more rapidly than females and this performance was correlated with paper and pencil tests of spatial ability.

1.4. CURRENT EXPERIMENTS AND THEIR METHODOLOGY

The present paper addresses the following hypotheses in a series of experiments. An individual's performance in navigating a virtual environment should show improvement with exposure as a cognitive representation is built up. Individuals with a high level of visual-spatial ability should perform better than those possessing a low level and for this reason males are generally expected to perform better than females. Presenting global motion information (the flow field) should result in better navigation knowledge than a similar exposure to a VE without this motion information. Finally, as an index of visual-spatial encoding effort, greater right hemisphere EEG activity should be evident during prolonged learning of a virtual navigation task.

In researching the way in which visual information may influence navigation performance, it is desirable first to separate the effects of static structure, flow field and degree of immersion by using very simple VEs. Static structure was presented in perspective view on a monitor in four of the experiments. This view was the 2D projection of a simple room showing the locations of doors which could be selected for moving to other rooms. This type of VE was called "static" since no motion cues were presented; a "move" or "turn" was performed in a single step between rooms. It is regarded as a VE in that

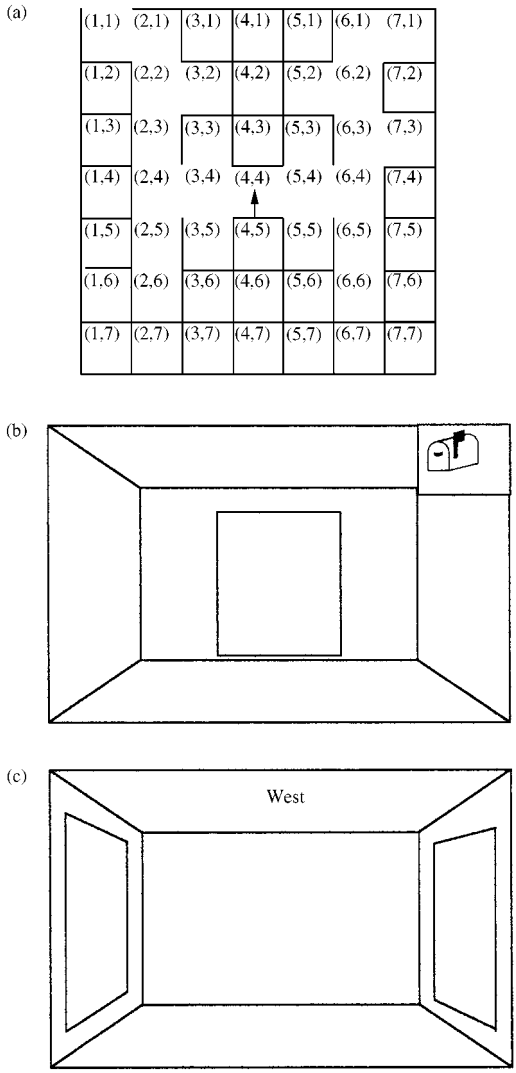

FIGURE 1. (a) One of the four mazes used in Experiments 1 and 2. Maze orientation is north up, and centre square (4,4) was always the starting location. (b) An example frame of the static maze, with a landmark cue that was used in Experiment 2 at location (2,6). (c) An example frame of the static maze, with a compass cue that was used in Experiment 2, at location (2,4).

the operations for moving follow spatial rules; for example, within a virtual maze [Figure 1(a)]. Motion cues were used in one of the other experiments to examine their contribution to acquiring navigational knowledge. By beginning with simple VEs which contain little structure and allow cues to be manipulated in a controlled fashion, the complex problem of determining exactly which factors influence navigation in VEs becomes tractable. It is also true, however, that performance in these restricted

environments will be less than optimal since potentially useful navigation cues may be absent. Results should be interpreted with this limitation in mind.

2. Experiment 1

Active movement through an environment entails taking control of the means of going from location to location. Passive movement entails simply viewing without having control over where or when movements take place. Experiment 1 was mainly concerned with assessing whether observers could learn to navigate through exposure to active or passive movement. A static VE maze was constructed in which an observer had a starting position (a room in the centre of the maze) and could perform simple actions: moving into a room on the left or right, turning around within a room and moving forward one room. The task was to find the exit from the maze. It was hypothesized that, if active learning engages cognitive processes important for navigation that are not engaged in passive learning, then better performance (fewer moves) would be observed in the active group. To test this hypothesis, each passive observer was shown a replay of an active observer's attempts to find the exit from the maze. Thus, the passive observers received identical visual stimuli and differed only in that they could not control the sequence of moves. No landmarks were present in the first experiment, limiting it to just the minimal conditions necessary to navigate the maze.

2.1. METHOD

2.1.1. Participants

Thirty-two participants (16 females and 16 males) were recruited from the first year course in behavioural sciences. The mean age was 23 (S.D. 8) yr. Participants were paid five dollars for participation.

2.1.2. Materials

A computer program was developed to present an interior view of a room. Rooms were connected together to form a maze. Each room contained from one to four doors (doors to the left, right or straight-ahead could be seen) to permit movement within the maze in the cardinal directions (north, south, east and west). A 32 cm high-resolution monitor and a three-button mouse were used as the interface. A seven by seven grid was used to create four variations of the maze. These four versions were used to give the results greater generalizability. Figure 1(a) shows one of these mazes. The total number of doors in the various mazes ranged between 21 and 33 and each had a different solution path to an exit. The number of doors along the solution path varied between 9 and 12. Figure 1(b) shows an interior view (a frame) of one of the maze rooms in which there is only a door straight-ahead. It also shows a landmark cue (defined below in Section 3) which was not used in Experiment 1 but was used in Experiment 2.

2.1.3. Experimental design and procedure

Active training consisted of being "placed" in the centre room of a maze [coordinates 4,4 in Figure 1(a)], with the same orientation for each trial. The goal in this task was to move

about in the maze and try to find the exit point. A trial ended when the maze exit was found (a screen prompt indicated this) or after 5 min, whichever occurred first. Passive training involved the real-time replay of the moves made during a recording of an active exploration of the maze.

Participants were paired on the basis of gender such that each active training female was paired with a passive training female and each active training male was paired with a passive training male. A practice maze was used to demonstrate movement using the mouse and keyboard. Doors could appear either to the left, ahead or right of the current position. Left, middle and right mouse buttons were used to select these doors, respectively, and the SHIFT key was used to turn around 180° in a room. When a door was selected, it was "highlighted" for 2 s, then an image of the next room was presented. Participants were thoroughly familiarized with using the mouse and selecting doors. Selecting a door or turning about each defined a "move" in the environment.

One of the four variations of the training maze was randomly assigned to each of the 16 matched pairs of participants and each variation was used four times. Four training trials on the same maze were given to the active participants and these moves recorded. The paired passive participants were shown a replay of their active partner's performance over the four training trials. A final active "test" trial was given to all subjects. There were two measures of performance: the number of moves and the time taken in each test trial. To provide a rough index of "success" in learning the route to the exit, a criterion of 15 moves was defined (this allows for a few incorrect moves in each maze).

2.2. RESULTS

For each of the experiments, a measure of effect size η^2, is provided for the important effects found significant in the overall ANOVA. The two measures of performance (number of moves and time used) were highly correlated, $r\ (15) = 0.95$, $p < 0.001$, as computed on the active participants grand scores. The time-to-exit distribution had a moderate negative skew, whereas the number of moves distribution was normal in shape, so the latter measure was the only one analysed further. A four mazes by three tests mixed ANOVA was performed.†

Only the main effect of test was found to be significant, $F(1.66, 23.17) = 3.88$, $p < 0.05$ ($\eta^2 = 0.123$). The first active trial (that is, the first trial of the active group) had a mean of 46.0 ± 7.1 moves,‡ the fourth active trial had a mean of 30.0 ± 7.0 moves and the passive condition had a mean of 24.5 ± 5.7 moves. This effect was further analysed using one-tailed tests for each of the three possible comparisons. The last trial's performance of the active group was found to have significantly fewer moves $t(15) = 1.79$, $p < 0.05$ than the first active trial. The performance of the passive group was also shown to have significantly fewer moves than the first trial of the active group, $t(15) = 2.44$, $p < 0.05$. The difference between the final trial performance of the two groups was not statistically significant.

† To correct for violations in sphericity for effects involving the repeated factor (tests), the Greenhouse-Geisser epsilons were used to compute the p values (Keppel, 1982). The adjusted degrees of freedom are reported throughout this paper.

‡ Means are reported $\pm$standard error of the mean.

There was information transfer from the active group to the passive group, as indicated by a significant correlation between the final tests for each group, $r(15) = 0.43$, $p < 0.05$ (one tailed). When the "success" criterion of 15 moves or less was used to assess performance, 8 active and 10 passive participants of the 16 in each group met the criterion. The χ^2 test was not significant.

2.3. DISCUSSION

These results show that a few exposures to static views of the simple maze environment lead to navigational knowledge, regardless of whether the exposure was active or passive. Many participants failed to make the criterion of 15 moves to exit the maze, attesting to the task's difficulty. However, it is possible that maze learning might be significantly facilitated with the introduction of additional cues.

Experiment 1 was unable to compare performance across gender since there was considerable age variation in the sample. Male subjects tended to be older in the sample and debriefing revealed a considerable range of experience with mouse-based screen interfaces. Experiment 2 examined the possible effects of gender without this age-experience confound.

3. Experiment 2

In this experiment, following Ruddle *et al.* (1997, Expt 3), landmark information in the form of a unique icon of an every-day object (e.g. a camera) was associated with each maze room to provide the navigator with location, but not bearing nor orientation, information. It was hypothesized that this cue would be useful in learning the sequence of moves in the solution path which takes the participant from the centre to the exit in the fewest moves. That is, over trials, each landmark would acquire an association with a correct operation (forward, left turn or right turn). This could be used as the basis of a route strategy. A second cue condition was the display of the current "compass" heading (north, south, east or west). This was expected to facilitate the development of a survey knowledge of the solution path. For example, in noting the final heading on finding the exit, this information could be used during future trials to reduce uncertainty about the absolute location (survey information) of the exit. Thus, the kinds of internal representations that support virtual navigation could be investigated in comparing performance on these two conditions. After Moffat *et al.* (1998), six learning trials were used.

Different strategies may be used by males and females to solve a navigation problem given the findings of gender differences in some fundamental visual-spatial skills as noted above. It was hypothesized that males would benefit most (in operational terms of learning to find the exit from a maze in as few moves as possible) from an orientation cue (compass heading). Females, on the other hand, were hypothesized to benefit most from a route-learning cue (landmark).

3.1. METHOD

3.1.1. Participants

Forty-eight participants were recruited from the undergraduate programme in behavioural science. There were 24 males with a mean age of 22 yr (SD 5) and 24 females with

a mean age of 21 yr (SD 4) with a range of 18–34 yr. All participants were experienced with mouse and screen computer interfaces.

3.1.2. Materials

The materials were similar to Experiment 1 except that two types of cue were added to the display. A picture was presented in the top right corner as a landmark icon for each room [Figure 1(b)]. The other cue was an indicator of direction (north, south, east or west) which was displayed at the top centre of the screen [Figure 1(c)]. North was defined as the starting orientation.

3.1.3. Experimental design and procedure

Participants were randomly assigned to one of three display conditions such that there were eight males and eight females in each condition. The "landmark" condition presented just the picture cue in each room, the "compass" condition provided just the compass heading cue, and the "no-cue" condition was identical to Experiment 1. The computer interface familiarization procedure was the same as in Experiment 1. Each participant was then randomly assigned to one of the four variations of the maze from Experiment 1, such that these were distributed equally over gender and cue conditions. Each participant was given six trials in which to actively explore the maze with the goal to find the exit. A trial was terminated if the exit was not found in 5 min. The number of moves was recorded for each trial.

Upon completion of the learning trials, participants were provided with a 7×7 grid on paper, which they asked to treat as a map. An upwards arrow was placed in the centre square to provide the initial spatial orientation. They were instructed to draw the shortest path through the grid squares that would lead to the exit. Only right-angle turns and straight-ahead moves were permitted. Three measures were recorded: absolute path distance error which was the absolute difference between the actual path distance (start to exit) and the path drawn by the participant; absolute Euclidean distance error which was the straight-line distance between the actual exit point and that drawn by the participant; and the number of correct turns used by the participant to specify the path to the exit. This last measure was used to assess the general shape of the drawn path with respect to the true path.

3.2. RESULTS

3.2.1. Number of moves during learning trials

The number of moves on each trial was analysed with a four-factor mixed ANOVA (maze, gender, cue condition and trials). There was a significant main effect of gender $F(1,24) = 4.52$, $p < 0.05$ ($\eta^2 = 0.11$), with males requiring fewer moves to find the exit. There was a main effect of trials, $F(3.98, 95.45) = 4.86$, $p < 0.001$ ($\eta^2 = 0.103$) with a decrease in moves over trials. The most interesting effect was the three-way interaction between cue, gender and trials, $F(7.95, 95.45) = 2.20$, $p < 0.05$ ($\eta^2 = 0.094$) (see Figure 2). This effect was analysed further by computing the two-way interaction between gender and trials for each cue condition separately. This two-way interaction was not significant for either the no cue or compass conditions, but the interaction was significant for the

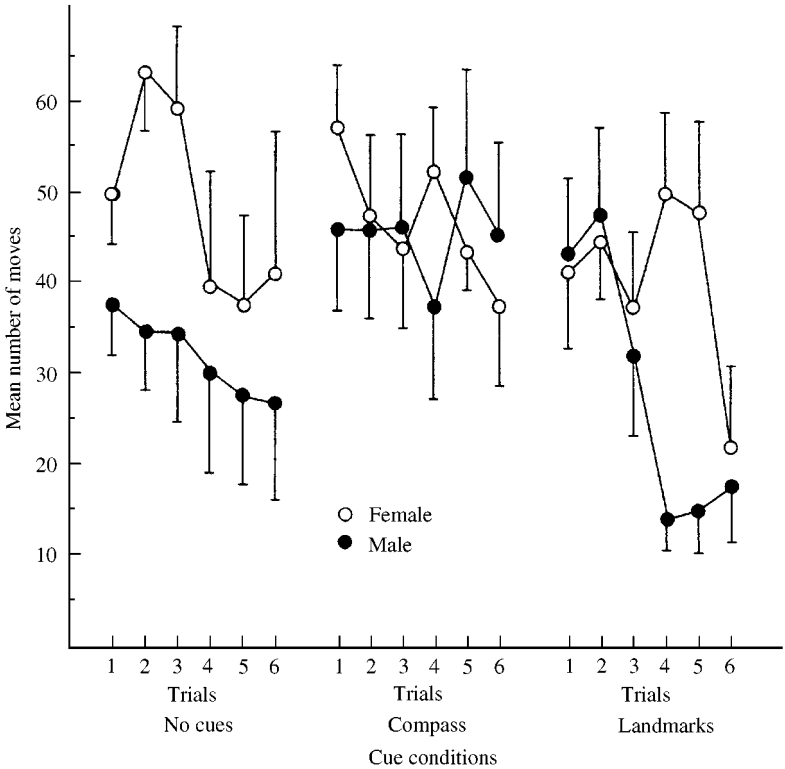

FIGURE 2. Experiment 2. Mean number of moves to the exit over six learning trials plotted for males and females for each of the three cue conditions.

landmark condition, $F(3.21, 44.87) = 3.48$, $p < 0.05$. A simple main effects analysis for the landmark condition showed the number of moves for both males and females to decrease over trials. However, a Dunnet test which compared each trial to the first trial (for each gender separately) in the landmark condition revealed that, for males, by the fourth trial the number of moves was significantly ($p < 0.01$) fewer, but for females this did not occur until the sixth trial.

3.2.2. Analysis of maps

One participant's map results was unscorable leaving 47 maps. Since each of the three map measures contained at least 74% unique variance (as determined by regressing two of the variables on the third), each of these measures was examined separately with a three-factor (maze, gender, cue condition) between groups ANOVA. For the passage distance accuracy measure the only significant effect was that of gender, $F(1,23) = 4.21$, $p < 0.05$ ($\eta^2 = 0.21$), with males being more accurate (mean error 1.26 ± 0.36 room-sized units). For the Euclidean distance to the exit measure, there was a main effect of group, $F(2,23) = 4.21$, $p < 0.05$ ($\eta^2 = 0.268$), as seen in the mean for no-cues, compass and landmark conditions: 4.12 ± 0.68, 2.68 ± 0.68 and 5.32 ± 0.85, respectively. Tukey's HSD comparisons between the three cue conditions showed the compass condition to be

significantly more accurate than the landmark condition, $p < 0.05$. The analysis of the number of correct turns measure revealed no differences.

3.3. DISCUSSION

This second experiment investigated the effects of cue type and gender on learning to navigate from the centre to the outside of a virtual maze. Males clearly made very effective use of the landmark cue. Females did also, but required more trials to achieve a similar level of performance. These findings are in general agreement with Moffat *et al.* (1998) and Sandstrom, Kaufman and Huettel (1998). Although the compass condition did not facilitate exit-finding behaviour, it did yield the most accurate estimates in the absolute location of the exit. This could be accounted for by a route representation having developed during the learning trials which is best facilitated by the presence of landmarks. Knowing the absolute location of the exit (survey knowledge) may not support actual navigation to the exit in such a closed environment with each view providing only local information. The result here favours the hypothesis that this kind of maze task may best be solved using a route strategy.

4. Experiment 3

Experiment 3 investigated cognitive variables theoretically related to performance in navigation of the environment. In particular, it was hypothesized that a test of visual-spatial ability might be used to define two groups of people, either high or low on this ability. The block design test of the WAIS-R battery (Wechsler, 1981) was used as it has very good psychometric properties and appears to tap visual-spatial ability without relying on memory. The person being tested is provided with a set of blocks each side of which is coloured either red or white, or half-red and half-white. A picture of a complex red and white pattern is provided and the task to copy it using the blocks. This test involves the ability to both decompose spatial patterns and synthesize them from pattern components. It is highly correlated with the visual-spatial IQ of the full battery (Wechsler, 1981).

Thorndike and Hayes-Roth (1982) have suggested that route knowledge precedes survey knowledge. A measure of route knowledge would thus be expected to show a more rapid acquisition across learning trials than a measure of survey knowledge. To test this hypothesis, VE distance estimation tests were given to groups that had been exposed for differing numbers of trials to a simple passageway VE. This type of VE permitted control over the amount of information that was presented, a control that is difficult to establish when free exploration is possible as in Experiments 1 and 2.

Gender was found to affect navigation performance in Experiment 2. As Moffat *et al.* (1998) point out, this may be partly due to males having greater experience with video games. On the other hand, it could be due to males having better spatial abilities (Voyer *et al.*, 1995). For these reasons, in the following experiments only female participants were used. While the conclusions must therefore be limited to this population it was deemed important to test the hypotheses that better navigation performance is related to superior spatial skills in a homogeneous sample.

4.1. METHOD

4.1.1. Participants

Thirty-seven female participants with a mean age of 24.4 (S.D. 8.3) were recruited from the undergraduate programme in behavioural science.

4.1.2. Materials

The navigation task was presented with the same software as in Experiments 1 and 2. A virtual passageway was generated consisting of 16 rooms connected by doors to form a passageway [see Figure 3(a)]. There were no choice points, each room led to only one other room. Only at the end of the passageway was an option present to turn around and navigate in the opposite direction. The maze software was modified to present two distance estimation follow-up tests. To assess the knowledge of distance to various points

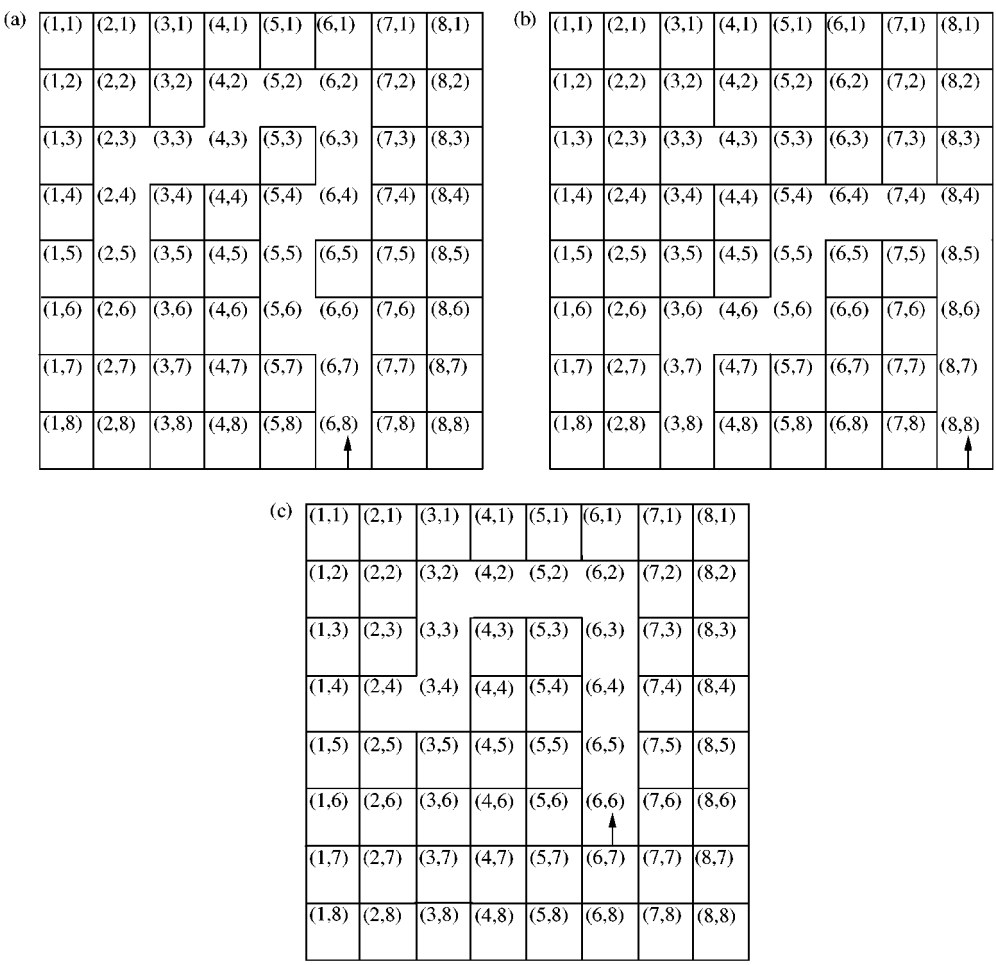

FIGURE 3. Passageway mazes used in (a) Experiment 3, (b) Experiment, 4 and (c) Experiment 5.

along the passageway, training was done using the landmarks (as per Experiment 2) in order to be able to refer to these locations in the test phase. In addition, the block design test of the WAIS-R battery was administered to participants in its standard format.

4.1.3. Procedure and experimental design

There were four phases in this experiment. In phase one the block design test was given and the age scaled scores recorded as described in the test manual. In phase two a practice maze with no landmarks was used to demonstrate the navigation task, followed by a single practice trial by the participant. In phase three participants were randomly assigned to one of four learning conditions: 2, 4, 8, or 16 trials. The same initial location ("start") was used on each trial. Participants were asked to move from room to room along the passageway to the end, then to turn around and return to the start room. The program then terminated the trial, and paused until the participant initiated the next trial. Participants were told to learn the layout of the passageway and to remember where each of the landmark icons were located as a test of this would occur at the end of the learning trials. In phase four, the two distance estimation tests were given, a passage distance test and a Euclidean distance test. For both of these tests, each landmark icon was presented on a white background on the computer screen and distances were to be estimated relative to the start room. For the passage test, the distance along the passageway was to be estimated in terms of the number of room-sized units. For the Euclidean distance test, the straight-line distance to the room with the landmark was to be estimated in these units; that is, as if there were no walls barring the way and one could move to that location in a straight line. The estimation error was recorded for each of these tests.

4.2. RESULTS

A median split was performed on the WAIS-R block design scores. Participants scoring above the median were classified as "high" on visual-spatial ability and participants scoring below the median were classified as "low" on visual-spatial ability. In fact, a score of 12 or less occurred for 57% of the sample with 43% scoring 13 or higher. This permitted the data to be statistically analysed as follows: two visual-spatial ability groups by four learning trial groups by two test measures. The dependent variable was the absolute error of distance estimation in room-size units.

There was a significant main effect of trials, $F(3,29) = 3.17$, $p < 0.05 (\eta^2 = 0.247)$, with distance estimation error generally decreasing with increased exposure across the four trial groups: 2.60 ± 0.34, 2.01 ± 0.25, 1.50 ± 11 and 1.75 ± 0.20. Trend analysis revealed that only the linear term was significant ($p < 0.01$). There was an interaction between group and test, $F(1,29) = 6.34$, $p < 0.05$ ($\eta^2 = 0.179$) (see Figure 4). Simple main effects analysis showed the two visual-spatial groups to be similar on the passage estimation test ($p < 0.5$), but the high visual-spatial group was significantly more accurate on Euclidean distance estimation than the low visual-spatial group, $F(1,35) = 4.67$, $p < 0.05$.

4.3. DISCUSSION

This experiment has shown that both route knowledge (as indexed by accuracy in passage estimates) and survey knowledge (as indexed by accuracy in Euclidean estimates)

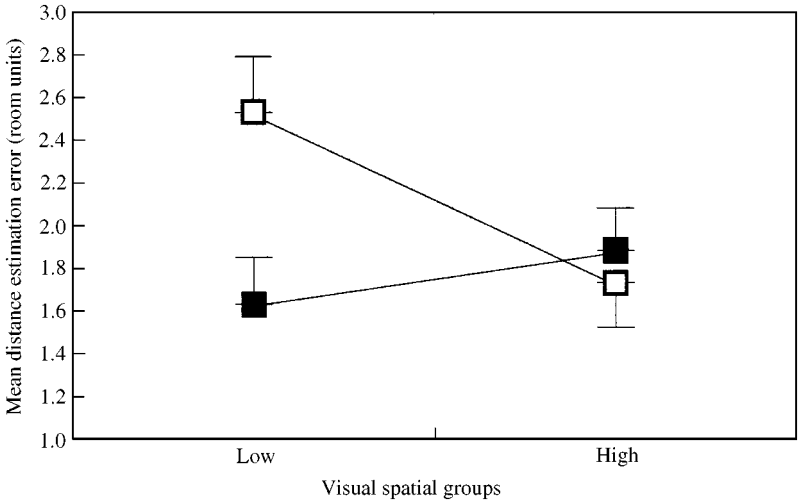

FIGURE 4. Experiment 3. Mean estimation error for the two distance estimation tests following learning trials: ■ passage; □ euclidean.

can develop with increased exposure to the navigation task in a static VE. More importantly, individuals identified to have superior visual-spatial ability appear to develop superior survey knowledge. It was concluded from Experiment 2 that a route representation accounts for maze-exit finding behaviour and Experiment 3 replicates this (in both groups) but goes further to show that survey knowledge may also be acquired by some individuals. Clearly, work on navigation of a VE should take into account the visual-spatial ability of the navigator when speculating on the nature and rate of acquisition of the representation that is learned following navigation experience.

5. Experiment 4

This experiment compared navigation of a VE with and without dynamic cues. That is, while the two VEs both contained static depth cues, only one of them presented flow-field information. There is no previous work which has specifically examined the influence of flow field cues on VE navigation; however, the additional information provided by optical flow was expected to facilitate the development on an internal representation of the VE. In particular, the spatial structure of the VE should be better encoded as optical flow provides information about movement of the observer. Identical passageway layouts were created, one as a static VE (as used in the above experiments) and the other as a dynamic VE. Participants were exposed to one of these VEs by navigating from one end of the passageway to the other in unidirectional training trials.

Experiment 3 found that participants could be usefully classified into low and high visual-spatial ability. In this experiment, a test of verbal-sequential ability was included as the putative opposite "pole" to visual-spatial ability. Scores on each of these measures were then subtracted from each another to result in a "cognitive style" measure: "verbal-sequential" at one extreme and "visual-spatial" at the other. Naglieri and Das

(1987) have proposed such a construct. Individuals classified as "verbal-sequential" would be expected to excel at VE navigation when the serial encoding of landmark information facilitates performance, but would have difficulty navigating in a direction opposite to that presented in learning trials. An analogy for this is the articulation of the alphabet. Adults can generally articulate the alphabet from "A" to "Z" effortlessly, but a significant cognitive effort is required to articulate it from "Z" to "A". This is, presumably, because the alphabet is stored in a biased or unidirectional fashion. At the other pole, individuals who have relatively higher visual-spatial ability will tend to acquire survey (or map-like) knowledge. That is, these individuals should be able to encode absolute Euclidean distance information more easily and be able to navigate a path well both forwards and backwards. Therefore, first it was hypothesized that the dynamic VE would enable better performance than the static VE. Second, it was hypothesized that the verbal-sequential group would be superior to the visual-spatial group on a forward navigation test, whereas the visual-spatial group was hypothesized to outperform the verbal-sequential group on the backwards navigation test.

5.1. METHOD

5.1.1. Participants

Twenty-four females were recruited from the same source as Experiment 3 and were already familiar with the point-and-click mouse interface.

5.1.2. Materials

A passageway with 14 rooms was designed [Figure 3(b)] and implemented as both a static VE (as in the above experiments) and as a dynamic VE. This latter environment was constructed using the Doom® software system with an editor package which permits the construction of maze layouts. For the dynamic VE, a simple grey speckled pattern was texture mapped onto the walls to provide the flow field information. This was identical throughout the maze. As before, the keyboard arrow keys were used to move forward, left and right in both VEs. Pressing the space bar opened a door in the dynamic VE.

5.1.3. Design and procedure

The block design and picture arrangement sub-tests of the WAIS-R were administered at the beginning of the test session. A polarity score was computed as follows: age-scaled score on block design minus the age-scaled score on picture arrangement. Participants were later classified into two cognitive style groups using a median split on the polarity score. Thus, the experimental design was two (cognitive style: verbal-sequential, visual-spatial) by two (VE types: static, dynamic) by two (navigation tests: forward, backward), with the latter two factors being repeated measures.

Participants were randomly assigned to one of the two VEs, then completed four trials. Participants were instructed to move from room to room and to try and remember the layout of the passageway and the location of the landmarks as these would later be tested. Each trial started from the same room or "start" of the passageway. When the "finish" room of the Passageway was reached the trial terminated. Thirty seconds later,

the next trial began. All participants completed each trial within 2–3 min. Following the learning trials, forwards and backwards navigation tests were given in counterbalanced order. Tests were identical except for the initial position. In the forwards test the initial room was the start room and in the backwards test it was the finish room. On these tests each room presented the participant with three doors (to move left, forward and right) of which only one permitted movement to the next room. The dependent variable was the number of doors correctly chosen on the first attempt.

5.2. RESULTS

A three-way mixed ANOVA was performed on the number of correct choices made for the forward and backward navigation measures. There was a significant main effect of cognitive style, $F(1,20) = 13.06$, $p < 0.01$ ($\eta^2 = 0.395$), with the visual-spatial group achieving higher navigation scores. There was a significant main effect of environment, $F(1,20) = 5.27$, $p < 0.05$ ($\eta^2 = 0.224$), with the better performance occurring for the dynamic environment. Cognitive style and environment factors interacted, $F(1,20) = 5.76$, $p < 0.05$ ($\eta^2 = 0.224$). Figure 5 illustrates that participants with a visual-spatial cognitive style perform significantly better in the static VE condition than participants with a verbal-sequential cognitive style, $F(1,10) = 12.11$, $p < 0.01$. On the other hand, there was no difference between the cognitive style groups for the dynamic environment. Figure 6 illustrates a significant interaction of navigation test with cognitive style, $F(1,20) = 6.09$, $p < 0.05$ ($\eta^2 = 0.233$). Simple main effect analysis showed that the visual-spatial group had a higher mean score on the backwards test, $F(1,22) = 11.19$, $p < 0.01$, but the forwards test was not significantly different between the groups.

5.3. DISCUSSION

The interaction of cognitive style and environment type indicates that visual-spatial ability is an important predictor of navigation performance in the absence of flow-field information but when this information is provided the cognitive style groups perform similarly (Figure 5). The absence of motion cues may put a higher demand on visual-spatial cognition and flow-field information may provide informative cues that overcome limitations in visual-spatial ability during navigation of a VE. This could occur from the flow field providing spatial information which facilitated the development of an internal representation of the passageway layout. The interaction between cognitive style and navigation test showed, however, that visual-spatial cognitive style improved performance in backwards navigation and it did not appear that verbal-sequential cognitive style provided any advantage in the forward navigation, contrary to expectations (Figure 6). Thus, an internal representation which is acquired with facility by individuals scoring relatively higher on visual-spatial ability, is sufficient for good performance of both forward and backward navigation of a path that has been learned in only one direction. This orientation-free representation may be regarded as a cognitive map of the environment in which navigation information can be easily accessed in either direction. Individuals in the verbal-sequential group, however, may learn a different representation which favours navigation in the same direction in which exposure occurred.

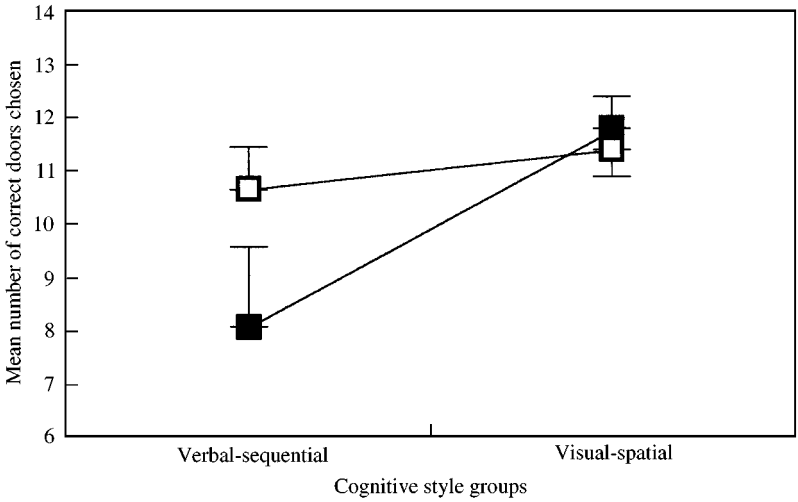

FIGURE 5. Experiment 4. Mean number of correct doors chosen, averaged over forwards and backwards navigation tests, by each cognitive style group under dynamic versus static VE conditions: ■ static VE; □ dynamic VE.

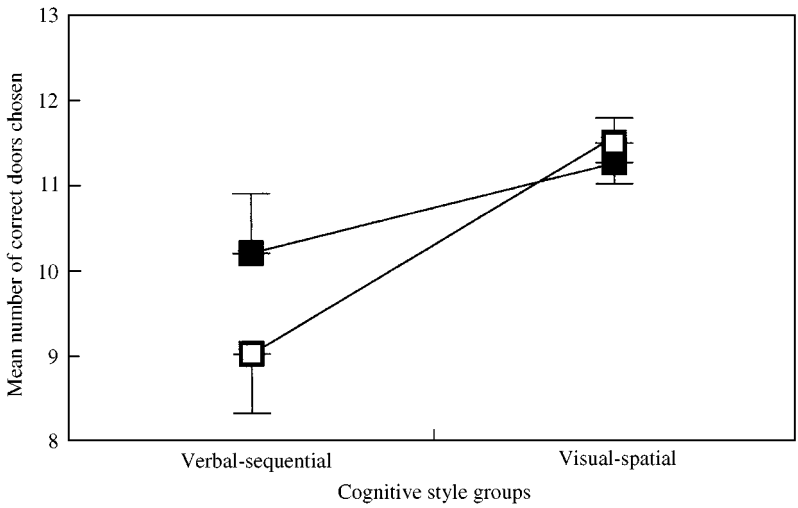

FIGURE 6. Experiment 4. Mean number of correct doors chosen in the forwards and backwards navigation tests: ■ forwards; □ backwards.

6. Experiment 5

Kolb and Wishaw (1990) review neuropsychological evidence supporting the thesis that the right cerebral hemisphere is involved in visual-spatial problem solving. More recently, Kosslyn *et al.* (1995) have argued that specialized right cerebral hemisphere

processes compute angles and distances between objects according to an imposed coordinate system. The EEG has been found to be a useful tool for determining cortical asymmetry of neural activation during cognitive tasks (Davidson, Chapman, Chapman & Henriques, 1990) and this may appear as relatively greater activation of the right hemisphere at higher EEG frequencies for visual-spatial tasks (Spydell & Sheer, 1982). Since VE navigation appears to involve visual-spatial ability, it was hypothesized that right cerebral hemisphere asymmetry would occur during Ve navigation.

Furthermore, Donchin, Kutas and McCarthy (1977) have shown that greater visual-spatial cognitive effort should amplify this asymmetry. Since a person weak in visual-spatial ability would have to exert greater cognitive "effort" to perform the navigation task, it was hypothesized that greater asymmetry would be shown in this group compared to a high visual-spatial ability group. Experiment 3 showed that eight training trials results in asymptotic performance using a 16-room passageway VE. To ensure that both groups would reach maximal performance in the present experiment, a relatively easy task was used consisting of eight training trials in an 11-room maze.

6.1. METHOD

6.1.1. Participants

Forty-eight female participants were given a pre-test for cognitive style. The 10 participants scoring on either end of this continuous scale were included in the remainder of the experiment. The mean age of this final sample was 20.1 yr (S.D. 2.9).

6.1.2. Materials

A static VE passageway of 11 rooms [Figure 3(c)] with landmarks was used. WAIS-R sub-tests block design, object assembly, digit span and arithmetic were used in their standard format. A Neuroscan™ Synamps system was used with a 10–20 electrode cap (Jasper, 1958).

6.1.3. Design and procedure

A slightly different measure of cognitive style was computed as compared to Experiment 3. Subjects were given the four WAIS-R sub-tests and a cognitive style score was computed using the following formula on age-scaled scores: the average of two visual-spatial tests, block design and object assembly minus the average of two verbal-sequential tests, digit span and arithmetic (Wechsler, 1981). Ten participants scoring at each extreme on this resulting scale were included in the remainder of the study. Standard procedures were used for recording EEG (Ray, 1990). The VE was presented on a computer monitor inside a shielded room with the participant seated 1 m away in a padded recliner. Demonstration, practice and passageway learning trials were given as per Experiments 3 and 4. Eight learning trials were presented with continuous EEG being recorded. Four post tests were then given in random order: two distance estimation tests (passage and Euclidean), as in Experiment 3, and two navigation tests (forwards and backwards) as in Experiment 4. The continuous recording was split into four-second epochs to quantify the EEG. Eye movement artefact was attenuated using the computational procedure described by Semlitch, Anderer, Schuster and Presslich (1986). The

average power (amplitude squared) was computed for two frequency bands, 15–30 and 30–40 Hz. Homologous electrodes were used to compute a power asymmetry for the sites: T3–T4, T5–T6, F3–F4, C3–C4 and Pe–P4. Asymmetry was defined as the difference in power between homologous sites (right minus left) divided by the sum of the power at homologous sites (Pivik *et al.*, 1993).

6.2. RESULTS

6.2.1. Behavioural results

A two (cognitive style groups) by two (navigation tests) mixed ANOVA was computed on the number of correctly chosen doors. The main effect of tests was significant, $F(1,18) = 10.86$, $p < 0.01$ ($\eta^2 = 0.376$); more correct doors were chosen in the forwards test (mean 8.8 ± 0.45) than in the backwards test (mean 7.50 ± 0.46) out of a maximum score of 10. The same ANOVA design was conducted on the distance estimation tests. Again, only the main effect of tests was significant, $F(1,18) = 17.53$, $p < 0.001$, ($\eta^2 = 0.493$); Euclidean distance (mean error 0.85 ± 0.06) was estimated more accurately than passage distance (mean error 1.56 ± 0.21).

6.2.2. EEG measures

A two (cognitive style groups) by five (homologous pair sites) by two (frequency band) mixed ANOVA was computed, with sites and bands as repeated measures. Figure 7 presents the mean power asymmetry for each site, frequency band and cognitive style group. Overall, there was significantly greater power in the right hemisphere, $F(1,18) = 14.38$, $p < 0.001$, ($\eta^2 = 0.444$). This is reflected in the figure by the prevalence of positive values. There was a marginal main effect of site, $F(4,72) = 2.35$, $p < 0.06$, ($\eta^2 = 0.116$) with the T3–T4 homologous pair having the highest mean asymmetry. There was a significant main effect of frequency band, $F(1,18) = 11.68$, $p < 0.01$, ($\eta^2 = 0.394$). However, there was also a significant interaction between cognitive style group and frequency band, $F(1,18) = 4.67$, $p < 0.05$ ($\eta^2 = 0.206$). For the high-frequency band, the verbal-sequential group showed significantly greater asymmetry (mean $= 0.14 \pm 0.04$) than the visual-spatial group (mean $= 0.04 \pm 0.04$), $t(18) = 1.73$, $p < 0.05$. For the low-frequency band, the verbal-sequential group (mean $= 0.15 \pm 0.05$) and visual-spatial group (mean $= 0.09 \pm 0.04$) did not differ significantly ($p > 0.3$).

6.3. DISCUSSION

Statistical analysis confirmed that there were no differences between the cognitive style groups across the four post-tests of VE knowledge and test scores were generally quite high. Thus, the goal of equalizing the two groups knowledge of a simple VE passageway appeared to be successful. This permitted the main objective to be examined: namely, that participants relatively weak in visual-spatial ability (i.e. the verbal-sequential style group) would have to expend greater cognitive effort to achieve a similar level of VE knowledge compared to a group with strong visual-spatial ability. This hypothesis was confirmed with the cognitive style group by frequency band interaction. The verbal-sequential group had significantly higher power asymmetry in the 30–40 Hz band than the visual-spatial group. Cognitive activity results in desynchronisation of EEG in

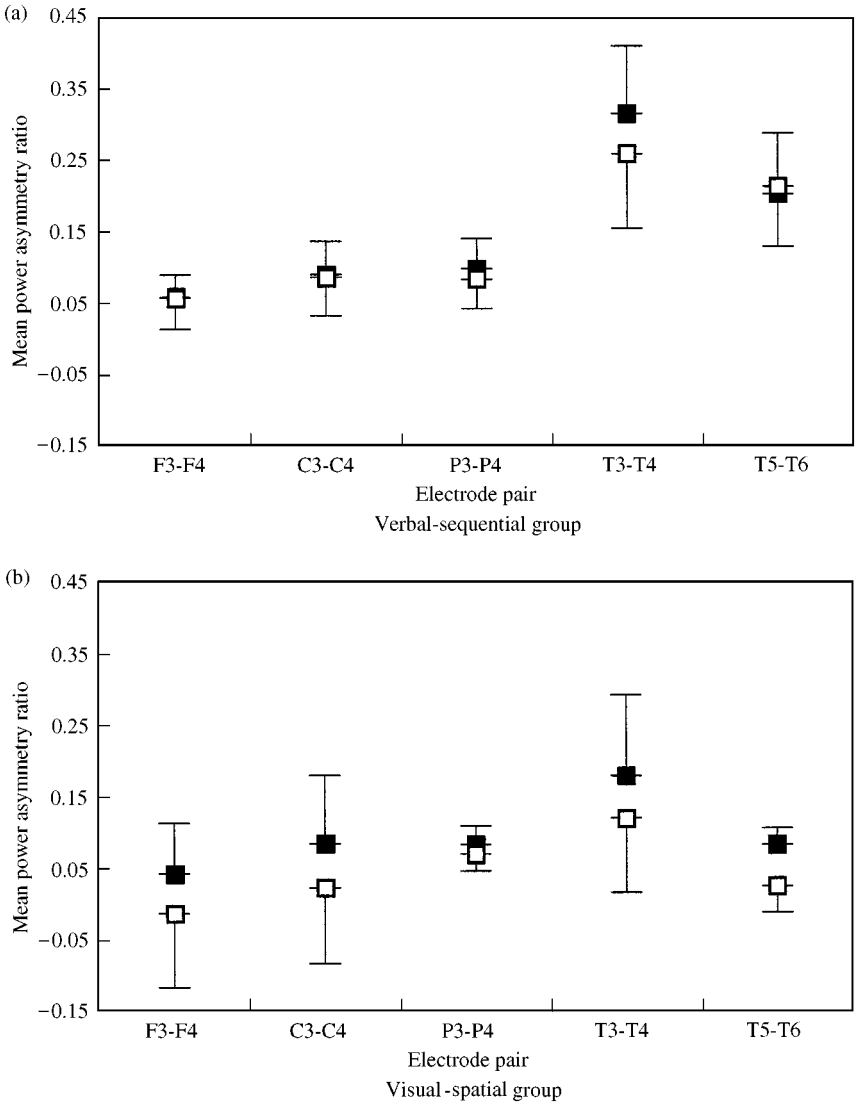

FIGURE 7. Experiment 5. Mean power asymmetry ratio for each cognitive style group—(a) verbal-sequential, (b) visual-spatial—shown at each homologous electrode pair for each frequency band: ■ low frequency; □ high frequency.

cortical regions where the activity occurs (Papanicolaou, Loring, Deutsch & Eisenberg, 1986) and this can be quantified by power analysis. Thus, the greater right hemisphere high-frequency asymmetry in the verbal-sequential group can be taken as evidence of greater right hemisphere involvement (or cognitive effort) during VE navigation (Donchin *et al.*, 1977; Earle, 1985).

This result is unlikely to be due to the motor demands of the task, which only required occasional button presses with the right hand (see Donchin *et al.*, 1977; Davidson *et al.*,

1990). Since EMG activity during problem solving tends to be bilateral and make little contribution to EEG activity (Spydell & Sheer, 1982; Loring & Sheer, 1984) this potential source cannot explain the asymmetry differences.

Finally, although baseline measures were not taken, the EEG laterality index used tends to show increased left hemisphere dominance during inactivity (Loring & Sheer, 1984) and thus it is unlikely that this can account for the results. Also, previous research has shown the right cerebral hemisphere to be involved in visual-spatial tasks (Springer & Deutsch, 1981). The overall right-hemisphere asymmetry (for both groups) during VE navigation is consistent with the proposal that this task engages brain regions responsible for visual-spatial processing (Loring & Sheer, 1984).

7. General discussion

7.1. THE ACQUISITION OF NAVIGATIONAL KNOWLEDGE

The five experiments reported here aimed to investigate some of the cognitive factors that may influence acquisition of navigational knowledge in a VE. The approach taken was based on the philosophy that these factors may best be studied by initially examining impoverished VEs and then adding elements that are hypothesized to influence VE navigation and knowledge acquisition.

In Experiment I, it was shown that a simple VE that presented the human with nothing more than a series of bare frames, each providing a view of a VE maze room, supported the acquisition of spatial knowledge about the VE. This knowledge was acquired by either active or passive exploration. Experiment 2 used this static VE and added two potentially useful cues, compass heading and landmarks. Compass heading did not appear to aid navigation in these maze exit-finding tasks. However, it was found that males made use of landmarks with significantly greater efficiency than females, although for both genders landmarks provided useful navigation cues. This gender difference is consistent with many studies which have found that males perform significantly better on visual-spatial tasks (Linn & Petersen, 1985; Kimura, 1992; Voyer *et al*., 1995).

Having demonstrated these gender differences, the remaining three experiments addressed the question of whether individual differences in visual-spatial ability determined rapid acquisition of navigational knowledge. Thorndike and Hayes-Roth (1982) argued, on the basis of real-world environment exposure, that navigational experience leads mainly to route knowledge. According to this view, survey knowledge should not be easily obtained from navigational experience (i.e. with only a few exposures). Experiments 3–5 provided evidence that exposure to VEs, both static and dynamic, can lead to what is best described as survey knowledge and this appears to occur with greater facility (or less cognitive effort) in people who are relatively better at visual-spatial processing than verbal-sequential processing.

Experiment 3 showed that people classified as having high visual-spatial ability were better at Euclidean distance estimation than people scoring low on this sub-test. This provided evidence that high visual-spatial ability can support the acquisition of survey knowledge which includes representation of relative distance. Following Naglieri and Das (1987), Experiment 4 went further to define the nature of the cognitive skill involved in VE navigation with the development of a bipolar construct with verbal-sequential

cognitive style at one pole and visual-spatial cognitive style at the other. Averaging over both environments, the visual-spatial group was found to perform better than the verbal-sequential group. However, this difference was particularly evident in the static VE. Additional motion cues appeared to compensate for lower visual-spatial ability. The presence of flow field information in the dynamic display may facilitate the development of an internal representation by providing visual information about the 3D structure of the VE. This experiment also showed, however, that irrespective of VE type, people who score toward the visual-spatial pole perform better on backwards navigation. Thus, Experiment 4 further confirmed the importance of visual-spatial ability for VE navigation. Furthermore, it showed that survey knowledge can be rapidly acquired provided the individual is equipped with the requisite visual-spatial cognitive ability. On the other hand, individuals who are more adept at verbal-sequential processing may rely more on route knowledge for navigation.

Finally, the results of Experiment 5 emphasized the importance of the right cerebral hemisphere in the acquisition of spatial knowledge in a VE. The right hemisphere is frequently described as excelling at visual-spatial tasks (Lezak, 1995) and this is consistent with the right-biased asymmetry noted for both groups. The observation that verbal-sequential participants showed even greater asymmetry in the high-frequency band, in the face of similar navigational knowledge, than visual-spatial participants, can be taken as evidence of greater (compensatory) cognitive effort, or access to right hemisphere resources, to learn the VE. Differences in EEG asymmetry have been found to differentiate cognitive style (Doktor & Bloom, 1977) or cognitive mode (Galin & Ornstein, 1972) and thus differences in hemispheric activation may characterize problem-solving strategies during many tasks, including spatial navigation. T3–T4 comparisons have often been found to show this effect and this was the case in Experiment 5 (see Figure 7).

7.2. PRACTICAL IMPLICATIONS

VEs are a relatively inexpensive means of providing simulations of real-world situations such as a walk-through of a new architectural design, for training drivers to learn the routes of a city or providing naval officers opportunity to learn to pilot ships in a river. In each of these examples, an appreciation of the large-scale space will assist in meeting practical objectives. The present series of experiments provides findings which are relevant for the design and use of VEs; in particular, the following.

(1) Individual differences in spatial ability can result in qualitatively different mental representations of the environment. This has implications for use of a VE as a training tool. If the goal of training is to acquire the ability to draw maps, estimate Euclidean distances and navigate in an orientation-free manner, then either (a) prior selection of people with superior visual-spatial skill is recommended or (b) extended training time for average individuals may be needed or (c) explicit exposure and practice using maps of the environment may be needed.
(2) Not all individuals may benefit equally from certain VE information. For example, in learning the layout of a new city would it be necessary to use a dynamic display (with flow field information)? Experiment 4 has shown that if individuals have

a relatively good ability to solve visual-spatial problems then a static display may be equally effective as a dynamic display. This is likely to be more cost effective. Indeed, further research might show that emphasizing landmark features might be more efficacious for such individuals. On the other hand, people who do not have good visual-spatial ability may benefit more from a dynamic display, perhaps with less emphasis on landmarks. The possible interaction of flow field and landmark information requires further study.

(3) Gender of recruits for jobs involving virtual navigation (e.g. training using a VE) may be a factor to consider when designing training programs.

(4) Intuition concerning what might constitute an effective navigational aid (such as bearing information, Ruddle *et al.*, 1997, p. 158) may be erroneous in certain contexts (see compass results in Expt. 2) and thus empirical verification of potential aids is indicated.

(5) Finally, it appears that passive navigation may be as effective as active navigation, at least for some tasks. If this is true, for example in using a VE to learn the street layout of a city, then effort could be devoted to determining the most effective routes to display to trainees to minimize training time and make the training regimen uniform.

7.3. THEORETICAL IMPLICATIONS

Aguirre, Detre, Alsop and D'Esposito (1996) provide functional magnetic resonance imaging results which support the hypothesis that humans have place cells in the parahippocampus that permit VE navigational information such as direction and location to be maintained. The experiments of this paper and others provide data that human subjects can acquire route and survey knowledge from virtual navigation experience without stimulation of vestibular or gross kinaesthetic sensory systems. Thus, visual stimulation alone may result in these neural effects. It is not yet well understood why some individuals have superior spatial ability, which appears to be an important factor affecting virtual navigation. Perhaps part of this answer lies in more efficient functioning of the hippocampal place cells.

Kosslyn (1987) and Kosslyn *et al.* (1995) have argued for the existence of two basic forms of visual processing and mental imagery. The left hemisphere is capable of processing categorical spatial relations among objects or parts of an object, and makes use of verbal labels in the process. The right hemisphere processes mental images using coordinate spatial relations. That is, a coordinate system is imposed on the set of objects to be related and can be used to compute angles and distances between these objects. It is tempting to speculate that categorical spatial reasoning is the basis for the development of a route representation and coordinate spatial reasoning is the basis for the development of a survey representation. The results of this study are clearly consistent with this possibility, particularly in regard to the EEG asymmetry findings. This theoretical integration of navigation processes into Kosslyn's more general framework could help to give the study of navigation a more firm theoretical basis than it has had to date.

7.4. FUTURE WORK

The last three experiments tested only female subjects. Thus, it is important that future work extend these findings to males to determine if gender interacts with any of the other

factors found to influence the acquisition of navigational knowledge. Further research is also needed to examine more fully the effect of moving texture (i.e. the effect of the flow field) in building internal representations of spatial layout of objects or in storing path information. A VE composed solely of a fixed set of random points dispersed in three dimensions could convey movement information without contamination from other sources such as landmarks or distant fixed navigation aids (such as the sun provides). This would extend the research within the philosophy adopted in the present study, to hold as many factors constant and manipulate only one or two to determine their unique contribution to the acquisition of navigational knowledge.

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