# *The cognitive mapping of virtual space*

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# THE COGNITIVE MAPPING OF VIRTUAL SPACE

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# Contents

# 1. Literature Review

*'Christopher Longuet-Higgins has devised a beautiful demonstration of the functional essence of representations. A simple robot moves around on top of a table. Whenever it is about to fall off, it rings an alarm bell to summon its human keeper. The robot has neither an electronic camera nor any kind of pressure sensors, so how can it possibly perceive the edge of the table? The answer turns - literally - on a representation. The robot has two main wheels, one on the middle of each side, which drives two smaller wheels that hold a piece of sandpaper up beneath its baseplate. The paper is the same shape as the table. As the small wheel turns, they move the paper around beneath the baseplate so that any moment their position on the paper corresponds to the position of the robot on the table. When the small wheels reach the edge of the paper a circuit is closed to ring the alarm bell. The main wheels are thu, both a means of transport and perceptual organs registering the robot's movement around the table. The position, A, of the robot corresponds to the position A', of the smaller wheels on the paper, and this position governs the robot's action of sounding the alarm. In short, the robot has a rudimentary representation of its position on the table-top.'*

*Johnson-Laird, 1993, p. xii*

## 1.1 Introduction

As the title of this thesis is the 'cognitive mapping of virtual space' a number of preliminary definitions are required to elucidate the area of research addressed.

*Cognitive mapping* is operationally defined as the process or processes by which a cognitive representation of an environment is acquired. The process of cognitive mapping necessarily gives rise to a cognitive map, definitions of which may be found below in section 1.1.2.

*Virtual space* is again operationally defined as a computer generated - hence *virtual* - environment which may be viewed and / or explored and which as a consequence may have spatial properties.

Therefore the domain of this enquiry is the nature of the cognitive representation of the spatial properties of virtual environments. The methodology adopted is one of inter-feature distance and angle estimation and the subject matter is a series of simple regular virtual environments.

### 1.1.1 Overview

This chapter reviews the research into cognitive maps and other relevant aspects of spatial cognition and has the following structure:

Introduction

- Is this section and describes the field of research and provides some preliminary definitions.

Spatial cognition I: an account of spatial cognition

- This, the largest section, gives a broad overview of the study of spatial cognition from a variety of different disciplines ranging from ecological to cognitive psychology.

Spatial cognition II: distance and angle estimation

- This section is of particular relevance as it reviews models of distance and angle estimation which will be employed throughout the experiments reported in this volume.

Spatial cognition III: primary & secondary spatial knowledge

- Spatial knowledge can also be acquired from representations of space such as maps and diagrams as well as textual descriptions. This section reviews such evidence.

Spatial cognition IV: computational approaches

- A number of different approaches to modelling spatial cognition are considered. The first has adopted a route often associated with artificial intelligence (i.e. the use of production rules and explicit data structures), the second employs a connectionist paradigm.

Spatial cognition V: an introduction to virtual reality

- Finally, the emerging psychology of immersive and non-immersive virtual reality is reviewed.

Summary

- Is just that.

Structure of thesis

- This final section outlines the chapters of this thesis.

### 1.1.2 Cognitive maps: some definitions

Although Tolman (1948) is widely credited as being the first to propose the existence of cognitive maps, both Gulliver (1908) who spoke of such a concept in passing and Trowbridge (1913) who wrote of *imaginary maps*, do predate him (noted in Kaplan and Kaplan, 1978, p. 75). The appeal of the term *cognitive map* is that it is immediately, although superficially, clear what is meant. An initial and naive view of a cognitive map might be ... *A cognitive map is a map-like cognitive representation of an environment*, which is the kind of definition which may be found in standard textbooks on psychology. However, despite decades of research, a more sophisticated and agreed definition of what constitutes a cognitive map still does not exist. One reason for this may be that research into cognitive maps and spatial cognition more generally has been informed by a number of different sources and disciplines which have included geography (e.g. Gould and White, 1974; Magaña, Evans and Romney, 1981), developmental psychology (e.g. Kosslyn, Pick and Fariello, 1974; Piaget and Inhelder, 1956; Pick and Rieser, 1982), environmental psychology (e.g. Evans, 1980), cognitive psychology (e.g. Baum and Jonides, 1979; Thorndyke and Hayes-Roth, 1982; Tversky, 1981), and Kaplan and Kaplan (1982) in their review add education, sociology and planning to this list.

The following selection of definitions of cognitive maps illustrate this diversity:

Tolman (1948)

- Tolman (1948) reported that he saw a rat's initial set of stimulus - stimulus (S-S) expectancies concerning an environment as becoming integrated, with experience, into a map-like representation including distance and direction information, writing, '*...information impinging on the brain, worked over and elaborated ... into a tentative cognitive-like map of the environment indicating routes and paths and environmental relationships.*'

Downs and Stea (1973)

- Downs and Stea have offered this formal definition: '*cognitive mapping is a process composed of a series of psychological transformations by which an individual acquires, codes, stores and decodes information about the relative locations and attributes of phenomena in his everyday spatial environment.*' ... and ... '*human spatial behaviour is dependent on the individual's cognitive map of the spatial environment.*'

Neisser (1976)

- Neisser has described cognitive maps as *'orienting schemata specialised to direct both perceptual and motor behaviour'*.

Kuipers (1978)

- Kuipers, in reviewing the reported attributes of cognitive maps, identified the following three principle attributes: *Cognitive maps are like maps in the head.* People have reported being able to 'see' such maps, but cognitive maps have properties which both go beyond maps and which are less than maps. *A cognitive map is like a network.* It is made up of routes and nodes and some spatial errors may be accounted for by the distortions required to preserve the network structure. *The cognitive map is like a catalogue of routes.* This is a reference to cognitive maps being a store of procedural knowledge, that is, how to get from A to B.

O'Keefe and Nadel (1978)

- From their work with the hippocampi, O'Keefe and Nadel have described cognitive maps as being networks of stimulus-response-stimulus connections. They suggest, for example, that these S-R-S connections are rather like instructions one might give to a rambler, i.e. at the church, turn right and then straight on until you see the river...

Downs (1981)

- *'Both the real world and the world in the head can be captured conveniently by the idea of a map. Although the precise interpretation of the cognitive map is unclear (that is, its metaphorical and / or analogical character), its centrality [to spatial cognition] is beyond question.'*

Menzel (1987)

- From a comparative psychological view point Menzel has observed: *'Cognitive mapping is by no means a complete explanation of how animals are able to get around in the world. It is a largely metaphorical statement about what sorts of information they collect and how they organise it. That is, it is a psychological structural concept, rather than a developmental, functional or evolutionary concept; and as such it does not answer but rather poses further questions.'*

Denis (1991)

- Cognitive maps are '... *internal representations of the environment, its metric properties, and topological relationships between landmarks.*'

As can be seen from these definitions, there is little more than a broad consensus. Tolman describes cognitive maps as something more than S-S connections while O'Keefe and Nadel reduce them merely to S-R connections. Downs and Stea take cognitive maps to be synonyms for spatial cognition. Downs (having reviewed his earlier position) and Menzel see cognitive maps as a metaphor or analogy of varying usefulness while in contrast, Denis appears to take them literally. Finally, while Neisser emphasises their functional role, Kuipers recognises the difficulty in defining them, suggesting that their appearance and characteristics reflect how they are measured.

## 1.1.3 By way of illustration...

While an agreed account of cognitive maps, or spatial cognition more generally, does not exist, what is not in question is our remarkable ability to wayfind. A specific example of a real world study of cognitive maps is presented here as something of a composite. It is drawn from the psychological and anthropological work which has investigated the extraordinary navigational abilities of the South Sea Islanders. Their, now well documented, abilities to set off in an outrigger without modern navigational aids and find a island which at the point of departure subtends an angle of less than 5° has been described by, for example, Oatley (1977) and Hutchins (1983). The seamen of the Caroline Islands (Hutchins, 1983) do not employ technological or mechanical devices to navigate distances of up to 450 miles, instead they employ a 'star compass' which is used to define the courses between islands. In addition to the star compass, they use a system of 'ETAKs' which is a way of expressing the distance from a reference island (which may be imaginary) from the navigator's home island; but perhaps most importantly they employ a conceptualisation (or cognitive map) in which the known geography is moving past the navigator, his outrigger, and the stars in the sky. These techniques are supplemented by observations of sea birds, and the pattern of the tides which act as confirmations of this dead-reckoning. Oatley describes these feats of navigation as a '*form of analogical reasoning in a spatial frame*' (p.537) which he believes involves the following:

- the employment of a cognitive map or spatial mental model in which elements, relationships and processes of the task (i.e. wayfinding) are represented;
- the establishing, or recognising, of correspondences between 'real world' cues, such as objects or places, and their symbolic equivalents in the map or model;
- using the map or model to make inferences.

While this is by no means of a complete account of spatial cognition it does identify its key features. Firstly there is the presumption of a cognitive representation (a map or model), secondly, the need to establish the relationship between the representation and that which it represents and finally, a set of operations on the representation to enable way-finding.

# 1.2 Spatial Cognition I: An account of spatial cognition

## 1.2.1 Route knowledge and map knowledge

The distinction between route knowledge and map knowledge is one which is common throughout the literature on spatial cognition.

*Route knowledge* is generally regarded as consisting of sequentially organised procedural descriptions, that is a sequential record of the space between starting points, subsequent landmarks and destinations (e.g. Siegel and White, 1975; Moar and Charleton, 1982; Thorndyke and Hayes-Roth, 1982;) or as a network of stimulus-response-stimulus connections (e.g. O'Keefe and Nadel, 1978).

In contrast *map (*or *survey) knowledge* is defined as consisting of knowledge of the metric and topological properties of an environment. These properties include the location of objects in the environment relative to a frame of reference such as a fixed co-ordinate system (e.g. compass bearing), the global shapes of large land features (e.g. streets, parks etc.), and the inter-object route and Euclidean distances. Overall there is considerable evidence for, and agreement on, this two component representation of spatial knowledge (e.g. Kozlowski and Bryant, 1977; Allen, Siegel and Rosinski, 1978; Lehtiö and Poikonene, 1980; Thorndyke and Stasz, 1980; Byrne, 1982; Kaplan and Kaplan, 1982; Thorndyke and Hayes-Roth, 1982; Dillon, McKnight and Richardson, 1993). Table 1-1 holds a summary of the commonly agreed distinctions between route knowledge and cognitive maps after Bartram and Smith (1984) (*quoted in Cohen, 1989*):

| *route knowledge* | *map knowledge* |
|---|---|
| Local | Global |
| Micro | Macro |
| Episodic | Semantic |
| Ground based | Bird's-eye |
| Procedural | Propositional |
| Concrete / Detailed | Schematic / Abstract |
| -- | Hierarchical Levels |
| Sequential | Flexible |

*Table 1-1*

## 1.2.2 Acquiring a cognitive map

Again there is a broad consensus that route knowledge which is acquired first then becomes transformed into a representation which is more map-like in nature. This sequence appears to hold for both developmental and cognitive psychology. For example, Piaget (Piaget, Inhelder and Szeminska, 1960; Piaget and Inhelder, 1967) has found that young children initially learn particular paths (e.g. the way to school), but only later are able to achieve 'co-ordination' of these paths in a form of representation which includes directions, distances and common elements. What is also agreed is that the key to transforming this initially acquired route knowledge into a cognitive map appears to be increasing exposure to the environment either directly or indirectly.

## The sequence of acquiring of spatial knowledge

Figure 1-1 illustrates two different accounts of the process of acquiring a cognitive map of an environment:

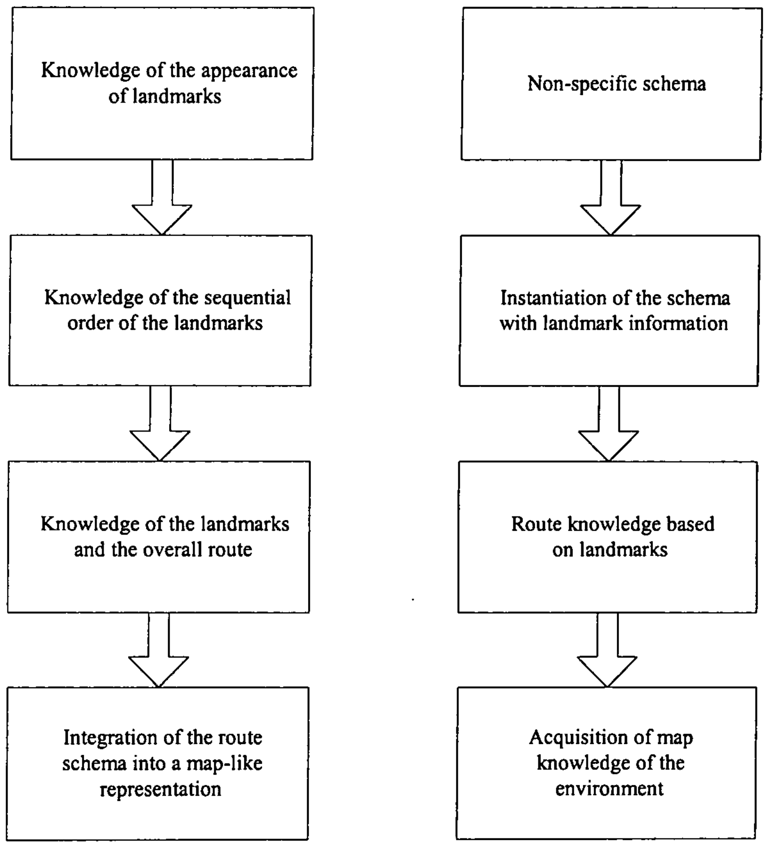


*Figure 1-1*

Describing these models in parallel:

Siegel and White (1975) - route schemata

1. When we first travel in or explore an unfamiliar area, we acquire knowledge of the appearances of landmarks, but we know little or nothing about the spatial relations among the landmarks.
2. With increasing experience, we acquire knowledge of the sequential order of landmarks.
3. As we gain more experience of the route, we achieve knowledge of the spatial relations between the landmarks and eventually a concept of the spatial layout of the complete route.
4. Finally, when we have gained sufficient information, we integrate the different route schemata into a map-like integration representation of the spatial layout of landmarks and routes in the area.

Dillon, McKnight and Richardson (1993) - global schemata

1. Dillon, McKnight and Richardson have modelled the process of acquiring a cognitive map beginning with Brewer's (1981) notion of a non-specific global schema is based on general knowledge.
2. This global schema becomes instantiated by the process of assimilating landmark information.
3. This is followed by learning a set of routes through the environment using these landmarks. This route knowledge is procedural, relatively inflexible and error prone.
4. Finally, the fourth stage is the acquisition of map or survey knowledge of the environment. This allows one to give directions, plan journeys, and know the relative position of features.

Contrasting these models, it is clear that the main differences lie with the starting premises, Siegel and White take a *tabula rasa* approach while Dillon *et al*, posit a pre-existing schema.

Considering these models in turn: Moar and Charleton (1982) have noted that Siegel and White's theory implies that if we learn two intersecting routes through an area, we still first acquire a separate route schema for each route. When we have learned each route sufficiently, we combine the two route schemata to create a more global cognitive map. They argue that schemata based in individual routes are the essential units of representation in the process of acquiring a cognitive maps of the environment. However when Moar and Charleton explicitly tested this assertion they found evidence to the contrary. Indeed they found some evidence for the acquisition of a more map-like representation prior to route knowledge in their experiments.

Turning to Dillon *et al*'s model. One immediate difficulty with this model lies with the concept of a generalised schema, a concept which is inherent circular in nature. Such schema are taken to have arisen from a process of generalisation of pre-existing (in this instance spatial) knowledge which in turn relies on the pre-existing generalised schema. This position is thus untenable.

Finally, Cohen and Cohen (1985) in a review of how urban residents acquire a cognitive map of their neighbourhood offer a simpler account of the sequence of acquiring spatial knowledge which is as follows: (i) landmarks and simple routes are learned fairly quickly (in the first three weeks); then after approximately three months (ii) a slight increase in the number of landmarks and routes follows, together with configuration knowledge. This second stage also corresponds to the acquisition of a more global, map-like representation of the environment. However, while numerous studies have found that map-like knowledge arises and improves with increasing residence in an environment or community (e.g. Beck and Wood, 1976) none of these studies (nor the two described above) has neither controlled the subject's access to maps or other indirect sources of knowledge[1] nor can account for the role of such information.

Yet despite these differences and difficulties it is generally agreed that route knowledge is acquired prior to map knowledge of an environment although there remains quite a wide difference in the detail of how this occurs.

## The rôle of activity in acquiring spatial knowledge

The evidence for the importance of activity in the acquisition of a spatial knowledge of an environment comes from a number of different sources and includes environmental, developmental and comparative psychology, examples of which are now briefly reviewed.

Environmental psychology. Francescato and Mebane (1973) have found that adults in both Rome and Milan, aged 30 and under, tended to draw maps of the cities with a bias towards paths, while older subjects drew more landmarks. They have suggested that older subjects may have been less likely to have learned the layout of the city by car than younger individuals. This interpretation, however, as Cohen and Cohen (1985) note, rests on the assumption that landmarks are more salient to walkers and paths are more salient to drivers and passengers. Similarly Walsh, Krauss, and Regnier (1981) (*quoted in Cohen and Cohen*) have found that active elderly adults drew more accurate maps of their environment than an equivalent group of

[1]The differences between spatial knowledge acquired from the environment and from representations of the environment are examined in section 1.3.6.

inactive elderly individuals.

Modes of transportation have been examined by comparing of spatial knowledge for people who typically travel in different ways (e.g. by car, bus or train, or as pedestrians). While pedestrians have the most direct sensori-motor experiences, walking does limit the amount of space covered. Bus and train travellers are the most physically passive participants of the three groups and are least involved in navigation decisions. Such travellers have been shown to draw less accurate maps of the environment than the more active travellers (e.g. Appleyard, 1970; Beck and Wood, 1976), and to make more errors on a paired comparison distance estimation task (e.g. Golledge and Spector, 1978[2]).

Experimental psychology. Goldin and Thorndyke (1982) have investigated the different types of knowledge acquired from direct navigation compared with simulated navigation. The direct navigation condition consisted of a bus tour of an area, while the simulated navigation condition consisted of watching a film of a trip through the same area. Further to this, subjects received either: a period of map study prior to their trip; a running commentary during the tour or no additional information (the control group). The map study consisted of studying at a map with landmarks and routes for 10 minutes prior to taking the tour. The running commentary of the tours named of the streets on the route, landmarks, the distance between intersections and the current compass direction. The subjects in both conditions were passive observers.

After the tour the subjects were asked to carry out an array of six tasks. These consisted of: location recognition, location sequencing, landmark location, route and Euclidean distance estimations and a basic spatial ability test which tested visual memory, spatial visualisation and perceptual independence abilities.

Goldin and Thorndyke found that the subjects in the film condition identified tour locations better than those who were on the actual tour. Within the film group the control group performed better than the two groups who had received additional information. This difference was not found for the subjects on the real tour. The subjects in the film groups proved to be more accurate at location-sequencing than the subjects on the real tour, and the narrative condition proved to have a negative effect on performance across both conditions.

However, the film group performed more poorly than the other groups in the orientation test, the subjects on the real tour being approximately 10° more accurate than those in the film group. Furthermore the subjects in the film condition made significantly more errors in excess of 90° than those subjects in the real tour condition.

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[2]*Cited in Cohen and Cohen (1985).*

Both the film and the real tour groups who had studied the map prior to the trip, performed more poorly on the orientation task than those in the control and narrative groups. No differences between the groups were found for the route distance estimation tasks, Euclidean estimations and landmark placement tasks.

In *post-hoc* tests differences were found for those in the film group who had received additional information. Those who had studied the map showed a higher performance than all of the other five groups, and those who had listened to the tour description had a lower performance than the other five groups. The results of the study clearly indicate that people can acquired spatial knowledge of environments from a range of media although it is equally clear that exposure to different media give rise to different patterns of spatial knowledge. For example, exposure to film gives rise to more accurate spatial memory for locations but much poorer memory for orientation than direct exposure to the environment.

Developmental psychology. Feldman and Acredolo (1979) measured the accuracy of memory for location of an object as a function of either self-directed or experimenter-directed exploration of the environment. Four and 10-year-old children either walked or were led through a rectangular hallway in search of an object, which they later were asked to relocate. For the younger children, active exploration facilitated memory for spatial location. However the older children's memories were not influenced by either condition.

Comparative psychology. Menzel (1978) has reported that young chimpanzees are capable of forming cognitive maps of an environment through passive exposure to it alone. Menzel had a chimpanzee carried around a field by an assistant, while allowing the animal to observe another person hiding food in clumps of grass, under leaves and so forth, in a number of different places. When the chimpanzee was released, the animal was observed to go directly to where the food was hidden. The chimpanzee did not retrace the explorer's route but typically followed a shorter, more direct route, which Menzel interpreted as evidence of the animal having formed a cognitive map of the environment.

An ecological perspective. It is widely held that perception and action are tightly interlocked processes (e.g. Neisser, 1976; Gibson, 1979; Reason, 1984) and that animals and people do not passively perceive the world but move about in it actively, picking up the information needed to guide their movement. There is thus a continuous cycle between the organism and the environment. The consequence of this viewpoint is that the rôle of perception is to furnish that information needed to organise action, which in turn implies that an understanding of perception requires an understanding of the systems controlling action. Active locomotion within a large-scale environment is seen to lead to a more accurate and flexible spatial representation than physically passive experiences. Actively moving through the environment brings the individual into contact with the multiple perspectives of space and facilitates the integration of views and the co-ordination of percepts with motor experience (e.g. Brewer and Dupree, 1983; Norman, 1981).

### 1.2.3 The structure of cognitive maps

There is a body of evidence for the premise that there is an internal hierarchical structure to cognitive maps (e.g. Lynch, 1960; Stevens and Coupe, 1978; Lehtiö and Poikonene, 1980; Allen, 1981; Hirtle and Mascolo, 1986; McNamara, 1986; and Couclelis, Golledge, Gale and Tobler, 1987). Lynch was perhaps the first to argue that cognitive maps [of cities] work primarily as orientation aids and reflect the basic elements of the physical layout of a city. His research has suggested that five key environmental, hierarchically organised features make up urban settings, which are as follows: paths, path intersections (nodes), landmarks, districts, and boundaries (edges). Similarly Rosch (1976) and Tversky and Hemenway (1983) have identified a taxonomy or hierarchy of environmental features. Hirtle and Jonides (1985) have also found that similar types of buildings tended to be grouped together, for example, commercial buildings were found to be recalled with other commercial buildings, and university buildings with other university building, despite the fact that the two types of buildings were geographically interspersed. Similarly, Hirtle and Mascolo (1986) have demonstrated the effects of semantic clustering on the memory of spatial locations. They found that semantic labels biased memory for the location of landmarks of a typical city, for example, government buildings tended to be remembered as being more closely co-located than they actually were. Cognitive maps are then believed to reflect this structure.

Lehtiö and Poikonene (1980) have also presented evidence of the hierarchical arrangement of [urban] spatial locations, with respect to relative distance and orientation. In a series of studies they asked residents of a city to make a number of simple spatial judgements (e.g. they asked subjects whether or not two named streets crossed). They found that their subjects appeared to activate a *low resolution mental map* first but had access to a more detailed fine-grained representation if required.

However, Ferguson and Hegarty (1994) have suggested that the evidence for a hierarchical structure to cognitive maps may simply be a reflection of working memory limitations. For example, if a given geographical region has only a small number of landmarks (say, < 5) then people will probably represent that region as a single 'chunk' however if a region is more complex, people may create subdivisions so that an hierarchical structure necessarily emerges (such chunking has also been observed by, for example, Egan and Schartz, 1979).

### 1.2.4 The non-veridical nature of cognitive maps

Cognitive maps do appear to have a number of map-like features in that they preserve relative distance information and the relative location of objects. In this respect they would appear to be broadly consistent with a limited two-dimensional Euclidean model of the environment. Yet as Downs (1981) notes, any map is by definition a model and therefore *less full* than the original space. In addition to being *less full*, cognitive maps have also been found to be subject to distinct, systematic distortions. A number of researchers (e.g. Stevens and Coupe, 1978; Tversky, 1981; Thorndyke, 1981; and Moar and Bower, 1983) have observed systematic distortion in the recall of spatial configurations. Moar and Bower (1983) have found that judgement of angles between routes are subject to systematicity in that there is a tendency to recall angles closer to a multiple of 90° than the actual angle. A related example of this systematicity or *normalisation*, is the finding of Brewer and Treyens (1981) that the recall of objects in a room are distorted in that they tended to be incorrectly recalled in their canonical positions. Similarly Thorndyke (1981) found that subjects' estimates of distance increase as a linear function of the number of intervening points along the routes when making judgements from memorised maps. This so-called 'clutter effect' has been observed when subjects have been asked to estimate the length of a route (which is filled with objects, landmarks or turns) they have traversed (e.g. Byrne, 1979; Cohen, Baldwin and Sherman, 1978; Sadella and Staplin, 1980, Thorndyke and Hayes-Roth, 1982). Similar but reduced effects have also been noted when subjects were asked to make judgements from their knowledge of the United States and while viewing a map. Finally, Holyoak and Mah (1982) have found that distances are judged differentially depending upon their proximity to reference points (i.e. landmarks), specifically, distances near a referent are over-estimated. They asked one group of students to imagine themselves on the East Coast of the United States, and another group to imagine themselves on the West Coast. Both groups were then asked to estimate distances between pairs of cities lying along an east-west axis, for example, San Franciso and Salt Lake City, New York City and Pittsburgh. The students who had been asked to adopt a West Coast perspective overestimated the distance between the westerly pairs relative to the easterly pairs, and the students asked to adopt an East Coast perspective did the opposite. Thus, it would appear that the vantage point or the frame of reference (see below) systematically distorted the judgements.

Finally, Sadalla, Burroughs and Staplin (1980) have found evidence that judged distances between spatial reference points and non-reference points are asymmetrical; non-reference points being judged nearer to reference points than were reference points to non-reference points. While these reported effects do appear to be robust, O'Keefe and Nadel (1978) have voiced the following objection:

*it is hard to imagine how the non-commutativity of distances could be encoded in the same structure which provides for the easy use of alternate routes to the same goal and for the rapid reversal of paths. Non-commutativity almost demands that the map represents paths in terms of individual responses, or landmarks, involving in traversing them...*

*O'Keefe and Nadel, 1978 p. 77*

This objection remains unanswered. Furthermore, and in contrast to the above there are numerous studies demonstrating the remarkable accuracy spatial knowledge from a well explored space. For example, both Baird, Merrill and Tannenbaum, 1979 and Baum and Jonides, 1979, who had students construct models of their campus, found that each landmark was placed extremely close to its counterpart in the true configuration.

### 1.2.5 Landmarks, spatial reference points and frames of reference

Lynch (1960) has suggested that navigation through cities is dependent on knowledge of landmarks; similarly Siegel and White (1975) have argued that landmark knowledge is a necessary condition for *way finding* to occur; landmarks are described as strategic foci to and from which individuals travel. Landmarks have also been found to play a rôle in the development and the maintenance of spatial orientation and Allen, Siegel and Rosinski (1978) have concluded that the acquisition of spatial knowledge in a novel environment begins with the identification of key environmental features (or landmarks), a finding which is consistent with the models of spatial knowledge discussed in section 1.2.1. The term *landmark* has additionally been used to denote central elements in an individual's cognitive representation of a region; the most easily recalled attributes of a region have been typically referred to as landmarks. From this, it is clear that the definition of a landmark has been rather circular. However the following components of what constitutes a landmark appear to be as follows:

- a significant feature of a route, which affords navigational decision points;
- a significant feature of a region, which allows an observer to maintain spatial orientation;
- salient information identified in the recall of an environment.

Sadalla, Burroughs and Staplin (1980) have further refined the idea of landmarks in a series of experiments in which they identified what they describe as *spatial reference points*. Using cluster analysis they found that *familiarity*, *dominates nearby places*, *near the centre of a region* and *cultural importance* accounted for 91% of the variance of what makes an environmental feature a spatial reference point. Furthermore, Sadalla *et al* in a series of five experiments confirmed that large scale spaces do indeed contain such reference points, and that these points serve as organising loci for other points in space. As already noted, they found evidence that the judged distances between reference points and non-reference points is asymmetrical. Results of additional reaction time experiments indicated that from a given point in space, the proximity of adjacent reference points may be more quickly verified than can the proximity of equivalently placed non-reference points. Further, the data indicate that the orientation of a particular point in space may be more quickly verified when the observer is cognitively located at a reference location than when the observer is cognitively located at a non-reference location. These data suggest that the cognitive location of many points in space are either stored or retrieved in relation to a smaller set of spatial reference points. Spatial reference points appear to provide an organisational structure that facilitates the location of adjacent point in space. Such spatial reference points should be distinguished from landmarks as it seems likely that there are (other) discriminable features of the environment which could be used to support navigation but that do not produce the above results - a *landmark*, Sadalla, Burroughs and Staplin conclude, is a less general term that spatial reference point. Finally Ferguson and Hegarty (1994) in studying spatial representations created from reading discourse, define an *anchor* as any landmark that is used in the text as a reference point for defining the location of other landmarks.

## Frames of reference

Just as a minimum of two landmarks are required to align a physical map with the environment, the cognitive process of orientation is seen as the means by which cognitive maps are aligned with the spatial environment which gave rise to them. Orientation is made with respect to a frame of reference, the word 'orientation' itself means 'aligned with the East' (Lat. *oriens*).

There are three generally accepted classification of these frames of reference (e.g. Downs and Stea, 1973), which are:

- ego-centric, that is, based about the representing individual. This is envisaged as a three-dimensional co-ordinate system wherein objects are located in terms of *in front of*, *to the right or left*, or *above* or *below* (e.g. Bryant and Tversky, 1992).
- a frame of reference based on the environment represented. Lynch (1960) notes that terms such as '*sea-ward*', or '*up stream*' denote such a frame of reference. The above comments on landmarks or spatial reference points also supports this, e.g. Sadalla, Burroughs and Staplin's (1980) evidence of landmarks as acting as organisation foci. Downs and Stea also observe that when a landmark is used as a frame of reference it is often in terms of polar co-ordinates with the landmark acting as the centre.

- An externally based frame of reference such as one based on compass co-ordinates.

As appealingly simple as this classification is, it does not address a number of questions: firstly, do frames of reference arise in this particular order and if so how does one acquire each step and how do they interact and to what extent are they orthogonal? Secondly, what determines the use of one over another? Is there an element of '*cognitive economy*'? Finally, how precisely do cognitive maps and frames of reference interact - which arises first or do they do so in parallel?

### 1.2.6 Methodological issues: A diversity of approaches

Since 1980 the study of spatial cognition and cognitive maps more specifically has become a major focus of both environmental psychology and social geography (including such things as the sub-discipline of demography) as distinct from experimental and cognitive psychology.

The differences between an environmental approach and a cognitive or experimental approach largely lie with the scale and context of the studies. The former are largely naturalistic with tasks such as asking people to draw a sketch map of their neighbourhood or asking students to construct a map of their campus (e.g. Baird, Merrill and Tannenbaum, 1979).

In contrast, the experimental and cognitive approach is frequently laboratory based with tasks such as distance estimation between two points on a map which subjects had learned, or subjects being asked to push one of two buttons to indicate whether a point in a given stimulus configuration is on the left or right (e.g. Hintzman, O'Dell and Arndt, 1981) or having their memory tested as to the vertical arrangement of abstract shapes (e.g. Tversky, 1981).

Consequently the practitioners and affiliates of the environmental approach are frequently critical of the latter for lacking in ecological validity (e.g. Evans, 1980), while the advocates of the experimental approach complain of the lack of controls in studies of the environmentalists (e.g. Levine, Jankovic and Palij, 1982; Taylor and Tversky, 1992a; 1992b). Overall, the approach adopted by ecological psychology is necessarily uncontrolled and while it may reflect and quantify real world spatial knowledge it does not appear to have a great deal to contribute directly to the understanding of the underlying cognitive processes. Between these extremes, there are, of course, a wide range of approaches: Jonides and Baum, 1978 had subjects imagine walking from one campus building to another; Piaget and Inhelder (1967) had their subjects imagine scenes from different perspectives; Attenneave and Farrar (1977) elicited judgements about locations and orientations of objects behind their subjects' heads; Kozlowski and Bryant (1977) asked their subjects to estimate the lengths of streets and their angles of intersection and to point to unseen objects (Kozlowski and Bryant, 1979); Byrne (1979) obtained judgements of the lengths of streets and the angles of their intersection; and Loftus (1978) measured the accuracy of visually presented compass directions, to cite but a few.

## Sketch maps

Lynch (1960) was one of the first to analysis sketch maps made by residents of their own cities. From his subjective analysis of hand-drawn sketch maps he devised a taxonomy of the urban which he has argued reflects the contents of people's cognitive maps, however he offered no account of the confounding effect of individual differences in ability to sketch a map.

His approach raised two primary difficulties with sketch maps have been addressed in a variety of ways.

- The subjective analysis of sketch maps has been replaced by a more objective categorisation. For example, Rodwin *et al* (quoted in Jakle, Brunn and Roseman, 1976) have created a classification system, facilitating the grouping of sketch maps into two broad categories - sequential and spatial, and these categories are, in turn, subdivided into, for sequential maps - fragmented, chain, branch and loop, and netted; and for spatial maps - scattered, mosaic, linked and patterned varieties. However it is far from clear what psychological relevance these categories have.
- The difference in the subject's ability to sketch is particularly relevant when the systematic distortions are observed in sketch maps which may reflect either the sketcher's lack of skill or real distortions in cognitive map itself. Evans (1980) is his review paper cites the work of Howard *et al* (1973) who examined the psychometric properties of sketch maps. They asked subjects to perform one of the following tasks:(i) to draw a map of the environment; (ii) to place objects in a scale model; (iii) to make magnitude estimates judgements of inter-object distances; and (iv) to make ratio estimates of inter-object distances by marking off a standardised line in proportion to the real distance. Howard *et al* found that all four methods proved to be reliable, with reliability coefficients (r) ranging from 0.987 to 0.995 which does indeed appear to lend weight to the validity of sketch maps as a means of eliciting spatial knowledge.
- However, more recently, Hirtle and Jonides (1985) have compared the accuracy of absolute distance estimates arrived at by variety of means: (i) magnitude estimates proved to be the most accurate, (actual / estimated distance, $r = 0.80$); (ii) constructed map, that is, subjects asked to draw a subset of the features in a memorised map, were almost as accurate ($r = 0.73$) but, (iii) sketch maps ($r = 0.63$) proved to be the least accurate means.

Nonetheless, sketch maps have proved to be a very popular means by which spatial knowledge and cognition has been studied and the work of Lynch has been built upon by a large number of others (e.g. Appleyard, 1970; Francescato and Mebane, 1973; Beck and Wood; 1976; Walsh, Krauss, and Regnier, 1981; Cohen and Cohen, 1985). Sketch maps have been the subject of work by Taylor and Tversky (1992a; 1992b) who have examined their interpretations (1992a) and their creation from textual descriptions (1992b). This work is discussed in some detail in section 1.3.6.

## Distance and angles estimation

The use of sketch maps, has in certain quarters been replaced by the use of other measures such as distance estimation (e.g. Baird, 1979 etc.), the estimation of angles and bearings (e.g. Loftus 1978; Hintzman, O'Dell and Arndt, 1981), comparative distance judgements (e.g. Baum and Jonides; 1979; Hirtle and Jonides, 1985) or the estimation of both angle and distance estimation, i.e. vectors (e.g. Byrne, 1979; Thorndyke and Hayes-Roth, 1982). Such methods have the very clear advantage that they are less likely to be biased by the artistic skill of the subject or the subjective rating of the experimenter. The findings of such approaches are reviewed in section 1.3.

## Other techniques

More recently, two additional techniques have emerged for the study of cognitive mapping. These are the use of spatial priming (e.g. McNamara, 1986; McNamara, Hardy and Hirtle, 1989) and the use of the ordered tree clustering algorithm (e.g. Hirtle and Jonides, 1985; McNamara, Hardy and Hirtle, 1989, but these will not be reviewed as their relevance to this enquiry is remote.

## What is being measured?

While there is no doubt that all of the above techniques are addressing aspects of spatial cognition it remains very unclear exactly what it is they are measuring. As will be seen in the next two sections different methodological approaches appear to be more suited to the study of spatial knowledge acquired from large scale spaces (e.g. cities) and others to spatial knowledge acquired from small scale spaces or representation of space, yet for all of these very clear differences there has been no attempt to establish the validity and reliability of one approach over another.

## 1.3 Spatial cognition II: Distance and angle estimation

### 1.3.1 Distance estimation

At the time of writing there is no agreed or verified model of distance estimation. The most comprehensive is that of Thorndyke and Hayes-Roth which they sought to verify in 1982[3].

### Thorndyke and Hayes-Roth (1982)

Thorndyke and Hayes-Roth began with the following premises: spatial knowledge acquired from maps is qualitatively different from spatial knowledge acquired from the free exploration of the environment. Spatial knowledge acquired from the free exploration of environment is initially *procedural*, that is knowledge of how to get from A to A[1] but this procedural knowledge gradually becomes more detailed and might include '*impressions of the distance travelled along each leg (straight-line segment) of the route, the angle of the turns between legs, and terrain features along the route*' - Thorndyke and Hayes-Roth, p.562. This sequential account of a route, with extended exposure to the environment, undergoes a further development in that it becomes *translucent*. This translucence may refer to the cognitive manipulation of an aspect of a cognitive map which allows individuals to 'see' through obstacles.

Thorndyke and Hayes-Roth's account of spatial knowledge acquired from maps is as follows, '*We assume that when learning maps intentionally, the individual acquires an image of the depicted space.*' - p.563. They describe spatial knowledge acquired from maps as *survey knowledge* which is further described as knowledge of the topographic properties of the environment relative to a fixed co-ordinate system such as compass bearings, the global shapes of environment features and the inter-feature Euclidean distances.

Given these fundamental difference in the ways in which spatial knowledge is acquired from these two different media, Thorndyke and Hayes-Roth go on to model how Euclidean and route distance estimates are made:

[3] It should be noted that some of these points have been made earlier in this chapter in a number of different contexts and Thorndyke and Hayes-Roth also offer an account of the cognitive processes involved in estimating angles which is intimately linked to their distance estimation model.

| Type of experience | Euclidean | Route |
|---|---|---|
| Map | Visualise map<br>Locate endpoints<br>Measure length<br>Generate response | Visualise map<br>Locate endpoints<br>Measure leg length<br>Sum lengths<br>Generate response |
| Free exploration | Mentally simulate route<br>Estimate leg lengths<br>Estimate turning angles<br>Perform informal algebra<br>Generate response | Mentally simulate route<br>Estimate leg lengths<br>Sum lengths<br>Generate response |

Clearly an important difference between distance estimation from spatial knowledge acquired from free exploration and spatial knowledge acquired from maps is the dependency between the Euclidean and route judgements. In the free exploration condition, Euclidean judgements are derived from route estimates.

## Their experiment

Having outlined this model, Thorndyke and Hayes-Roth then explicitly tested it. In doing so they set out to investigate the differences in spatial knowledge acquired from maps and spatial knowledge acquired from the free exploration of a particular environment.

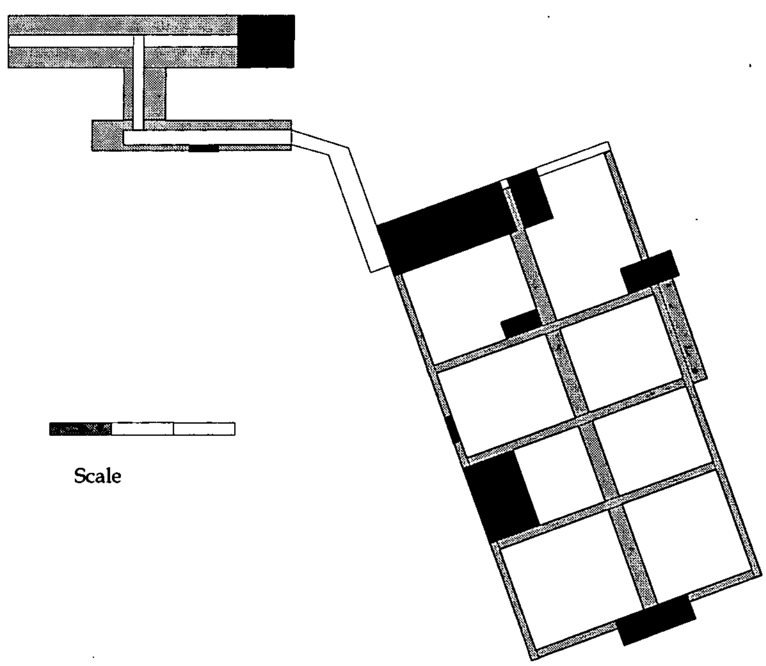


*Figure 1-2*

Thorndyke and Hayes-Roth selected as their environment the first floor of the Rand Corporation in Santa Monica, USA. The first floor consisted of two buildings separated by an enclosed hall with a 50° 'jog' (or dogleg). The building contained a number of distinct and prominent public areas which, with the exception of the hall, were all set at right-angles to each other. Figure 1-2 is a very approximate copy of the map used by Thorndyke and Hayes-Roth.

Their 48 subjects were divided into two groups, those who had previously acquired knowledge of the building by either actually working there (the route knowledge or navigation condition - navigation hereafter) and those who were requested to acquire such knowledge by studying floor plans of the building (the map knowledge condition). Within each condition, a further subdivision was made.

For the map condition, (i) subjects were required to learn a map of the building so that they could reproduce it without error; (ii) as group (i) but with a further 30 minutes of over-learning; and (iii) as (i) but with a further 60 minutes of over-learning.

For the navigation condition, (i) subjects were identified who had worked at the Rand for 1 to 2 months; (ii) for 6 to 12 months; and (iii) for 12 to 24 months.

Both groups were asked to estimate:

- Euclidean (i.e. 'straight line') distances from the centre of one room to another;
- route distances again from the centre of one room to another;
- orientation, that is, subjects were asked to point to a given location from their current location, and;
- location, that is, to locate a designated location from a partial map.

## Map-learning

As noted above Thorndyke and Hayes-Roth have argued that subjects who have acquired spatial knowledge from a map effectively acquire an image of that map. Subjects are then able to estimate distances by scanning the image of the map from point to point in a manner which is analogous to visually scanning an actual map.

When estimating a *Euclidean* distance, subjects scan the image and estimate the distance by comparing it to the provided scale distance. However as Euclidean distance estimates do not depend on the route information, the error in subjects' estimates of Euclidean distance will be independent of the number of the legs on the connecting route.

However when subjects estimate *route* distances, they must estimate and sum the lengths of the component legs on the route. This additional processing is a potential source of error into the estimation process. The greater the number of component legs to be estimated and combined, the greater the opportunity for error. As a consequence, the error in map-learning subjects' estimate of route distances should exceed the error in their estimates of Euclidean distance.

Given these predictions Thorndyke and Hayes-Roth found that the performance of the map learning subjects with regard to distance estimates was characterised as follows:

- the correlation between the Euclidean and route distance estimates was high (r = 0.82). This finding matches their prediction.
- more and larger errors were made in estimating route distance than Euclidean distance and these error were not reduced with over-learning. This finding matches their prediction.
- the relative accuracy of the estimates was equally divided between Euclidean and route distance estimates (i.e. for 50% of the sample the correlation between actual and route distance was higher than the correlation between the actual and Euclidean distances). While this finding does not match their prediction it is not a contradiction.

As noted above these results were taken to be a qualified confirmation of their theory regarding map-learning.

## Navigation-learning

While the distances estimates made by the navigation subjects proved to be less uniform than the map learning subjects, they did offer further confirmation of Thorndyke and Hayes-Roth's model, specifically:

- the judgements of route distances were more accurate than Euclidean distances, but as the amount of navigation experience increased, the differences in accuracy of judgement between route and Euclidean distances diminished. This finding matches their prediction.
- Euclidean judgements were found to become more accurate with extended navigational experience though the accuracy of route distances judgements was unchanged. This finding matches their prediction.

## In summary

Thorndyke and Hayes-Roth have produced a model of large scale[4] distance estimation which makes a number of very specific predictions that have some measure of empirical support. Firstly, route distance estimates made from spatial knowledge acquired from free exploration tend to be more accurate than Euclidean judgements. The reverse is true for spatial knowledge acquired from maps. Secondly, although initially route estimates are more accurate than

[4]Thorndyke and Hayes-Roth describe their field of study 'large scale space', p. 562.

Euclidean estimates this difference diminishes with increased exploration. No such improvement is observed in the map learning.

However, the model does rest on an unproved premise, namely that when an individual uses a map he or she commits it to memory and the representation of the memory is an image ('*...when learning maps intentionally, the individual acquires an image of the depicted space.*' - Thorndyke and Hayes-Roth, p.563). It can be further argued that their emphasis is on *learning the map* and **not** the spatial knowledge acquired from it. The point to be recognised is that Thorndyke and Hayes-Roth are addressing a special case and one which has dubious validity. Their position is likely to have been based on the work of Thorndyke and Stasz (1980) who investigated individual differences in ability to acquire knowledge from the environment by studying maps. The tasks were based upon acquiring specific knowledge from maps this knowledge consisted of the relative and absolute distances between objects, their locations and being able to reproduce the map afterwards. Two maps were used; a town map and a country map. The subjects consisted of a small number of catographers (experts) and a group of individuals who were unfamiliar with map reading. The surprising feature of the results was that the experts did not necessarily perform better, the differences in performance could largely be attributed to the quality of subject's visual memory. However Gilhooly, Wood, Kinnear and Green (1988) demonstrated that the failure of the experts to show superior memory for the maps was due to the fact that planimetric (that is, tourist map like) maps rather than contour maps had been used by Thorndyke and Stasz. When the latter were used then the experts showed superior recall over the non-experts once again demonstrating the domain specificity of experts' knowledge (e.g. de Groot, 1965; Egan and Shwartz, 1979; Adelson, 1981; Anderson, 1983).

So, continuing with the above discussion, Thorndyke and Hayes-Roth do not present convincing evidence that people effectively memorise maps and further, the word 'map' could equally be replaced with 'figure', 'diagram' or 'schematic' and in doing so it is difficult to maintain that what is being acquired is still spatial knowledge. Furthermore given that maps are not, in general, committed to memory (except by secret agents, perhaps), Lieblich and Arbib (1982) have argued, '*Maps are meaningless ... unless we have a process for using them*' (p. 628). They go on to say that in using a map to, say, get from one town to another, we must recognise the representations (and orientations) of the towns, identify paths between them and on that basis formulate a plan of action. In short, a map's function is to represent paths and other spatial relations which can be turn into 'programs' for directing actions.

## 1.3.2 The cognitive representation of distance information

There are a number of possible means by which distance information may be represented in memory. Here is a selection:

### Euclidean

Baum and Jonides (1979) and Kerst and Howard (1978) are among those who have explicitly argued that format of spatial information stored in memory is essentially Euclidean. Specifically, Baum and Jonides (1979) have compared judgements of distance made from memory (i.e. distance between two different landmarks on a University campus) and judgements made from perception (i.e. figures displayed on a VDU), measuring size of error, and response latency. While judgements in the perceptual condition were significantly quicker and more accurate than judgements made from memory, Baum and Jonides also found a clear linear relationship between distance estimates and the amount of time subject took to arrive at these estimates for both the perceptual and memory conditions. From these data, they concluded that the cognitive mechanisms underlying the judgements were not fundamentally different and that an image scanning paradigm (such as Kosslyn's) could account for the results from the memory condition.

This position is further substantiated by the body of evidence that have demonstrated correspondences between perceptual and memorial performance data on other tasks that utilise spatial stimuli (e.g. Cooper, 1976, Finke and Schmidt, 1978; Kosslyn, 1973, 1975; Kosslyn and Pomerantz, 1977; Moyer, 1973; Podgorny and Shepard, 1978; Shepard, 1978; Shepard and Podgorny, 1978). These results support the position that the memory representation used to perform these spatial tasks has much in common with the perceptual experiences of the objects themselves. In particular, it has been argued that memory representations, like percepts, can have continuously varying analogue properties that accurately reflect the objects they represent (e.g. Holyoak, 1977; Kosslyn, 1973, 1975, 1978; Kosslyn and Pomerantz, 1977; Shepard, 1978; Shepard and Podgorny, 1978). Typically, such representations have been described as visual images that can be generated and manipulated in memory (Kosslyn and Pomerantz, 1977; Kosslyn and Schwartz, 1977).

However, as Baird[5], 1970 writes '*A Euclidean model of size and distance has permeated the perception literature almost from the outset. It would indeed be convenient if an observer's judgements of environmental extents reflect the operation of a ready-made Euclidean metric,* *invariant over changes in target position...But the problem is more complicated than was recognised at first, and it is now certain that metric constancy is only a special case that occurs with a particular combination of stimuli, methods and instructions.*'

## Power function

In contrast to the findings of Baum and Jonides (1979) there are studies which have indicated that estimates of distance and line length based on memory are related to true distance by psycho-physical power functions similar to those obtained in perceptual experiments (e.g. Kerst and Howard, 1978; Moyer et al, 1978). Kerst and Howard (1978) have also found evidence of a power function[6] relationship between the estimated area (estimated from memory) of a body of land (a country or a state of the US) and the actual area. This evidence is taken to be consistent with the findings of Björkman *et al*, 1960 and Lundberg and Ekman, 1971 both of whom they quote.

## Ordinal

Finally, Nelson and Chailkin (1980) have argued that the available evidence is not sufficient to support either the Euclidean or power function positions. Instead they offer a *Weighted-Distortion Theory* as a basis for a new theory of spatial memory, the main points of which are as follows: (i) the accuracy of a spatial memory is a monotonically decreasing function of the physical distance between the to-be-remembered spatial location and a landmark; (ii) the direction of distortion for a spatial location from memory is towards the landmark; and, (iii) the magnitude of the direction-of-distortion effect is a monotonically decreasing function of the physical distance between the to-be-remembered spatial location. While this model is supported by a (pessimistic) view of the evidence it has not found wide support.

## In conclusion

From the evidence presented above, it is clear that there is neither a simple nor single answer to the question of the nature of the cognitive representation of distance information in memory. In part it would appear to depend upon the scale of the study (i.e. real life knowledge of the environment compared with spatial knowledge acquired from an artificial setting); and how the

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[5]Cited in Nelson and Chaiklin, 1980 p. 530.

[6]They describe the power function as follows: $\Psi = k\Phi^n$, where $\Psi$ is the psychological magnitude, $\Phi$ the physical magnitude, k is a scaling factor depending on the units of measure taken and n, a parameter depending on the judgement continuum.

spatial knowledge has been acquired (i.e. is primary or secondary); and ultimately how the experiment measured the nature of the representation.

### 1.3.3 The characteristics of judgements of angles and orientation

Again like distance estimation there is no agreed and verified model of angle or orientation estimation. However some of the characteristics of judgements of angles such as directional bias and systematicity have been investigated. This section will begin by considering the characteristics of judgements of angles and orientation, it will also review the biases in judgement of angles and orientation ending with some notes on people's sense of direction.

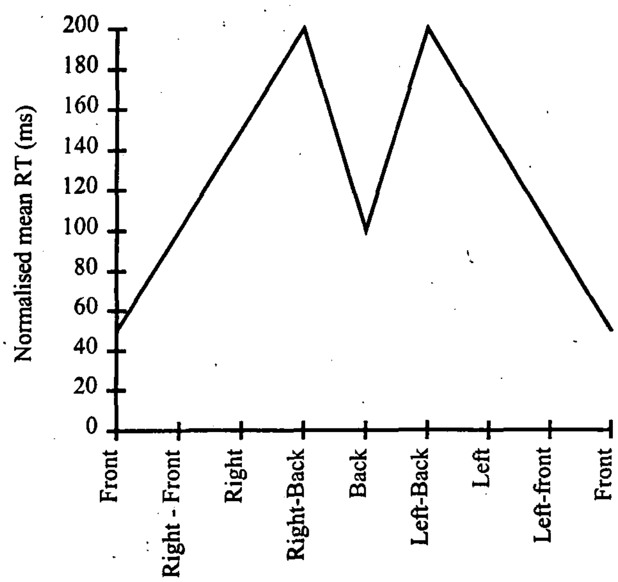
### Angle estimation

One of the most thorough investigations of the judgement of angles was conducted by Hintzman, O'Dell and Arndt (1981) in a series of 14 experiments. Throughout their basic measurement was the time taken to judge the angle of a *target* from a given starting orientation. In all fourteen experiments the task was one in which the subject was told to imagine being at a particular place facing a particular direction (the orientation) and to indicate with respect to his or her own body (i.e. employing an ego-centric frame of reference) the co-ordinates of a particular object, (the target).

These experiments were then subdivided into:

- visual maps. Visual maps were the subject of two of the experiments and consisted of presenting subjects with an arrow (the orientation) and a point (the target). The experiments were conducted to establish a baseline for future comparisons. The results indicated a general increase in reaction time with rotation of the arrow from the upright, excepting straight down. Hintzman *et al* interpreted these data as evidence for mental rotation although they suspect that judgements front and back may involve a different mechanism. In these direct presentation conditions, targets were most quickly located when they were adjacent to or opposite the imagined orientation echoing Loftus' findings (Loftus, 1978) below.

- cognitive maps: in all, eleven experiments investigated cognitive maps specifically. These experiments which involved making judgements from memory ranged from making judgements from named American cities; pointing to particular targets in the subject's local environment; to judging angles from pictures of pairs of objects previously memorised in the room. The range of stimuli allowed Hintzman *et al* to compare cognitive maps stored in both long-term and what they described as *immediate memory*. Although the reaction times across these conditions and subjects were irregular they all produced a characteristic and regular M-shaped profile, as illustrated below. Again Hintzman *et al* interpreted these data as evidence for mental rotation




- tactile maps, created by two successive taps on the head, were the subject of two experiments. Again the M-shaped reaction time profile was found, suggesting that the cognitive mechanisms underlying the judgements made from cognitive maps are at work here.

## 1.3.4 East - West / Right - Left

Loftus (1978) after informally observing that airline pilots, as a matter of routine, were given a single number as their direction information (i.e. a number between 0° - 359°) found that they translated this into a heading by firstly computing the nearest cardinal position and mentally facing that way. Then the difference between the cardinal direction and the desired direction was calculated followed by a mental rotation until the desired direction was faced. Testing this in the laboratory, he confirmed these findings but found that the way in which the direction information was presented had a profound effect on the reaction time to draw the direction. If the directions were presented as a simple number, then a monotonic increase in reaction time was observed as the value increased; however, if the directions were presented visually, angles close to North and South (±10°) were significantly more quickly responded to / processed than angles close to East and West.

Right-left or East-West have been shown to be more difficult to discriminate than up-down or front-back. This right-left effect has been demonstrated by a number of researchers (e.g. Farell, 1979; Just and Carpenter, 1975; Maki, Maki and Marsh, 1977; Maki and Braine, 1985). A study by Maki et al (1977) has been the most extensive, showing the right-left effects on reaction time for both memorised familiar (e.g. maps of the US states), abstract locational (e.g. left of, above, and so forth) and orientational (vertically- versus horizontally-oriented) stimuli. Maki (1979) has noted that in previous studies discrimination of cardinal compass points may have been confounded with discriminations of the ego-centric up-down and right-left directions. She therefore designed an experiment to discriminate whether East-West takes longer to discriminate than North-South in a natural three-dimensional space. Stimuli were directions on a campus where, objectively, East-West does not necessarily correspond to right-left and North-South and certainly not to up-down (but possibly front-back). However East-West discriminations were still found to be slower than North-South discriminations, but there does remain the suspicion that subjects, in using compass directions as labels, still employed a ego-centric spatial reference system with North up (or front), South down (or behind), East right, and West left. The conventional correspondence in maps between these compass directions and the egocentric directions may pre-experimentally have made this way of labelling compass directions natural. As a consequence, whatever causes right-left to be difficult to discriminate also causes East-West to be difficult. Maki concludes that the locus of the difficulty of discriminating right-left may be related to the right-left symmetry of the body.

Franklin and Tversky (1990) have also found that reaction times for reporting the location of objects which were described in a body of text which subjects had read depended upon the orientation of the subjects' bodies. When subjects were standing, reaction times were fastest for reporting objects which were located beyond the subject's head / feet, yet when the subjects were reclining front / back were fastest. Franklin and Tversky regard these data as supporting a spatial framework model according to which space is conceptualised in terms of three axes, the accessibility of which depends on the relation of the body to the world.

### 1.3.5 North - South / Top - Bottom

Shepard and Hurwitz (1983) have noted the extended use of the upward direction and the term *up* more generally, and have identified what they describe as a hierarchy of the uses of the concept which are applied to horizontal directions. Firstly, they argue that the concept was originally based on the unique, upright direction (defined by gravity) which holds over the entire surface of the earth. They continue that as even a very slight upward inclination of the local terrain is perceptually more accessible to us than the points of the compass and because we are constrained by gravity to move on the surface of the earth which is orthogonal to the pull of gravity, the concept *up* has been extended to refer to any uphill direction. Next, the notion of *up* has been metaphorically extended to refer to the direction towards a significant reference point without reference to the actual lay of the land (as illustrated in the expression 'going *up* to London'). This use of *up* has been further extended to mean North and to refer to the direction one is facing (based on the ego-centric frame of reference) again illustrated by the use of expression of 'I walked up to her'. All of these uses of *up* with the exception of the metaphorical use of the term, are designed to help us navigate or communicate information relating to the environment[7].

Shepard and Hurwitz (1983) have found support for these observations in a highly simplified map reading task. Subjects were required to interpret a single turn in a path and have their reaction times recorded. The most consistent of their findings was that the identification of a map-like representation of a right or left turn took increasing longer as the angle of the turn departed from the upright. These findings have also been echoed in the naturalistic studies of Levine (1982). It would also seem that a relatively high cognitive cost is incurred if one departs from this preferred orientation. Levine found that when people consulted *you-are-here* maps in such places as shopping malls and hospitals, they were usually successful in finding their way providing the map was in the preferred direction; but when the map was inverted people went off in directions that were incorrect by in excess of 90° more than 25% of the time. Finally, the work of Presson and Hazelrigg (1984) and Levine, Jankovic, and Palij (1982) on the orientation of the cognitive representation of spatial knowledge, which is highly relevant to these issues, is discussed more fully in section 1.4.

## Other systematic errors

Tversky (1981) has reported that remembering one spatial location with respect to another can lead to distortions of direction. When subjects were asked to remember two nearly-aligned maps they tend to be remembered as being more closely aligned than they actually were. In her experiment she gave subjects two maps of the Americas, one of which was correct, the other having South America moved westward with respect to North America thus more closely aligning the two land masses. A significant number of the subjects where found to incorrectly identify the altered map as the correct one. In a further experiment, another group of subjects incorrectly selected a world map in which the Americas had been moved north relative to Europe and Africa. Alignment errors were also found in

[7] The caveat that these observations probably only apply to the northern hemisphere should be noted.

- students' judgements of directions between cities;
- in memory for their local environment (spatial knowledge of which was most likely obtained from free exploration);
- in memory for artificial countries and maps, and
- in memory for blobs which could not be interpreted as maps.

Tversky has attributed these errors to two heuristics found in models of perceptual organisation. The first is *alignment* whereby figures are lined up relative to one another due to their mutual proximity. The second is *rotation* where the natural axes induced by a figure converge with frame axes (North-South, East-West, or horizontal-vertical), a phenomenon which Tversky believes is related to the Gestalt 'law' of perceptual organisation by *common fate*.

## Sense of direction

Kozlowski and Bryant (1977) have found that self-reports of how good or bad people thought their sense of direction were positively correlated with their actual spatial orientation ability. According to these self-report data, individuals with a good sense of direction were better than those with a poor sense of direction in giving or following directions (either oral or written) and in remembering routes while passengers in cars, and remembering written directions to a place. Furthermore and unlike those with a poor sense of direction, people with a good sense of direction liked to read maps, enjoyed giving directions, tried to remember details of the landscape when travelling to a new area, and, when driving felt it important to find new routes to places.

People with a good sense of direction were found to be better than those with a poor sense of direction at pointing at unseen goals (e.g. local buildings) in a familiar environment. Yet in a novel environment (a maze) Kozlowski and Bryant found that both people with good and poor sense of direction did not initially differ in the accuracy of their judgements. However with additional exposure to the maze, and with an explicit instruction to attend to intra-feature orientation, the good sense-of-direction group showed improved performance over the poor sense-of-direction group. From this Kozlowski and Bryant concluded that this improvement is neither automatic nor simple, but required repeated exposure to an environment and a conscious effort to orient oneself. Finally, they also noted that Tryon's (1939) experiments on maze '*bright*' and maze '*dull*' rats led him to conclude that neither sensory abilities nor learning abilities in these *good* and *poor sense of direction* rats differed, but rather, he argued, good maze learners were better at developing directional sets. In other words, an intentional, relatively high-level cognitive process may be the source of the relevant individual differences between good and poor sense of direction people.

### 1.3.6 Quantifying the accuracy of angle estimation

Unfortunately there are very few published accounts of real world experiments - only three have been found which can be used for such a comparison. Kozlowski and Bryant (1977) found a mean pointing error of 10.79° for people with a good sense of direction (by self-report), rising to 25.71° for those with a poor sense of direction (again by self-report) when they asked subject to *imagine* themselves in a particular place on campus and to point to various buildings out of the line of sight. Further evidence comes from Thorndyke and Hayes-Roth's (1982) experiment (described in section 1.3.1). Thorndyke and Hayes-Roth had subjects estimate the angle from the centre of one room to the centre of another in a specific building in two different ways which they described as *orientation* and *simulated orientation*. In the *orientation* condition the subjects, who were either drawn from people who had worked in the building for varying amounts of time (the navigation subjects) or who had studied a map of the building, were taken to different rooms and asked to estimate the angle from the centre of that room to the centre of a target room elsewhere in the building.

In the *simulated orientation* condition the same group of subjects were asked to imagine him or herself at the centre of a particular room and to estimate the angle to the centre of a target room elsewhere in the building.

Thorndyke and Hayes-Roth found that the navigation subjects were very reliably more accurate than the map-learning subjects on both tasks. Furthermore performance of all subjects was more accurate on the *orientation* task than the *simulated orientation* task. Concluding their experiment Thorndyke and Hayes-Roth presented the subjects with a number of pages upon which were two labelled dots designating the location of two areas within the building. Subjects were then required to indicate the location of a further room by making a mark on the page. Thorndyke and Hayes-Roth found that the map-learning subjects were very reliably more accurate than the navigation subjects on both tasks, although the latter improved with experience.

The final piece of evidence for the magnitude of the errors made in judging angles comes from Moar and Bower (1983). While their interest was in the presence of systematicity[8] in the judgement of the angles made by intersecting pairs of roads, they nonetheless tabulated the actual angles and mean judgements (table 1, p.109) from which it is possible to calculate the

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[8] i.e. the tendency to bias judgements to a multiple of 90°.

mean errors. From these data, it is clear that the mean errors ranged from 37.5° to -11.4° with all but one of the mean errors being negative (i.e. biased in an anti-clockwise direction).

In conclusion it would appear there is very little clear evidence as to the precise nature of the accuracy of judgements of angles.

# 1.4 Spatial cognition III: Primary & secondary spatial knowledge

## 1.4.1 Primary and secondary spatial knowledge

Presson and Hazelrigg (1984), in the light of their own research and in reviewing the related work of others, have drawn a distinction between primary and secondary spatial knowledge. They describe primary spatial knowledge as being acquired directly from exploring the environment by direct observation or interaction with it. In contrast, secondary spatial knowledge is acquired from secondary sources such as maps or other representation of the environment.

Presson and Hazelrigg define primary or direct spatial activity as involving direct interaction with the immediate surrounds. Primary spatial activity, they argue, creates a sense of immediacy with respect to which one can act directly. In contrast secondary or indirect spatial activity is defined as dealing with information on which we cannot act directly. Presson and Hazelrigg offer examples of secondary spatial learning as including such things as reading, drawing maps, mental rotation, and perspective tasks. These secondary, more abstract uses of space usually entail the use of spatial symbols (e.g. maps or figures) and the information represented therein must be translated before acting directly on it. Furthermore, secondary knowledge appears to have picture-like properties whereas primary knowledge does not (e.g. Evans and Pezdek, 1980; Presson and Hazelrigg, 1984). For example, there is strong evidence indicating that maps are encoded in the same orientation that they are experienced. Alignment effects (e.g. Levine, 1982; Levine, Jankovic, and Palij, 1982; Presson and Hazelrigg, 1984) and mental rotation effects (Evans and Pezdek, 1980) have also been reported when the spatial relations depicted in the map were learned in one orientation and tested in a different orientation. Evans and Pezdek (1980) found that when they presented subjects with either slides of states (i.e. US states) or of buildings on a college campus, that the reaction times for recognition increased as a linear function of the degree of rotation of the figure of the state but not of the buildings. These results may be explained by the assumption that the subjects had perceived the college building from multiple perspectives, whereas they had only ever seen the states from maps (or aerial photographs). Furthermore, when physical maps are aligned with the surrounding space, they are much easier to use than if they are not aligned, both for children (e.g. Bluestein and Acredolo, 1979; Presson, 1982) and for adults (e.g. Levine, 1982). Rossano and Warren (1989) have suggested that in order to make proper directional judgements when using mis-aligned maps, a person must engage in a cognitive strategy which results in rotation of the map into alignment with the environment. In their experiments they observed that although subjects were given no instructions on how to solve trials with mis-aligned maps, many spontaneously reported using a mental rotation strategy. Furthermore, the general increase in response times corresponding to the increase in degree of misalignment suggests a mental rotation operation. Finally, whether or not maps have been experienced from multiple vantage points - which is a primary characteristic of free exploration, the spatial knowledge acquired from a map, is still recalled in a specific orientation for later judgements (Presson, McAdams and DeLange, 1987[9]).

This stands in contrast with primary or direct learning which does not produce a mental representation that has a specific orientation. This conclusion follows from findings of the absence of alignment effects (e.g. Presson and Hazelrigg, 1984) and no mental rotation effects (e.g. Evans and Pezdek, 1980) when primary knowledge was tested. However, there is some evidence that direct learning does produce a representation with a preferred *orientation* but that orientation is very flexible, so that 'forward' in the environment is 'forward' in the cognitive maps (e.g. Scholl and Egeth, 1980 cited in Scholl, 1987 p. 616). Primary and secondary experiences also typically differ on several other factors, such as scale and context.

Scholl (1987) has also investigated stimulus materials at different scales:

- using a map of the subjects' university campus;
- a map of the cities in the north east of the USA (a source of secondary spatial learning);
- subjects' direct experience of the university campus;
- subjects' direct experience of the cities of the USA.

In general her results support the findings of the primary - secondary spatial knowledge divide, although it should be noted that she was testing a related though different hypothesis[10]. Scholl has argued that despite the differences in scale, it is unlikely to account for the reported alignment effects, in that, for example, the judgements of angular headings are unaffected by the variation in scale. Moreover similar alignment effects occur when symbolic information is used with no reduction in scale (e.g. Pufall and Shaw, 1973).

Presson, DeLange and Hazelrigg (1989) revisited Presson and Hazelrigg's 1984 research in a series of experiments which attempted to further clarify the primary - secondary spatial cognition divide. Firstly, they tested for the rôle of the instructional set, i.e. whether the use of

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[9] Cited in Presson *et al*, 1989, p. 896

[10] Scholl was testing Neisser's (1976) account of cognitive maps which he describes as orienting schemata. The parallel with the primary / secondary spatial knowledge divide is that 'forward' in (or to) an orienting schemata is the preferred or privileged direction.

terms (by the experimenters) of 'path' and 'map of a path' was significant, and found no effect. Next they varied the size and scale of the maps and paths presented to the subjects and found reliable evidence for the rôle of size in determining whether the figure was encoded in an orientation free or orientation specific manner. In contrast to the speculations of Scholl (above), Presson *et al* found that smaller arrays were found to be encoded in an orientation specific manner, characteristic of secondary learning, whereas large figures were not. Presson *et al* went on to speculate that larger displays are more like an environment in their own right and as such they 'afford' a wider range of experience and exploration.

## 1.4.2 Equi-availability and orientation-specificity

Predating and paralleling the work of Presson and Hazelrigg, Levine, Jankovic and Palij (1982) tested the specific hypothesis that the spatial knowledge contained in cognitive maps is essentially picture-like. They were motivated by the apparently conflicting evidence about cognitive maps, namely that they relatively accurately represent the environment of which they are a *map* and yet that they are subject to systematic distortions. However, rather than focusing on the distortions they proposed a model of veridical spatial representation. So, their opening hypothesis was that, like a picture, all information contained in a cognitive map is equally accessible, and like a picture, a cognitive map has a specific orientation. They refer to the former as the *equi-availability principle* and the latter as the *specific-orientation hypothesis*. According to the equi-availability principle, a person is able to represent information about the relative location of spatial landmarks acquired sequentially in a '*simultaneous system*'. This system functions like an aerial picture or map of the environment, making all relations among known landmarks equally available to the person. In a series of five experiments, with a very strong emphasis on controlling the amount and type of information made available to their subjects[11], they tested these hypotheses. The experiments achieved this by using artificial, and hence, unfamiliar environments (for example '*a table top terrain*' and an especially prepared room), and high levels of control from the experimenters, for example, moving subjects' hand over maps, and walking blindfolded subjects around a room. Overall the results of these experiments supported both the equi-availability principle and the specific-orientation hypothesis.

[11]This is in sharp contrast to the naturalistic acquisition of spatial knowledge.

## In summary

In all there is clear evidence for two distinct forms of spatial learning and representation. Spatial knowledge acquired from the representations of the environment is orientation-specific in that the distribution of errors for aligned and counter-aligned judgements of angle show qualitative difference for small but not for large arrays. In terms of representation it is visual and picture-like. The specific figural qualities of the scene, relative to a ego-centric frame of reference are preserved.

Spatial knowledge acquired from the environment is said to be orientation free but has with a preferred-orientation. In terms of representation it is more like an integrated model of the world preserving the invariant, integrated aspect of spatial relations in an externally based frame of reference, and when people recall information in this case, they can visualise a scene within which they are positioned.

## 1.4.3 Spatial mental models

It is accepted that the comprehension of texts describing spatial configurations is facilitated by way of a spatial mental model which analogically encodes the spatial relationships among the components of the configuration. In short, people create spatial mental models of those scenes described in the text (e.g. Ehrlich and Johnson-Laird, 1982; Foos, 1980; Mani and Johnson-Laird, 1982; Perrig and Kintsch, 1985; Franklin and Tversky, 1990; Payne, 1993; Ferguson and Hergaty, 1994). These spatial mental models are a '*non-linguistic representation of a situation derived from a propositional representation by means of inferences based on general knowledge*' - Johnson-Laird, 1983. Spatial mental models contain information about the characters and objects within the scene, their orientation and locations. The spatial information preserved in them includes categorical spatial relations, such as those expressed in the words *above, in front of, north of, across from* and so forth, and sometimes includes more analogue information about distances. These spatial mental models appear to be rapidly updated and transformed as narratives supply new information about objects, locations and orientations.

This area of study is both huge and very complex and only a little of it is relevant to this enquiry. So instead of attempting to survey the entire field, attention will be given to two of the most relevant sets of experiments in this area which are those of Taylor and Tversky (1992a & 1992b). These experiments are reviewed in the next two sections.

## Comprehending route and survey descriptions

Taylor and Tversky (1992a) have noted that (tourist) guidebook descriptions of cities and the like take on one of two perspectives, a route and a survey perspective.

A *route* perspective takes readers on a mental tour of the environment, describing landmarks in an ego-centric frame of reference, i.e. in terms of the reader's front, back, right and left. For example, '*As you sail up the Seine from the Place de la Concorde, you first come to the Musee D'Orsay on your right*', p.261.

In contrast, a *survey* perspective gives reader's a bird's-eye view, and describes landmarks relative to other another in an absolute frame of reference, i.e. in terms of north, south, east and west. For example, '*The Washington Mall is bounded by the Capitol at the East and the Lincoln Memorial at the west*', p.261. These two perspectives clearly mirror the distinctions made between route and survey spatial knowledge.

Taylor and Tversky investigated the consequences of these different perspectives in a series of four experiments. In the first of the series, they had subjects read either a route or survey perspective of each of four different environments. Two of the environments were large scale (e.g. a small town), and the remaining two were small scale (e.g. confined to a single building or enclosure, namely a zoo and a convention centre). Each environment contained a number of clearly defined landmarks. Taylor and Tversky prepared four pairs of descriptions of these environments. Each pair described one of the four environments from one of two perspectives: bird's eye (survey) or mental tour (route). The survey descriptions reflected the hierarchical structure of each environment and adopted an external frame of reference using such canonical terms as *North, South* or *in the centre*, while the route descriptions had a linear organisation and adopted an ego-centric frame of reference using terms such as *in front of you* or *to your right*. The texts were judged to be equally informative, coherent and roughly equal in length. After studying the description, subjects responded true or false to a series of statement: (i) verbatim statements taken from both the perspectives read; (ii) statements taken from the other perspective to that which had been read; and, (iii) inference statements from both perspectives. The inference statements contained information that was not explicitly stated in either text, but could be inferred from information in either text. Taylor and Tversky reasoned that if perspective was encoded in the mental representations, then inference statements from the read perspective should be verified more quickly than inference statements from the other perspective. After responding to the statements, subjects were asked to draw sketch maps of the environments.

The speed and accuracy to answer the true or false questions suggested that the readers had formed at least two mental representations of the text, one of the language of the text, and the another of the situation described by the text, that is the spatial relations among the landmarks. Responses to verbatim statements were faster and more accurate than responses to inference statements, although the overall accuracy did not reliably differ between types of statement. This results did suggest that perspective was encoded in the mental representations. These results were replicated across all four experiments. From studying the descriptions, subjects were able to produce maps that were virtually error free, indicating that language alone was sufficient to accurately convey coarse spatial relations.

## Producing spatial descriptions

In contrast to the descriptions of the above experiments, this is very much the other side of the coin. Taylor and Tversky (1992b), in another series of experiments, gave subjects maps to study, and then asked them to write descriptions of the environments from memory. A compass rose appeared in each of the maps, allowing orientation with respect to the canonical axes. In a further experiment, Taylor and Tversky asked subjects to write descriptions of familiar environments they had learned from experience.

It emerged that the descriptions produced by the subjects used either route or survey perspectives, or a combination of both. No other style of description emerged. In the mixed perspective descriptions, either one perspective was used for parts of the environment and the other perspective for other parts, or both perspectives were used simultaneously for at least part of the description. Across a wide variety of environments, survey, route and mixed descriptions were obtained, their relative frequency depending in part on features of the environment. This finding is in contrast to the widespread claim that most spatial descriptions take a consistent perspective, specifically, a route perspective. The descriptions that subjects the subjects produced from memory were quite accurate and allowed a further, naive group of subjects to place nearly all the landmarks featured on the maps correctly.

Taylor and Tversky found that the key to a route description lay in describing the locations of landmarks relative to a single referent with a known perspective, in this case, the moving position of the reader. Furthermore in route descriptions, although the referent was constant, the orientation and location of the referent kept changing. Readers had to keep track of that orientation and location relative to the canonical frame of reference (namely, the compass rose). In contrast, a survey description is distinguished by describing the location of a landmark relative to the location of another landmark from a fixed perspective. Unlike route descriptions, in survey descriptions, the referent keeps changing, but the orientation is constant. Survey descriptions establish referential continuity by using a single orientation, but they are complicated by changing the referent element. When either type of information is consistent and complete the individual pieces of information can be integrated into a coherent representation of the spatial among landmarks independent of any specific perspective.

## In summary

Again Taylor and Tversky have presented evidence for a two component account of spatial cognition comprising route and map knowledge, together with two distinct frames of reference.

## 1.5 Spatial cognition IV: Computational approaches to spatial cognition

This section reviews a number of contrasting computational models of spatial cognition, two of which are considered in detail.

### Introduction

Computational models have been developed in recent years as an alternative to traditional experimental techniques. The primary means of distinguishing among these models lies with the choice of the form and content of the representation adopted by a particular model which appears to be strongly influenced by the range of tasks to be addressed. For example, CITYTOUR (Andre, Bosch and Rist, 1987) is designed to answer natural language questions about the spatial relations among objects in a city. CITYTOUR is able to answer questions such as, 'Is the post office behind the church?' because the system 'knows' where each object is in the city and has defined their intrinsic fronts and backs. Other models like TOUR (e.g. Kuipers, 1978) and NAVIGATOR (Gopal, Klatsky and Smith, 1989) focus on different aspects. TOUR does not fully ground itself in the psychological evidence pertaining to spatial cognition, but instead has adopted a social geographical cum developmental approach. Nonetheless the resulting model is an engine for solving a wide range of spatial problems including how new spatial knowledge is acquired. NAVIGATOR adopts a similar approach.

In contrast to these computational model which owe much to artificial intelligence paradigms, a second group of models are concerned with biologically plausible models of place recognition and goal location in a connectionist framework. Zipser (1986), Munro and Hirtle (1989) and Wender (1989) are among a number of researchers who have developed connectionist models of cognitive maps and other aspects of spatial cognition. Zipser (1986) in particular has investigated the neurological basis of spatial cognition based on the work of O'Keefe (1979) and O'Keefe and Nadel (1979) who have studied the functional properties of the hippocampi in rats. O'Keefe and Nadel have presented evidence that the hippocampus is the neurological basis for the cognitive map.

### 1.5.1 The TOUR Model

Kuipers (1978), the creator of the TOUR model, begins with the concept of the cognitive map which he states is built up from observations gathered as the individual travels through the environment. The nature of the observations available are described as sequences of places and paths encountered *en route*, the magnitude of turns and distances travelled, and the observed positions of distal landmarks. Kuipers supplements this mainstream position with evidence drawn from other sources, for example, Lynch's (1960) work on the categorisation of the landscape of cities; Appleyard's (1970) analysis of sketch maps of such landscapes; and a number of other social geographers' research is also used to supplement Kuipers' account (and starting position) of cognitive maps. The psychological evidence adopted by Kuipers appears to be essentially developmental in origin. While he cites the work of Piaget and Inhelder (1967) with children's conceptions of space, he uses Siegel and White's (1975) review of spatial cognition (which he states demonstrated parallels between a child's spatial abilities and an adult's) to justify this. Hence Kuipers' vocabulary of spatial concepts is derived primarily from Lynch and Piaget and Inhelder.

The TOUR model adopts Lynch's segmentation of spatial knowledge and has data structures for each of the five categories (i.e. paths, path intersections, landmarks, districts, and boundaries), a mechanisms for carrying out inferential operations upon the data structures and a 'You are Here' pointer. To illustrate how this pointer has been instantiated, and to contrast Kuipers' approach with the connectionist model below, here is a pseudo-code fragment (Kuipers, 1978, p. 143) from the TOUR model which defines the 'You are Here' pointer:

YOU ARE HERE:

| | |
|---|---|
| PLACE: | <place description> |
| PATH: | <path description> |
| DIRECTION | <1-D[*imension*] orientation: +1 or -1) |
| ORIENT: | <co-ordinate-frame description> |
| HEADING: | <2-D orientation: 0 to 360> |

Central to the TOUR model is the concept of a '*view*'. Kuipers defines a view as, '*the sensory image received by the observer at a particular point*'. Views are used to recognise places and these places can, in turn, be used as a node at which additional information can be stored. Consequently the key operation on views is that of comparison, for example, by comparing the current view with views stored in long term memory, it is possible to retrieve all the information associated with it. This information consists of the details of paths between it and other places, which in turn are stored as sequences of actions and views. In conclusion, Kuipers describes this model as having demonstrated how different kinds of knowledge can be stored, how new information is assimilated, change from one representation to another, and used to solve problems. He concludes by outlining the deficiencies of the model, both theoretical and empirical. TOUR does not address the rôle of imagery; or peoples' exposure to and use of maps; or the interface with the sensory systems which pick up the raw data used by a view. Furthermore TOUR fails to model a variety of aspects of human spatial behaviour, including developmental aspects and the kinds of errors people make, for example, systematicity, the effects of clutter, the non-commutativity of distances, and so forth (e.g. Stevens and Coupe, 1978; O'Keefe and Nadel, 1978; Tversky, 1981; Thorndyke, 1981; and Moar and Bower, 1983). Nor is there any attempt to deal with the distinction between primary and secondary spatial knowledge (Presson and Hazelrigg, 1984).

## 1.5.2 Zipser's connectionist models

Zipser (1986) introduces his connectionist models by contrasting them with models of spatial cognition which have been instantiated in an unrestricted computer context, that is, without reference to biological plausibility, which for that reason he rejects. Zipser then considers the neurological evidence: he notes the powerful correlations between single cell neuron activity and events in the world which is found in cells of the hippocampus (Becker *et al*, 1980; O'Keefe, 1976 are cited as examples). In studies with the rats, for example, it has been found that they have single cells that fire at their maximum rate only when the animal is in a particular location relative to a set of distal landmarks. These locations are called '*place fields*'. Removing too many landmarks or radically altering their spatial locations abolishes the place-field response of these units (O'Keefe, 1979; O'Keefe and Nadel, 1979 are cited as examples). Measurements of the location, size and shape of the place fields, and how their responses change when the environmental landmark cues are manipulated (for example Muller *et al,* 1983) were made. Quantitative experiments of this kind have shown that the response of place-field units is determined in a systematic, rule-governed manner by the configuration of the surrounding scene. Muller, Kubie and Ranck have also shown that when every feature of the environment is scaled to a different size, the relative location of place-fields, and their areas scale with the environment. Given these experimental findings Zipser developed a computational model which attempted to relate the configuration of landmarks (their location, size, distance etc.) and place fields. The fundamental question is, '*How do the place-field neurons know that the observer is at the location where they are supposed to fire?*' Such a matching task is potentially very complex, however experiments revealed that only a few landmarks are actually required. This can be seen in figure 1-3. The location of point ***P*** can be uniquely determined by its distance from the three landmarks ***a***, **b**, and ***c***. The circles are perimeters

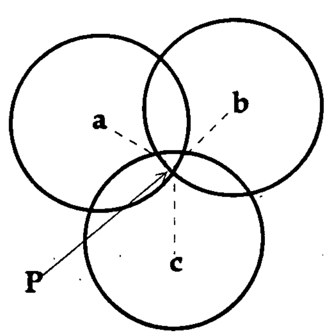

*figure 1-3*

along which the distance of an observer from the landmark remains the constant (Zipser, 1986 pp. 437.)

In all Zipser constructed three different models (instantiated as computer, connectionist programs). The first was based on the above reviewed data and analysis of landmark recognition, and figure 1-4 illustrates its structure. The *Sensory System* processes input from an environment and produces two outputs. These are X which is a description of the landmark; and $d_X$ which is the value of a location parameter such as distance. The units in layer 1 are tuned to individual landmarks and have distance information stored which is used to compare with the value of $d_X$. If the value of X = A then the unit $A_p$ will generate on output based on $d_X$-$d_a$. The rôle of the layer 2 unit is to integrate the outputs from the layer 1 units until the scene changes (i.e. the observer moves). However, while this model is biologically plausible, evidence presented by Kubie, Muller and Ranck, 1983 (cited by Zipser, p. 441) suggests that rats, at least, do not use distance information as a location parameter, furthermore the model does not distinguish between left and right, and viewer orientation more generally.

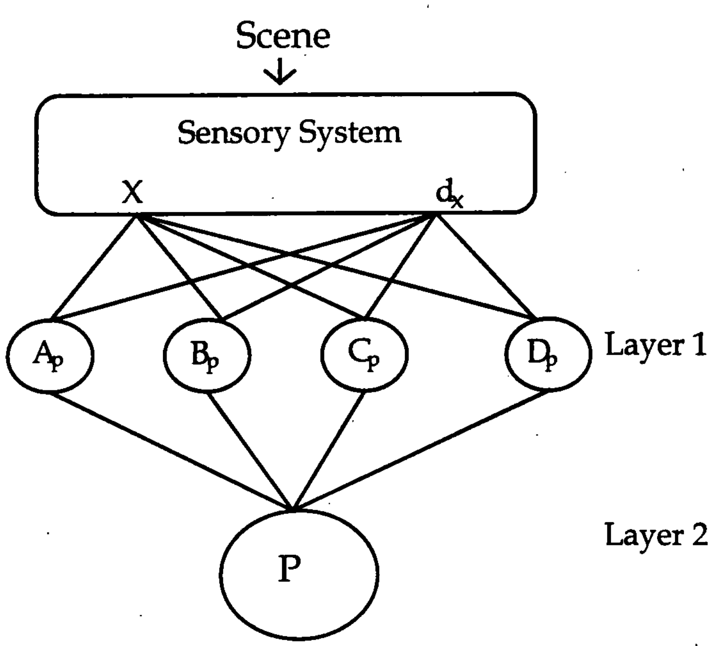


*figure 1-4*

Zipser's second model is more speculative than the first, in that it added a 'goal vector' to the place fields which is a hypothesised output of the place field neurons. The goal vector was included in an attempt to address the essential aim of navigation - goal location (e.g. '*How do I get home from here?*'). This second model is called the *distributed view-field* model and is illustrated in figure 1-5 (after Zipser, pp. 450). The object units have a similar function as the layer 1 units in the first model. The major difference is the inclusion of orientation specific units (i.e. left, centre and right), and these units only recognise landmarks in their own visual fields. The view-field units are, again, analogous to the layer 2 units in the first model. Together the object and view-field units recognise an oriented place-field (P). However, unlike the first model, the output of the view-field also depends on the orientation. In the network shown in figure 1-5, information about the goal location is also encoded in an additional unit the output of which is passed to the motor system which is interpreted as the direction of the goal. With this kind of network, to head to a goal from a given location, the observer would first examine the landmarks before it, which would activate an associated view unit. This in turn would activate a goal unit, the output of which could direct the observer to the goal.

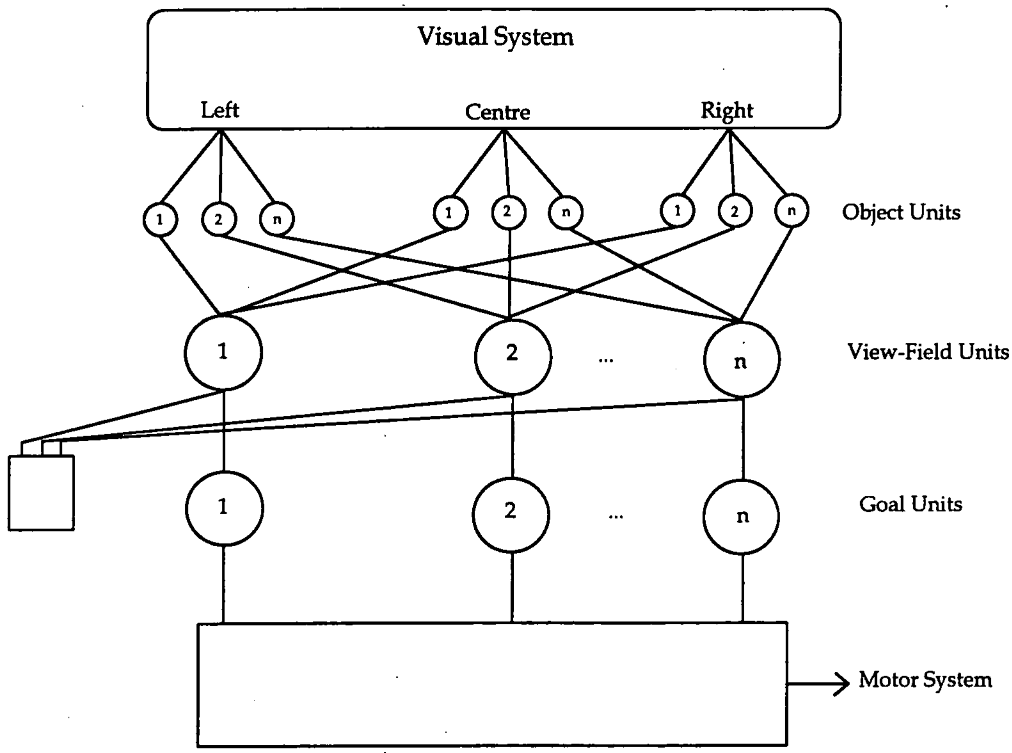


*figure 1-5*

There are, however, problems with this network. It is not realistic to have a unique field-view unit for every possible permutation of place and orientation in the environment. Secondly, it is unlikely that an observer would be at the exact centre of a place-field. Thirdly, it is not clear how information about the environment is assimilated in the first place. The final model (the β -coefficient model) was not based on the place field data, and while it was based on the biologically plausible behaviour of simulated neurons, is much more speculative. The rationale for its creation was to overcome the drawbacks of the previous models. The β-coefficient model needs to record information about a set of landmarks and a goal only once, and this recorded information can be later used to locate the goal from any position from which the landmarks are visible.

## In summary

As capable as these models are, two criticisms can be made. Firstly, neither of the models can account for a truly significant part of human spatial cognition much less all of it. They use highly impoverished models and datasets as their basis; and secondly, as mentioned in the introduction to this section, the choice of representation and operations on that representation have been carefully and narrowly selected by their authors. Even connectionist approaches such as Zipser's biologically plausible models fall well short of offering an account of spatial cognition.

## 1.6 Of cognitive maps and spatial cognition

This section attempts to identify the strengths and weaknesses of cognitive maps.

### Cognitive maps are appealing

Downs (1981) has argued that we automatically and unquestioningly accept ideas of maps and mappings as logical ways of expressing the idea of space and of representing the world in which we live. '*Cartography,*' he writes, '*has played and continues to play a central role in the attempt to understand spatial cognition and its development. There is an inescapable connection between cartography and cognition: cartography as a way of thinking is both pervasive and persuasive. In a sense, cartography is a 'natural' way of thinking and the use of spatial expressions appears to be fundamental to the structure of natural language and thinking with an apparently perfect match between experience language and thought.*' However,... '*the relationship between spatial cognition and cartography is incredibly complex; there are similarities, parallels, interdependencies, and interactions that border on paradoxes*'

Downs, 1981, p.324.

### Cognitive maps as an incomplete account of spatial cognition

While a considerable body of evidence has been presented for a two component model of spatial knowledge, there is also a case for considering whether it may not be better considered as a continuum. For example, both Thorndyke and Hayes-Roth (1982) and Moar and Charleton (1982) have variously argued and presented evidence that a person's 'route' knowledge contains more detailed information about the travelled route. This information might include impressions of the distance travelled along each leg (straight line segment) of the route, the angle of the turns between legs, and terrain features along the route. Thorndyke and Hayes-Roth (1982) have also argued that cognitive maps contain information which is not available from direct experience in the environment, but which is more normally portrayed in maps. An individual's perspective of the environment usually corresponds to the canonical horizontal view he or she has during navigation or free exploration and not a global or bird's eye view. This observation also lends weight to the argument that route knowledge is *transformed* into a more map-like representation with experience rather than the simple accumulation of more spatial knowledge of the same type. However they believe that this knowledge is not identical with survey knowledge derived from maps. Instead they see this change as the development of (that is, the reported experience of) *translucence* in the ground-based procedural representation.

This translucence may refer to the cognitive manipulation of a view (or image) of an aspect of a cognitive map which allows navigators to 'see' through obstacles, revealing obscured relationships which can be examined. Cognitive maps have been also been treated as though they are two-dimensional in that there is a conspicuous absence of research into the characteristics of height and depth information in spatial knowledge as noted by Shepard and Hurwitz (1983).

Furthermore Tversky (1993) has argued that the traditional use of the cognitive map metaphor does not reflect the complexity and richness of environmental knowledge. She goes on to say that environmental knowledge takes in a wide variety of forms, fragmentary memories of maps we have seen, routes we have taken, areas we have heard about, facts about distances and directions. Even knowledge of time zones, flying or driving times, climate, historical conquests and linguistic families can be used to make inferences about spatial proximity. This information may also contain errors, systematic or random, and when we need to remember or to make a judgement, we call on whatever information seems relevant. Because the fragments of information may be incomparable, we may have no way of integrating them. For those situations, she suggests had a cognitive collage is a more fitting metaphor for environmental knowledge. Tversky defines a cognitive collage as '*thematic overlays of multi-media from different points of view. They lack the coherence of maps, but do contain figures, partial information, and differing perspectives.*'

So a cognitive map cannot be a map as such, particularly as Rumelhart *et al* have noted [read cognitive map instead of schemata]:

> *Schemata are not explicit entities, but rather are implicit in our knowledge and are created by the very environment that they are trying to interpret... nothing stored corresponds very closely to a schema. What is stored is a set of connection strengths which, when activated, have implicitly in them the ability to generate states that correspond to instantiated schemata.*
>
> Rumelhart et al, 1986, pp. 20-1

Instead, the term *cognitive map* should be treated as a metaphor or as shorthand for the cognitive representation of spatial information. A cognitive map may have analogous *functionality* to a cartographic map but cannot have similar physical properties (Downs and Stea, 1973). Spatial information can, in principle, be represented in a great variety of different ways many of which are not analogues of the environment they represent.

# 1.7 Spatial cognition V: A review of virtual reality

## Introduction

This section briefly reviews:

- a number of instantiations of virtual reality.
- immersive compared with non-immersive virtual reality (VR).

The history of virtual reality is varied and its origin subject to apocryphal stories. However it does seem likely that various instantiations of VR were developed more or less simultaneously at a number of locations mainly in the USA. As consequence, virtual reality is not a unitary phenomenon and there are no agreed definitions. Virtual reality also has a number of synonyms indicating variously its ætiology and the lack of a canonical definition (in its earliest incarnations it was also described as *artificial reality*). This new 'reality' can be found instantiated in such things as graphical user interfaces, computer aided design applications, flight simulators, and arcade games. However despite this diversity it can be divided into two basic forms, immersive and non-immersive (or desktop) virtual reality. Immersive virtual reality requires the users to wear a light-excluding helmet which houses the display, and a tactile data glove which facilitates the manipulation of virtual objects within virtual reality (e.g. Sturman and Zeltzer, 1993). Non-immersive virtual reality, in contrast, is displayed on a cathode ray tube most typically found in a personal computer's monitor. While immersive virtual reality has captured the public imagination, desktop virtual reality is more commonly found.

## 1.7.1 A variety of manifestations

A taxonomy of virtual reality may not be possible as virtual reality and its attendant fields of research are both immature and rapidly evolving so that any definition would neither be exhaustive nor in the strict spirit of Linnaeus. What follows is not based on the fundamental defining characteristics of virtual reality but instead on its pragmatic, and functional characteristics. Very broadly, virtual reality is currently used in three fairly distinct ways:

- for the visualisation or representation of complex, perhaps multidimensional information (e.g. the image of a new building development, or the flow of traffic on a telecommunications network). An example of this has been British Telecom's (BT) use of virtual reality for network visualisation[12]. Using BT's system, the operator can view the network from a distance, then close in and navigate around it, viewing the telecommunication linkages from different view points. The application supports a virtual reality system which displays telecommunication links and boxes linked in three dimensions. Specific examples of the visualisation of complex, multidimensional information include the work of McConathy and Doyle (1993) working with medical art have created stereoscopic images of 'three-dimensional' exploded organs; Eyles (1993) has produced a computer graphics system for visualising spacecraft in orbit; Fitzmaurice, Zhai, and Chignell (1993) describe the creation and use of a 3D spreadsheet; and Koike (1993) has used virtual reality visualisation techniques to aid software development;

- as a means of tele-presence, that is, affording a user a view of a hazardous or otherwise unreachable situation or environment (e.g. the inside of a nuclear reactor, the surface of Mars, within a flight simulator - or an arcade game). Tele-presence has been realised in the research by, for example, Roscoe (1991) who has reported on the difficulties faced in the use of imaging systems for military aircraft. However, while these and other fields of research are interesting in their own right, their focus has very much been on the algorithms required to drive the graphics; and finally,
- as a new user interface to computer systems themselves, Robertson, Card and Mackinlay (1993) are among a number of researchers who are experimenting with virtual reality as a means of exploring new user-interface paradigms.

### 1.7.2 Immersive virtual reality

Cognitive, sensori-motor and other psychologically related research into immersive virtual reality has included such things as: grasping and reaching for and the manipulation of virtual objects (e.g. MacKenzie, 1994), the role of gesture (e.g. Wexelblat, 1995; Prime, 1996); moving through virtual reality environments (e.g. Slater, Usoh and Steed, 1995); perception (e.g. Greenhalgh and Benford; Prime, 1996); ego- and allo-centric frames of references (e.g. Prime, 1996); and spatial cognition (e.g. Osberg, 1994).

## Wayfinding in virtual reality

This section now reviews two investigations into wayfinding in virtual environments which are judged to be representative of current research.

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[12]Reported in New Scientist, 18.xi.93.

Regian and Shebilske (1990) conducted a series of studies of the use of virtual reality as a training medium for visual-spatial tasks, with one of their experiments involving wayfinding. The environment used in the wayfinding study was a virtual maze. It consisted of three storeys, with four rooms in each storey. Every room was connected to at least one adjoining room by a hallway or passageway leading to a room above. The walls were all coloured grey, the floors red and the hallways yellow. Each room was the same size and each contained either a star, cube sphere, or pyramid coloured red, green or blue. Subjects were given verbal directions on where to move through the virtual environment. Three different tours were taken after which the subjects were free to self-explore the environment for one hour. After this period of free exploration the subjects were asked to find the shortest route to a room having a target object. The number of rooms traversed were recorded. These numbers traversed were contrasted with data from a random walk algorithm and found to be significant smaller. Regian and Shebilske have taken this as evidence that subjects can learn to navigate in a virtual environment. However, there must remain a question as to whether comparing a random walk with purposive behaviour is meaningful.

Darken and Sibert (1993) have reported on an informal study looking at toolsets for wayfinding in virtual environments. The tools available to the participants were flying (the ability to rise above the virtual environment), spatial audio markers, visual markers (breadcrumbs), co-ordinate feedback, grid navigation and two map-views of the world. The map views available were track-up and North-up. Track-up maps change dynamically so that the user is always represented in the middle of the map, and the map revolves so that the user's forward view is always presented at the top of the map. A North-up map has a similar central representation of the user, but the representation rotates not the map. North is always represented at the top of the map. Only one type of map could be chosen and seen at one time. While the mechanics of how to use the tools were explained, the benefits and what information could be retrieved from them were not. Only one type of tool was available to the subject during each scenario for each condition. The environment was a large landscape with grid markings on the floor. The landscape was sparsely populated with objects such as ships and rectangles. The focus of this study was to examine how subjects would use a specific tool under three different types of conditions. The first condition was just to explore the environment. The second condition was a naive search, where the subject knew what the object looked like but did not know its location. The final condition was an informed search, where the subject knew both the description and location of the object. The subjects were instructed to search for the target. When the subject was close to the target a bell would sound and they were told to return to the starting position as efficiently as possible. The subjects were encouraged to talk aloud as they moved through the environment and as they used the navigation tool to help them. The co-ordinate tools were mainly utilised in two ways. The first was at the start position, where the subject would move along one axis of the grid lined floor and note the feedback. During the return portion of the task they commented that they had remembered their initial position. The breadcrumbs were used more as landmarks than as trail making objects, which they were originally intended for. The first breadcrumb was usually dropped at the starting position. It was also observed that groups of breadcrumbs were dropped in a shape to show directional information. Informal observations indicated that people used the different tools in a variety of ways. One of the most useful tools was a synthetic sun, which improved performance in both the search and return phases. In fact before the sun was added all subjects moved in the incorrect direction in the homing phase. From this Darken and Sibert concluded that subjects showed different behaviours when they used different tools in wayfinding and further work was required.

### 1.7.3 Non-immersive virtual reality

Finally, it should be noted that <u>no published research on the topic of the cognition of non-immersive virtual space was found in the course of this enquiry</u>. This is with the exception of related research by Barfield and Robless (1989) and Carswell, Frakenberger and Bernhard's (1991) investigations of the relative ease of comprehension of two- and three-dimensional graphs. Barfield, Salvendy and Foley (1989) have also considered the mental rotation of 3-D graphic figures presented on a VDU. Such work stands in contrast to the large body of evidence about the real-time perception of virtual environments. Such research has typically focused on use of flight simulators, electronic instrument displays and so forth (e.g. Roscoe, 1993). However a study which may be of some relevance is reported by Eby and Braunstein (1995) who investigated the effect of a visible frame around a real three dimensional scene on perceived depth within the scene. In all they conducted three experiments: (i) subjects were asked to judge the slant of an object that had been rotated about a vertical axis and found that the judged slant was reduced when the frame was illuminated. Next, subjects judged the width to height ratio of objects with in the scene (ii) with and without an illuminated frame (iii) when a frame was added to the illuminated scene. In both cases the presence of the frame reduced the perceived depth within the scene. Eby and Braunstein (1995) concluded that the presence of the frame serves as a <u>flatness</u> cue. It should be noted that the frame of the computer monitor is just such a frame.

## 1.8 The rationale and structure of this thesis

### 1.8.1 Rationale

It is expected that the exploration of virtual environments will give rise to spatial knowledge, and it is the nature of this knowledge which is here being investigated. The spatial knowledge which is acquired from interacting with virtual space can, perhaps, be of three forms:

- It can be essentially the same of the spatial knowledge which arises from exploring everyday, three-dimensional space, (i.e. primary spatial knowledge). If it is, it would then be expected to exhibit a range of characteristics which this literature review has established.
- In contrast, such spatial knowledge might instead more resemble that which is acquired from studying maps and diagrams (i.e. secondary spatial knowledge). Again, if this is the case, it would exhibit such characteristics as orientation-specificity.
- Or some admixture of these two.

### 1.8.2 Methodology

#### Distance and angle estimation

Wayfinding may be characterised as needing to know how far and in which direction to travel. So, to obtain a clear picture of wayfinding in virtual environments, the accuracy and other characteristics of both the estimation of inter-feature angles and distance estimation are the subjects of this investigation.

Judgements of angles. Experiments I to IV (inclusive) and part of experiment VII examine the consistency of knowledge acquired from virtual environments from the perspective of angle estimation.

Judgements of distance. Similarly, experiments V to VIII (inclusive) and part of experiment VII examine the accuracy of inter-feature judgements of distance.

#### The subjects

The subjects who participated in the eight experiments reported in this volume were drawn from the technical and administrative staff of MARI Computer Systems, an independent software house located in Gateshead, which is the author's place of work at the time of writing.

The experiments were conducted over a period of 15 months. The subjects were predominantly male and aged between 18 and 50. The women were typically aged between 18 and 35. All of the men and women were very experienced in the operation of PCs.

### 1.8.4 The chapters

Chapter 1

Is this chapter and has introduced the field of this enquiry with a review of the literature focusing on spatial cognition.

Chapter 2

Experiment I investigated the consistency of the cognitive representation of a virtual environment as evidenced by accuracy of the judgement of angles between features in that environment. It also considered the rôle of incidental and intentional learning in spatial cognition. Experiment II investigated the accuracy of inter-object judgements of angles while actively exploring a virtual environment. Experiment III further investigated the findings from the first experiment that the judgements of angles in a virtual environment are biased in an anti-clockwise direction. The chapter concludes with a general discussion of the findings of the first three experiments.

Chapter 3

Experiment IV addressed the question of whether spatial knowledge acquired from exploring a virtual environment shows the same orientation-specificity as knowledge acquired from studying maps or figures. Experiment IV also considered the integration multiple view points in virtual space to form a perceptual / conceptual whole.

Chapter 4

Experiments V paralleled part of Thorndyke and Hayes-Roth's (1978) investigation into the differences in spatial knowledge acquired from maps and from the environment, substituting virtual space for real space.

Chapter 5

Experiment VI investigated the accuracy of inter-object judgements of distance while actively exploring a 'cluttered' virtual environment. Experiment VII investigated whether the well-documented clutter phenomenon pertains in virtual space and contributes the distortions in distance judgements. Evidence for systematicity of angular judgements was also sought. Experiment VIII paralleled (experiment 2) of Kosslyn, Ball and Reiser (1978) image scanning studies. The chapter concludes with a general discussion of the findings of experiments V to

VIII inclusive.

Chapter 6

Is general discussion of the findings from the experiments, and offers suggestions for further work.

Chapter 7

Contains a full listing of all references cited in this thesis.

Appendix A

Contains the raw data from experiments I - VIII.

Appendix B

Contains a description of ACK3D.

# 2. Experiments I, II & III

Experiments I, II, and III are investigations into the cognitive representation of the spatial properties of virtual environments. Their focus is judgements of inter-feature angles within virtual environments. The first experiment is something of a pilot, in that it employs a virtual reality game, while subsequent experiments use a simple virtual reality construction kit to create custom-made virtual environments.

Experiment I explores the rôle of intentional and incidental learning in the acquisition of spatial knowledge of a virtual environment. Further, it investigates the internal consistency of the cognitive representation of this virtual environment which has been explored, by comparing the accuracy of judgements of inter-location angles made from different locations within the virtual environment.

Experiment II investigates the evidence for directional bias in the judgements of angles in virtual environments.

Experiment III examines the accuracy of judgements of angles while actively exploring a virtual environment, with the objective of establishing a baseline for the accuracy of judgements of angles.

## 2.1 Introduction to experiment I

### Intentional - incidental learning

Learning is central to cognition (e.g. Norman, 1986), and until recently almost all accounts of learning assumed that it is intentional. However, Hasher and Zacks (1984) are among a number of researchers who have offered evidence that intention is not always required and that some learning occurs in an implicit or incidental manner (Hasher and Zacks describe it as *automatic encoding*). Berry and Broadbent (1988) are not alone in noting that it is not always clear what is meant by the distinction between intentional and incidental learning. Berry and Broadbent distinguish (firstly) between knowledge acquired by an individual some of which may be reportable, and some of which is not, so in this sense it parallels the procedural - declarative knowledge divide (e.g. Rumelhart and Norman, 1985). Secondly, the incidental - intentional distinction may apply to the way in which the knowledge was acquired. They illustrate this distinction by suggesting that learning itself may be explicit when deliberate instructions are given to learn something - e.g. 'discover the underlying rule in some set of materials', or it may be implicit - 'learn this material', during the course of which the underlying rule is learned. Research into the intentional (or explicit) - incidental (or implicit) distinction has variously focused on tasks which range from computer control tasks (for example, Berry and Broadbent, 1988; Hayes and Broadbent, 1988) to the learning of artificial grammars (e.g. Reber, 1976).

## Spatial knowledge acquired incidentally

An unverified but common-sense observation is that in the course of traversing, say, a city, one remembers more than the simple sequence of distances traversed and angles turned through. Although there has been relatively little research into the field of incidental spatial learning, examples are as follows: Brewer and Treyens (1981) arranged to have subjects called, one at a time, to wait in a room they had especially prepared. When they were invited into a second room the subjects were given the unexpected task of recalling the contents of the first room. The first room had been made up to look like a typical graduate student's office containing both a set of schema-relevant objects (e.g. table, typewriter and coffee pot) and a set of schema-irrelevant objects (such as a skull, and a toy top), and all of these objects had been previously rated for saliency by an independent group of subjects. Subjects asked to recall the contents of the first room typically included items which were not actually present but which were schema-relevant, and included such items as books and a telephone. In all, Brewer and Treyens concluded that an important aspect of incidental learning was schema relevance, in that people tend to recall objects which have high schema-relevance better than schema-irrelevant objects. Furthermore it was also observed that the subjects displayed a tendency to recall the various objects in their canonical positions rather than their actual locations. In conclusion, Brewer and Treyens argued that this evidence offers an account of the recall of spatial knowledge. Another example is reported by Mandler, Seegmiller and Day (1977) who have observed that in studying the rôle of incidental learning in acquiring spatial information, such learning is not truly incidental as subjects often deliberately use locations to help organise objects for recall. They therefore devised a series of experiments in which there was a true incidental task in that neither objects nor locations were expected to be recalled. In the first of their experiments they distinguished between intentional learning, i.e. 'remember the location of these toys', from a *standard* incidental condition, i.e. 'remember these toys', from a *true* incidental condition, i.e. 'estimate the value of these toys'. They found that the intentional and *standard* incidental conditions did not differ from each other but both showed higher levels of recall (numbers of toys) over the a *true* incidental condition. However, the data from this experiment (and a replication of this using children as subjects) indicated that almost as much spatial information is retained when it has not been intentionally attended (they calculated the loss of location information at less than 20% comparing the *true* and *standard* conditions).

Finally, in an experiment by Kozlowski and Bryant (1977) which in many respects closely resembles the current experiment (experiment I), subjects were led through a windowless maze, measuring 3 metres high by 2 metres wide, illuminated by lights every 2 - 3 metres. The subjects had been misleadingly told that this was a time-estimating exercise, but on being led back to the beginning of the maze were asked to draw an arrow leading back to the end of the maze. The route was travelled a further four times and a further three measures taken. In addition to these estimates, the subjects were asked to rate their sense of direction, yielding two groups, those with a self-report of a good and poor sense of direction. As to the findings of this experiment, Kozlowski and Bryant reported the two groups did not differ in their mean pointing error. However, over the repeated trials those with a self-report of a good sense of direction significantly improved the accuracy of their judgements (errors falling from approximately 55° to 25°) while the accuracy poor sense of direction group's judgements became poorer then plateau-ed (errors rising from approximately 45° to 60°). Kozlowski and Bryant attempted to account for the improvement in the *maze-bright* group by speculating that they prided themselves on having a good sense of direction and in some way worked to improve on it.

## In summary

The precise rôle of intention in acquiring spatial knowledge is equivocal. People appear to be able to acquire spatial knowledge of an environment whether or not they have been intentionally trying to acquire it.

## 2.1.1 Experiment I

This experiment employed a non-immersive virtual reality game - *DOOM*, which is described in detail in section 2.1.3. Subjects were assigned to either the incidental ('pick up various objects') or the intentional learning ('learn the layout of the rooms in the game') condition and then were given a fixed amount of time to carry out these instructions. They were then asked to explore the first level of the game which consisted of a series of corridor-linked rooms. When subjects entered or re-entered particular rooms, they were identified verbally by the experimenter as follows: this is the *balcony*; this is the *computer room*; this is *the poisoned lake*; this is the *exit*, as appropriate. This identification served two purposes: firstly, to clearly identify the individual rooms from which they were to make inter-room judgements and secondly, to assist in the coding and retrieval of spatial information as demonstrated by, for example, Pezdek and Evans (1979). After the period of exploration, the subjects were asked to make a number of inter-room judgements of angle. The judgements were of the form, '... from position A, assuming you are facing 0°, what is the angle to B, C and D' - where B, C and D were different rooms on the first level of the game. That is make a judgement from source room to target room. In all, two sets of judgements were elicited from the subjects employing two different source rooms and four different target rooms. The accuracy of these judgements was taken to be an explicit test of the consistency of the cognitive representation of the spatial knowledge the subjects had acquired from exploring this virtual environment.

### 2.1.2 Hypothesis

The explicit (i.e. intentional) instructions to learn the spatial organisation of the rooms making up the first level of *DOOM*, followed by a period of free exploration of these rooms, will yield more accurate judgements of inter-room angles than a similar period of exploration prefaced by instructions to execute an incidental task. Furthermore, it is expected that the judgements made from two different starting locations will not differ in accuracy.

### 2.1.3 Method

#### Materials

*DOOM* is a PC-based non-immersive virtual reality game in which the player, armed with a range of weapons, aims to explore various buildings and in the process improve his or her armour, weapons, and health. Unsurprisingly the player is faced with 'monsters' which attempt to kill him or her and which he or she must attempt to kill. The game is played using the cursor keys to move, the *Ctrl* key to fire and the spacebar to open doors. A variety of objects may be collected *en route*, which are picked up by simply walking over them, and include helmets and other forms of armour, blue flasks and first aid packs, weapons, ammunition and miscellany (keys and so forth). The game has a variety of levels of difficulty, and the player may save and reload their current position. To remove the distraction of subjects having to fight monsters, *DOOM* was configured to disable all monsters, placing the game in an exploration mode only, using the '*doom -nomonsters*' start-up command. The game itself has very detailed graphics giving a very strong impression of a 'three-dimensional' maze of rooms, connecting corridors and doors. *DOOM (*the *shareware* version) was run on 486SX PC (at 33MHz with 8Mb of memory and a SVGA graphics card; the card has 1Mb of video memory and a resolution of

800x600 with 256 colours) where it had been previously installed on the PC's hard disc, and using this configuration, the game ran very smoothly with no discernible jerkiness in scrolling or performance.

## Subjects

Twenty subjects (6 women and 14 men), drawn from the technical staff at MARI Computer Systems Ltd. agreed to participate in this experiment. All of the subjects used computers on a daily basis, and as such are wholly familiar with their operation. However, it was ascertained that none of the subjects had played *DOOM* before. None was paid.

## Design

An independent groups design was employed with subjects being randomly assigned to either the incidental or intentional learning conditions.

## Procedure

Subjects were invited to sit at the experimenter's desk upon which sat the PC used in the experiment. The experiment had three components: a practice session to familiarise the subjects with the game and its controls, the free exploration of the first level of the game, and a set of post-experimental measurements.

Prior to the pre-experiment practice session, the following was read to each subject:

> *'This is the game Doom. It has been configured so that there are no 'monsters' to kill (or to kill you). It is played by using the cursor keys to move, and the space-bar to open doors. In addition to forward, backward, left and right you are able to climb stairs by simply walking towards them.*
>
> *You have one minute in which to practice the game.'*

Whereupon the subjects played *Doom* for one minute - it should be noted that they practised on a level different to the one about which they would be asked to make judgements.

Subjects were then randomly assigned to either the incidental or intentional condition, upon which one of the following instructions were read to the subjects after the practice session.

## Incidental learning condition

> *'Would you please explore the rooms in this game with a view to collecting as many objects you find there as possible. The objects which you can pick up are helmets and blue flasks.*

*You pick them up by walking over them. As you enter and re-enter particular rooms they will be named for you. You have three minutes. Afterwards you will be asked some questions.'*

## Intentional learning condition

*'Would you please explore the rooms in this game with a view to understanding their organisation and layout. As you enter and re-enter rooms they will be named for you. You have three minutes. Afterwards you will be asked some questions.'*

The figure of three minutes exploration time was arrived at by piloting the experiment with two subjects who did not subsequently participate in the experiment proper.

## A map of the first level of *Doom*

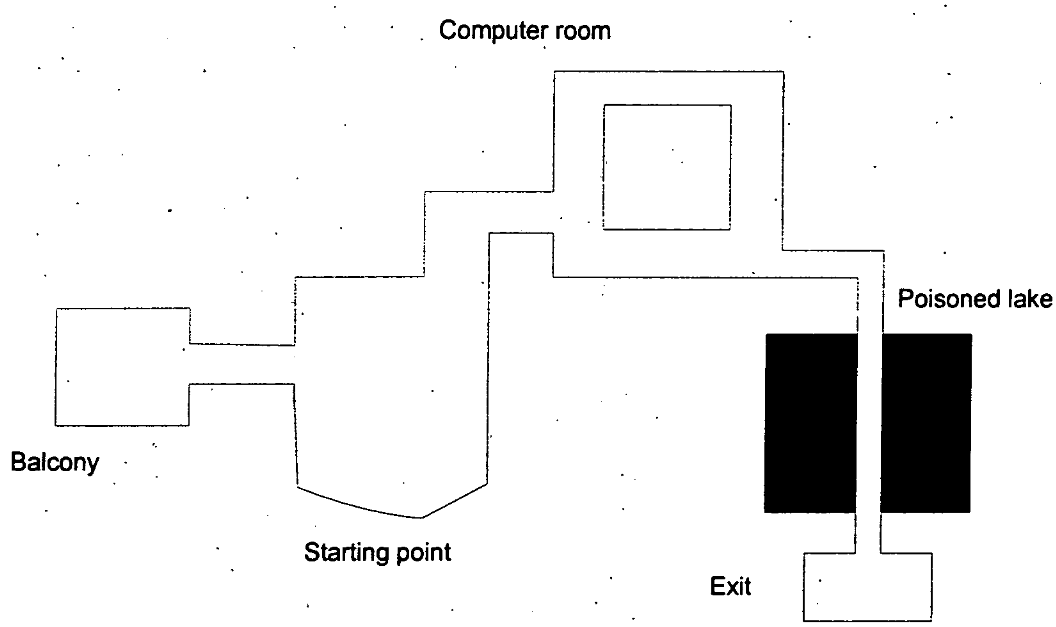



*Figure 2-1*

Figure 2-1 is a schematic representation of the organisation of the rooms which make up the first level of *DOOM* used in this experiment. Screen-dumps of *DOOM* are unfortunately not available as the authors of *DOOM* have disabled the mechanism by which screens are captured.

The subjects started in a room with a sealed door behind them, through which they had notionally entered. The organisation of the rooms was pre-defined by the authors of the game, and is approximately as depicted in the above figure. When subjects entered or re-entered particular rooms, they were identified verbally by the experimenter as follows: is the *balcony*;

this is the *computer room*; this is *the poisoned lake*; this is the *exit*, as appropriate. (The rooms were named on the basis of their principal characteristics, and to ensure consistency when they were referred to during the angle judgement component of the experiment.) Finally the subjects were given a stapled set of 5 pages of A4 on which were the following sets of questions (below). The order in which these instructions were presented was randomised.

The first set consisted of the following:

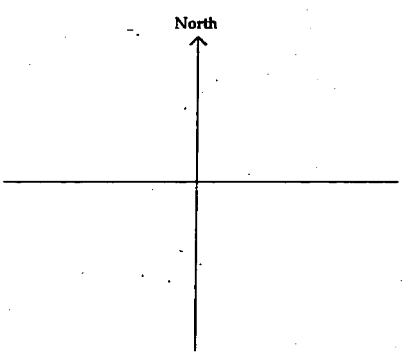
> *'Assume that your starting position was due North, that is 0°, please estimate the angle from the starting point to the centre of the following rooms. Both draw and estimate the angle.'*

*DOOM* was then restarted so that the subjects are clearly able to view the starting position. This was followed by four named positions from which to judge the angle, namely, the balcony, the computer room, the poisoned lake and the exit.

The second set:

> *'From this second saved position assume that you are facing due North, that is 0°, please estimate the angle from here to the centre of the following rooms. Both draw and estimate the angle.'*

*Doom* was then restarted from the second saved position so that the subjects are clearly able to view the exit. This, again, was followed by four named positions from which to judge the angle, namely, the starting room, the computer room, the poisoned lake and the exit. Drawing in both instances was facilitated by providing compass axes for each judgement, as below.




The instruction to both 'say aloud' and 'draw the angle' to elicit the subjects' judgements of inter-location angles was used to help the subjects make as an accurate judgement as possible. It was recognised that they may have had a preferred method of making such a judgement, for example, scanning an image of the virtual environment and then 'reading off' the value from the image (as suggested by Thorndyke and Stasz, 1981) or using pen and paper to facilitate what ever mechanism was involved and then reading off the angle from the sketch. Informal observation of the subjects indicated that some stated aloud the angle then sketched it, others did the reverse, and for others there appeared to be an interaction between the two.

The actual inter-room angles were determined by making a scale drawing of the layout of the rooms on squared paper and then using trigonometry to calculate the angles. A map of the layout of the rooms was available on pressing the *TAB* key within the game, a feature which was concealed from the subjects[13].

The data collected from the subjects consisted of two pairs of measurements (the raw data may be found in appendix A):

- the stated value; and,
- the angle drawn on the compass axes which was measured using a protractor.

First of all, a cross-product correlation was applied to these stated and drawn line values which were found to be very highly positively correlated, $r(115) = 0.995$, $p < 0.01$ and given this very high degree of correlation, the mean of each pair of judgements has been calculated and taken to be the estimate of inter-location angle. In calculating the mean, it was ensured that the difference between the estimated value and the actual value was kept to a minimum.

Finally, as this is a pilot experiment a null condition has been included. Condition 2d requires subjects to the angle from the exit to the exit, and angle of 0°. The inclusion of this condition verifies that subjects do recognise at least one of the source rooms and are capable of judging a simple angle.

[13]The close and proportionate correspondence between the map and the virtual rooms of the first level of the game is central to this experiment. While this cannot be established beyond doubt, two arguments can be offered in mitigation. Firstly, the rooms in the game are constructed from graphic blocks, and the number of blocks per wall appears to be directly proportionate to the length of the walls in the map view. Secondly, a configuration tool for modifying the layout of the game called *AutoDoom*, came to light after the experiment, and from this it is clear that the layout of rooms is composed on a Cartesian co-ordinate basis. Given this evidence there is no reason to suppose that the virtual space in *Doom* does not follow Cartesian geometry in its construction.

## The test materials

Table 2-1 contains a list of the 8 judgements asked of the subjects together with the actual angle from source to destination. Condition 2d, as can be seen, is the null condition.

| Judgement | From | To | Actual angle |
|---|---|---|---|
| 1a | the starting point | the balcony | -35° |
| 1b | the starting point | the computer room | 37° |
| 1c | the starting point | the poison lake | 80° |
| 1d | the starting point | the exit | 112° |
| 2a | the exit | the starting point | -58° |
| 2b | the exit | the computer room | -18° |
| 2c | the exit | the poison lake | 180° |
| 2d | the exit | the exit | 0° |

*Table 2-1*

## 2.1.4 Results

### Comparing the signed and unsigned errors for the two learning conditions

Table 2-2 holds the mean *signed* and *unsigned* errors for the two learning conditions. The data from the null condition 2d and errors greater than 90° have been excluded[14].

| | Incidental learning condition | Intentional learning condition |
|---|---|---|
| Signed mean errors | -14.6° | -14.5° |
| Unsigned mean errors | 37.2° | 35.4° |

*Table 2-2*

Comparing the signed errors: a value of $t(18) = 0.00$ (one-tailed) fails to reveal a reliable difference between the two learning conditions. Given this evidence, the hypothesis component which suggested that intentional learning would yield more accurate judgements than incidental learning cannot be supported. However the mean errors of -14.5° and -14.6° do suggest the presence an anti-clockwise bias in the direction of the judgements. Comparing these data sets with the no-bias condition (i.e. 0°): for the mean signed intentional errors, $t(9) = -2.26$, $p < 0.06$ (two-tailed) indicating a reliable anti-clockwise bias; for the mean signed incidental errors, $t(9) = -2.26$, $p < 0.06$ (two-tailed) which again indicates a reliable anti-clockwise bias.

Comparing the unsigned errors: a value of $t(18) = 0.06$ (two-tailed) fails to reveal a reliable difference in the absolute magnitude of the errors between the two learning conditions. This finding also constitutes further evidence that the hypothesis component which suggested that intentional learning would yield more accurate judgements than incidental learning cannot be supported.

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14 Errors of 90° or more have been discarded on the grounds that errors of this magnitude are indicative of the subjects having become disoriented.

## Comparing the signed and unsigned errors for the two locations

Table 2-3 holds the mean signed and unsigned errors for the two learning conditions by location. The data from the null condition 2d and errors greater than 90° have again been excluded.

| Signed mean errors | Intentional learning condition | Incidental learning condition |
|---|---|---|
| First location | -34.8° | -3.3° |
| Second location | -12.1° | -10.2° |
| Unsigned mean errors | | |
| First location | 46.6° | 35.3° |
| Second location | 14.4° | 38.6° |

*Table 2-3*

Analysing the signed errors with a two-way ANOVA: $F(1,9) = 4.42$, $p < 0.07$ which indicates that the magnitude of the errors differed with the learning conditions, but location did not have a reliable effect, $F(1,9) = 0.19$. Nor was there any suggestion of an interaction between learning and location, $F(1,9) = 1.90$, $p < 0.2$.

Analysing the unsigned errors with a two-way ANOVA: $F(1,9) = 2.35$ which indicates that the magnitude of the errors do not differ with the learning conditions, but location did have some effect, $F(1,9) = 3.55$, $p < 0.1$. There is no suggestion of an interaction between learning and location, $F(1,9) = 0.67$.

## Comparing the variability of the judgements

Analysing the magnitude of the 95% confidence intervals for the signed errors in the two learning conditions (excluding estimates from condition 2d), a value of $t(6) = 1.36$ (two-tailed) indicates that there are no reliable differences in the variability of the judgements between learning conditions. The same holds true for the 95% confidence intervals of the unsigned errors: $t(6) = 1.03$ (two-tailed). (NB, the reduced level of degrees of freedom are due to missing data - please see Appendix A for details.)

### 2.1.5 Discussion of results

This experiment has revealed the following about the accuracy of judgements made from spatial knowledge acquired from exploring virtual environments.

- There is evidence of a reliable difference in the magnitude of the signed errors between the intentional and incidental learning conditions ($p < 0.07$). There is no such evidence in the unsigned errors.
- There is an overall reliable tendency ($p < 0.06$) to bias the judgement of the inter-room angles in an anti-clockwise direction.
- There is no reliable difference in the variability of the judgements across conditions.
- There is no difference in the magnitude of the signed errors between the judgements made from two different locations. This result lends support the hypothesis component that judgements made from different locations would be equally accurate. The unsigned errors, however did show some evidence ($p < 0.1$) that location did have some effect.
- Finally, most judgements proved to be quite inaccurate with less than 15% of judgements in each conditions being within 10° of the actual value. Further 30.5% of the judgements in the *intentional* and 30.2% of the judgements in the *incidental* condition were found to be in error by more than 90°.

### Informal observation of the subjects

The finding that there is no evidence for reliable differences in the accuracy of judgements between the intentional and incidental judgements is something of a surprise. This is particularly so given the following observations:

- All of the subjects in the incidental learning condition expressed great surprise (and horror usually coupled with expletives) at being asked to judge angles, yet their performance is not reliably poorer to the intentional condition.
- As already noted, it was informally observed that subjects in the incidental condition spent more of their time in the rooms immediately adjacent to the starting room, namely the balcony and the computer rooms, than those in the intentional condition (this observation was confirmed by those subjects who were unable to make judgements about those rooms most distant from the starting room, because they had not visited them). Yet for all this additional exposure to fewer rooms there is no trade-off in improved performance (i.e. angle judging) for those rooms. In all 69 (out of 80) judgements were made in the intentional learning condition and only 46 (out of 80) judgements in the incidental learning

condition.

## 2.2 Introduction to experiment II

Experiment I, employing a virtual reality game, found evidence for an overall tendency to produce judgements, from memory, of inter-room angles which were biased in an anti-clockwise direction. Experiment II further investigates this evidence for the observed anti-clockwise bias in the judgements of angles in virtual environments. However, in contrast to the first experiment, this experiment employs a virtual reality construction kit - ACK3D - enabling especially designed '3D' virtual environments to be created. The virtual environments which can be created using ACK3D differ from that of the first experiment in two principal ways:

- the virtual space of DOOM used in experiment I is a tribute to the game designer's art consisting of a highly detailed series of rooms and corridors, whereas ACK3D is very simple and regular;
- the virtual space was highly asymmetric. Using ACK3D the variables of complexity and symmetry can be closely controlled. This application is described more fully in section 2.2.3.

### 2.2.1 Experiment II

Two 'L-shaped' virtual environments were created consisting of monochrome green walls with four different coloured panels forming the *landmarks* between which subjects were asked to judge the angle - see figures 2-2 and 2-3. The virtual environments differed only in their orientation being mirror images of each other, one being 'right-oriented', the other 'left-oriented'. Subjects were assigned to either the right- or left-oriented virtual environment condition and then given two minutes in which to explore them and learn their spatial arrangements. After the period of exploration, subjects were asked to judge the angles between the landmarks. The judgements were of the form, '... from the A panel, assuming you are facing 0°, what is the angle to the B, C and D panels' - where B, C and D are the other distinct panels. In all, twelve judgements were asked of each subject.

### 2.2.2 Hypothesis

On the evidence of experiment I, it is anticipated that an anti-clockwise bias in the judgements of inter-feature angles will be observed.

## 2.2.3 Method

## Materials

Two 'L-shaped' virtual environments were created using the PC application ACK3D (full detail of which may be found in appendix B). At start up ACK3D reads a file (ACKMAP.L01) and executes the spatial description of the '3D' configuration therein contained. This spatial configuration file is created from another program called *mapedit* which provides a 64x64 grid which may be populated with a variety of graphical objects. ACK3D which was run on a PC (at 33MHz with 8Mb of memory and a SVGA graphics card; the card has 1Mb of video memory and a resolution of 800x600 with 256 colours) had been previously installed on the PC's hard disc.

The walls of these virtual rooms measured 16x16 panels (units) and the corridor was 3 panels wide and were coloured a monochromatic green. Two of the panels in the walls were coloured differently being purple and red respectively and a further two gave the appearance of being either a window or a wall clock[15]. Movement within the virtual environments is achieved by means of the PC's cursor keys. Figure 2-2 a plan view of the right-oriented virtual room.

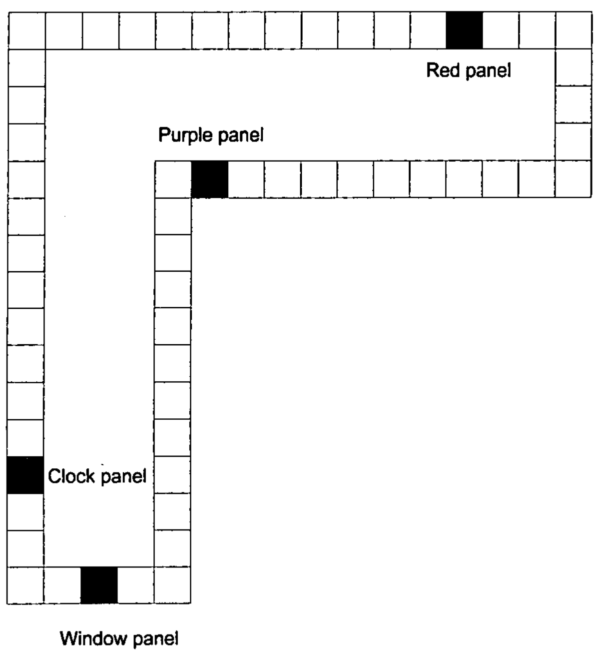



*Figure 2-2*

[15]The choice of objects is limited by the ACK3D application.

Figure 2-3 is a plan view of the left-oriented virtual room.

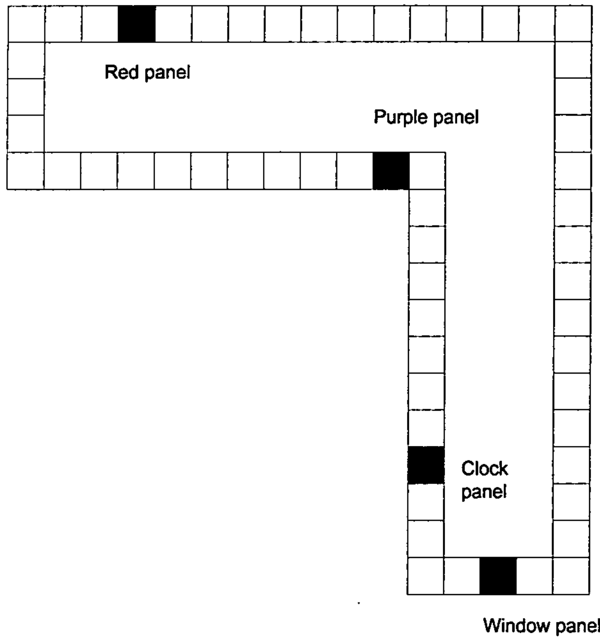
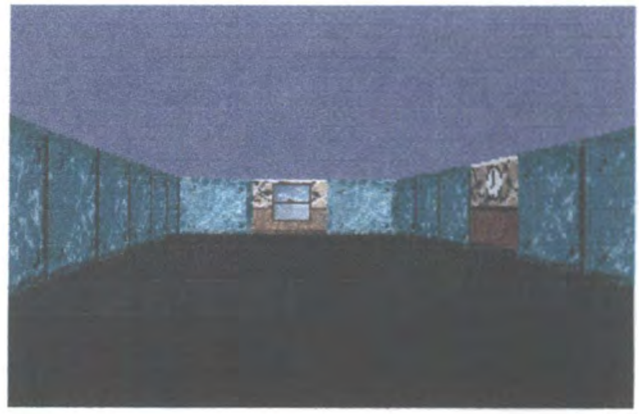



*Figure 2-3*

## Colour Illustrations

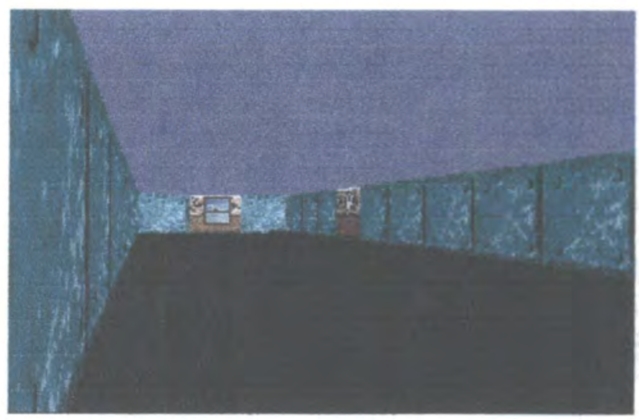
The screen-shots overleaf are taken from the two virtual room.

Taken from the left-oriented environment, looking towards the window panel.



Taken from the left-oriented environment, looking towards the red and purple panels.

Taken from the right-oriented environment, looking towards the window and clock panels.



Taken from the right-oriented environment, looking towards the purple panel with the red panel in the distance.

## Subjects

16 subjects (10 men and 6 women) drawn from staff at MARI Computer Systems Ltd, agreed to participate in this experiment. All of the subjects used computers on a daily basis, and as such were wholly familiar with the operation of PCs. None was paid.

## Design

An independent groups design was employed with a half of the subjects being randomly assigned to each condition. The two conditions were the left-oriented virtual environment or right-oriented virtual environment.

## Procedure

Subjects were tested individually. The experimenter informed each subject that the purpose of the study was to investigate the accuracy of people's spatial knowledge acquired from exploring a virtual room.

The following instructions were then read aloud.

> *'This is a virtual room which I would like you to explore for 2 minutes. Use the cursor keys to move. When you have done so I will ask you a number of questions like this:'*
>
> *'Imagine you are standing with your back to the XXX panel facing due North (i.e. 0°). Estimate (i.e. say aloud the straight-line angle from the XXX panel to the YYY panel. (Where XXX and YYY will be one of the four panels.) There will be 12 such questions.'*

After the instructions were read to the subjects they were asked if they understood what was required of them, and if not the instructions were re-read and then they were asked again. These instructions were supplemented by producing an *ad hoc* sketch to further clarify what was required of them.

## Test materials

Table 2-4 contains a list of the 12 judgements required of the subjects together with the actual angle from source to destination for the right-oriented and left-oriented virtual environments.

| Source | Destination | Left-oriented environment | Right-oriented environment |
|---|---|---|---|
| Window panel | Clock panel | -30.0° | -30.0° |
| Window panel | Purple panel | -15.0° | 16.5° |
| Window panel | Red panel | -35.0° | 35.0° |
| Clock panel | Window panel | 60.0° | 60.0° |
| Clock panel | Purple panel | -15.0° | -60.0° |
| Clock panel | Red panel | -36.0° | 45.0° |
| Purple panel | Window panel | 155.0° | -163.5° |
| Purple panel | Clock panel | 165.0° | -150.0° |
| Purple panel | Red panel | -65.0° | 65.0° |
| Red panel | Window panel | -35.0° | 55.0° |
| Red panel | Clock panel | -36.0° | 45.0° |
| Red panel | Purple panel | -65.0° | 65.0° |

*Table 2-4*

## 2.2.4 Results

### The evidence for an anti-clockwise bias

Table 2-5 holds the mean signed and unsigned errors for the two conditions. Errors greater than 90° have been omitted.

| | Right-oriented environment | Left-oriented environment |
|---|---|---|
| Signed mean errors | 1.3° | -27.2° |
| Unsigned mean errors | 27.9° | 43.5° |

*Table 2-5*

The left-oriented signed errors reveal a reliable anti-clockwise bias, $t(7) = 5.16$, $p < 0.001$ (one-tailed) when compared with no-bias condition (i.e. 0°) but there is no such evidence in the right-oriented signed errors do not reveal an anti-clockwise bias, $t(7) = 0.31$ (one-tailed).

However both the mean unsigned and signed judgements are reliable different from the actual values, $t(7) = 12.30$, $p < 0.001$ (two-tailed) and $t(7) = 5.03$, $p < 0.002$ (two-tailed) respectively.

Comparing the signed errors, $t(14) = 4.46$, $p < 0.0003$ (two-tailed) which indicates that the errors incurred in the left-oriented environment are very significantly larger than those incurred in the right-oriented environment. For the unsigned errors, $t(14) = 2.76$, $p < 0.02$ which indicates that the errors incurred in the left-oriented environment are again very significantly larger than those incurred in the right-oriented environment.

### The signed and unsigned errors: by judgement

Comparing the errors from the two conditions: for the signed errors, $t(22) = 2.68$, $p < 0.02$ (two-tailed) the errors in the left-oriented environment being reliably larger than those in the right-oriented environment. The unsigned errors, $t(22) = 1.41$(two-tailed) do not differ.

### Comparing the variability of the judgements

Analysing the magnitude of the 95% confidence intervals for the signed errors in the two conditions, a value of $t(13) = -1.39$ (two-tailed) indicates that there are no reliable differences in the variability of the judgements between conditions. The same holds true for the 95% confidence intervals of the unsigned errors: $t(13) = 1.05$ (two-tailed).

### 2.2.5 Discussion of results

This experiment has revealed the following about the accuracy of judgements made from spatial knowledge acquired from exploring virtual environments.

- There is a reliable ($p < 0.0007$) anti-clockwise bias in the judgements of inter-feature angles in the left-oriented but not in the right-oriented virtual environment.
- Both the signed and unsigned errors made in judging angles from a left-oriented environment are reliably larger than those made in the left-oriented environment.
- The precision of the judgements made by the subjects did not reliably differ.
- The judgements varied in accuracy with almost a third of judgements in right-oriented condition (31%) but only 14% in left-oriented conditions being within 10° of the actual value. While nearly one fifth of the judgements in the *right-oriented* condition (18.5%) and nearly a quarter of the judgements in the *left-oriented* (24.2%) were in error by 90° or more.

### A confounding error

Post-experimentally it was noticed that the two virtual environments are not exact mirror images of each other. It can be seen from figures 2-2 and 2-3 that the clock panel is to the left of the window panel in each virtual environment.

What then is the consequence of this error? The answer is slight. If the statistical analyses in the results section are repeated excluding those judgements involving the clock panel, no differences in the results are found.

This error could have been avoided had the design of the virtual environments been properly reviewed before the experiment was conducted.

## 2.3 Introduction to experiment III

Experiments I and II have examined the accuracy of judgements of inter-feature angles made from immediate memory. In contrast, experiment III aims to establish a *baseline* measure of accuracy against which these judgements from memory may be compared. Specifically this experiment addresses the following issues:

- how accurate are judgements of angles while actively exploring a virtual environment?
- is there a directional bias in the judgements of angles while actively exploring a virtual environment?
- how is the accuracy of judgements made of inter-feature angles affected by the features being *in the line of sight* and *out of the line of sight* of each other.

### 2.3.1 Experiment III

To address these questions, two virtual environments were created which were designed so as to have a number of features which were either *in the line of sight* of each other or *out of the line of sight* of each other. These virtual environments were made up of monochrome green walls with four different coloured panels forming the landmarks between which subjects were asked to judge the angle. The two conditions differed from each other in the following ways:

- most significantly, in the *in the line of sight* condition each landmark was in plain view of each other while in the *out of the line of sight* condition this was not the case - this is most easily seen by examining figure 2-4 and figure 2-5;
- with the *in the line of sight* condition subjects could adopt a variety of view points from which to make their judgements, this, again, was not so in the latter condition. Judgements made in the *out of the line of sight* were, to some extent, made from memory in that only one landmark was in view at any one time.

Subjects were assigned to either the *in the line of sight* or the *out of the line of sight* condition and then given one minute in which to familiarise themselves with the virtual environment. After the period of familiarisation, subjects were asked to judge the angles between the landmarks while still in the virtual environment and able to freely move within it. The judgements were of the form, '... from the A panel, assuming you are facing 0°, what is the angle to the B, C and D panels' - where B, C and D are the other distinct panels. In all, twelve judgements were asked of each subject.

### 2.3.2 Hypothesis

It is anticipated that:

- Judgements of angles made while actively exploring a virtual environment will tend to be more accurate than those made from immediate memory. However, judgements made of inter-feature angles which are *in the line of sight* of each other will be more accurate than those made *out of the line of sight* of each other.
- An anti-clockwise directional bias in the judgements of angles is anticipated in the judgements made of inter-feature angles *out of the line of sight* of each other. No such bias is expected for judgements made of inter-feature angles *in the line of sight* of each other.

### 2.3.3 Method

#### Materials

Two virtual environments were again created using the PC application ACK3D, full detail of which may be found in appendix B. The two virtual rooms were constructed as follows: the walls of the first virtual room measured 11x11 panels (units) and were coloured a monochromatic green. Two of the panels in the walls were coloured differently being purple and red respectively and a further two gave the appearance of being either a window and a wall clock - the choice of objects is limited by the ACK3D application. The walls of the second virtual room measured 16x16 panels (units) and were again coloured a monochromatic green. A purple and red panel together with a window and a clock were also included. ACK3D which was run on a PC (at 33MHz with 8Mb of memory and a SVGA graphics card; the card has 1Mb of video memory and a resolution of 800x600 with 256 colours) had been previously installed on the PC's hard disc.

Figure 2-4 is a representation of the virtual room employed in the '*in the line of sight condition*'.

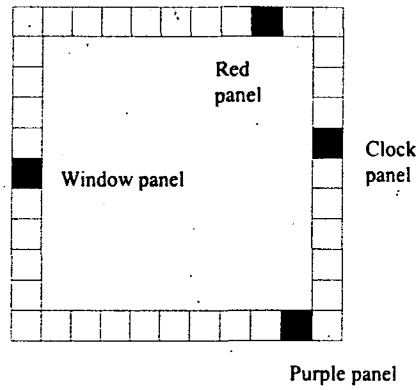



*Figure 2-4*

Figure 2-5 is a representation of the virtual room employed in the *out of the line of sight* condition.

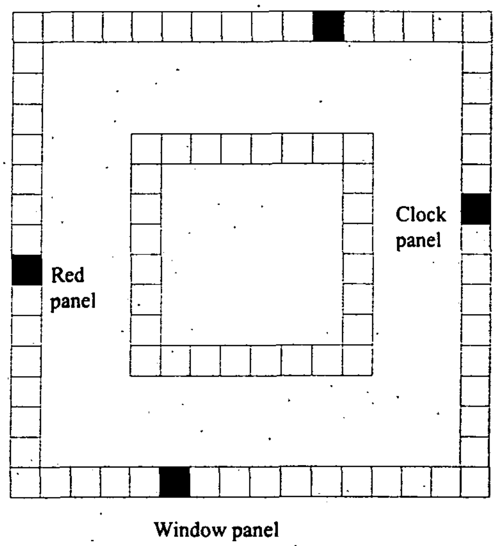
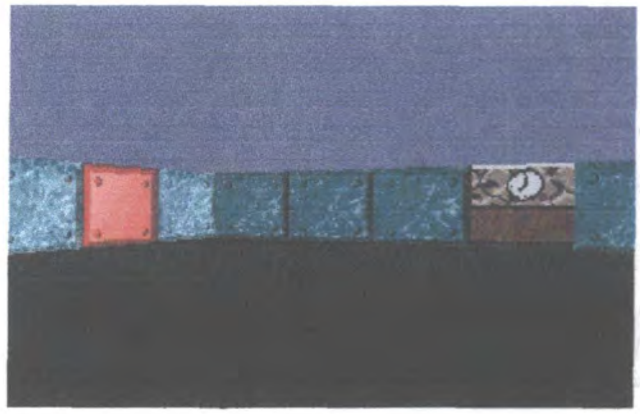



*Figure 2-5*

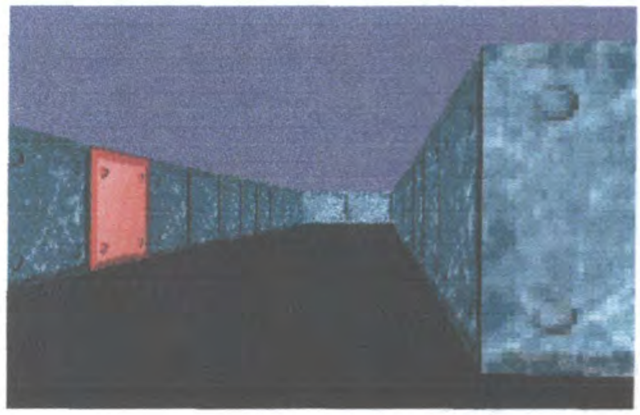
## Colour Illustrations

The two figures overleaf are screen-shots taken from the *out of the line of sight* virtual room and from the *in the line of sight* virtual room.

This image has been taken from the *in the line of sight* condition. The red panel and clock panel can be clearly seen.



This image has been taken from the *out of the line of sight* condition. Only the red panel and the obscuring walls can be seen.



## Subjects

16 subjects (14 men and 2 women) drawn from staff at MARI Computer Systems Ltd, agreed to participate in this experiment. All of the subjects used computers on a daily basis, and as such are wholly familiar with the operation of PCs. None was paid.

## Design

An independent groups design was employed with a half of the subjects being randomly assigned to either condition. The two conditions were the *out of the line of sight* and *in the line of sight* conditions.

## Procedure

Subjects were tested individually. The experimenter informed each subject that the purpose of the study was to investigate the accuracy of people's spatial judgements of angles in a virtual room.

The following instructions were then read aloud.

> *'This is a virtual room with which I would like you to familiarise yourself for 1 minute. Use the cursor keys to move. When you have done so I will ask you a number of questions like this:'*
>
> *'While still in the room, estimate (i.e. say aloud) the angle from the XXX panel to the YYY panel. (Where XXX and YYY will be one of the four panels.) There will be 12 such questions.'*

After the instructions were read to the subjects they were asked if they understood what was required of them, and if not the instructions were re-read and then they were asked again. These instructions were supplemented by producing an *ad hoc* sketch to further clarify what was required of them.

Table 2-6 contains a list of the two pairs of 12 judgements asked of the subjects together with the actual angle from source to destination.

| Source | Destination | in the line of sight | out of the line of sight |
|---|---|---|---|
| purple panel | red panel | -7.5° | 52.0° |
| purple panel | window panel | -63.0° | 20.0° |
| red panel | window panel | 59.0° | 55.0° |
| clock panel | purple panel | -85.0° | 51.0° |
| window panel | purple panel | 27.0° | 20.0° |
| window panel | clock panel | -7.0° | 49.0° |
| purple panel | clock panel | 5.0° | -39.0° |
| red panel | purple panel | -7.5° | 38.0° |
| red panel | clock panel | 23.0° | -8.0° |
| clock panel | red panel | 67.0° | -8.0° |
| clock panel | window panel | 7.0° | -41.0° |
| window panel | red panel | -31.0° | -35.0° |

*Table 2-6*

## 2.3.4 Results

Table 2-7 holds the mean signed and unsigned errors for the two learning conditions. Errors greater than 90° have been excluded.

| | in the line of sight | out of the line of sight |
|---|---|---|
| Signed mean errors | -6.0° | 9.1° |
| Unsigned mean errors | 43.3° | 41.7° |

*Table 2-7*

Comparing the signed errors: a value of $t(14) = 3.01$, $p < 0.005$ (one-tailed) confirms that the *out of the line of sight* errors are reliably larger than the *in the line of sight* errors. In contrast, the unsigned errors do not differ in magnitude, $t(14) = 0.65$ (one-tailed). This result tend to support the first hypothesis component, namely that judgements made of inter-feature angles which are *in the line of sight* of each other will be more accurate than those made *out of the line of sight* of each other.

The *out of the line of sight* signed errors reveal a reliable anti-clockwise bias, $t(7) = 1.9$, $p < 0.05$ (one-tailed) when compared with no-bias condition (i.e. 0°), as do the *in the line of sight* signed errors, $t(7) = -4.0$, $p < 0.005$ (one-tailed). This result offers only partial support to the second hypothesis component namely that an anti-clockwise directional bias in the judgements of angles was anticipated in the judgements made of inter-feature angles *out of the line of sight* of each other. No such bias was expected for judgements made of inter-feature angles *in the line of sight* of each other.

The *out of the line of sight* and *in the line of sight* unsigned error are also reliable different from the actual values, $t(7) = 21.8$, $p < 1.08E-07$ (two-tailed), and $t(7) = 12.30$, $p < 5.4E-06$ (two-tailed) respectively.

## Comparing the variability of the judgements

Analysing the magnitude of the 95% confidence intervals for the signed errors in the two conditions, a value of $t(13) = -0.66$ (two-tailed) indicates that there are no reliable differences in the variability of the judgements between conditions. The same holds true for the 95% confidence intervals of the unsigned errors: $t(13) = 0.53$ (two-tailed).

### 2.3.5 Discussion of results

This experiment has revealed the following about the accuracy of judgements made from spatial knowledge acquired from exploring virtual environments.

- The signed errors in the *out of the line of sight* condition proved to be reliably larger ($p < 0.005$) than the *in the line of sight* errors, agreeing with the first hypothesis component but this effect was not statistically reliable. However the unsigned errors did not differ in magnitude.
- However the unsigned *out of the line of sight* errors proved to be reliably larger than the *in the line of sight* errors $p < 0.05$, again agreeing with the first hypothesis component.
- There is a reliable ($p < 0.05$) anti-clockwise bias in the judgements of inter-feature angles in the *out of the line of sight* condition and in the *in the line of sight condition.*
- The variability of the errors did not differ.

## A confounding error

Post-experimentally it was noticed that a number of errors in the construction of the two virtual environments had been introduced during their construction. As can be seen from the figures 2-4 and 2-5 the location of the panels used as landmarks from which the judgements of angles have inadvertently been moved with respect to each other between conditions..

Despite this error the essential hypothesis testing remains valid. Judgements made *out of the line of sight* and *in the line of sight* can still be compared and the results are meaningful.

This error could have been avoided had the design of the virtual environments been properly reviewed before the experiment was conducted.

construct a maps of their campus, the students were most likely to put those landmarks that were in reality in front of them at the top of the page. This finding clearly echoes the work of Shepard and Hurwitz (1983) who it may be recalled have noted the extended use of the upward direction to refer to (i) any uphill direction; (ii) to mean north; and (iii) to the direction one is facing based on the egocentric frame of reference (see section 1.3.5 for a fully discussion of their work).

Whether orientation-specificity will be observed in the spatial knowledge acquired from exploring the virtual mazes is the first of the two major themes of this experiment. If orientation-specificity is found then it would tend to support the position that exploring virtual environments gives rise to secondary or indirect spatial knowledge, unlike primary spatial knowledge which is acquired directly from the environment.

## Building cognitive maps

The second issue addressed by this experiment concerns the process of building a coherent cognitive model or map of the virtual environments being explored. Ittelson (1973) has noted that in order to acquire spatial knowledge of the large-scale spaces which surround the individual, active cognitive integration of multiple views from multiple vantage points is required. To understand this process in a virtual environment, the virtual mazes have been constructed so that from a range of locations within the first maze (condition 2a, figure 3-2) all four landmarks are visible; in the second maze (condition 2b, figure 3-3) this changes so that any three landmarks are visible from specific view points, then two (condition 2c, figure 3-4) and finally only one (condition 2d, figure 3-5). So, if the cognitive mapping of these virtual mazes is similar to, or analogous with, the process in the real world, then the integration of multiple view points should require proportionately more cognitive time and effort as the number of view points increase. Evidence for some of this has already been noted in section 1.3.3. For example, Evans and Pezdek (1980) found evidence for the rôle of mental rotation in the recognition of the (US) states presented by 35 mm slides but not for a set of buildings. They found that RTs for recognition increased as a linear function of the degree of rotation of the picture of the states but not of the buildings. These results may be due to the fact that the subjects had experienced the college building from multiple perspectives, whereas they had only ever seen the states from maps - and probably canonically presented (i.e. 'North' at the top). Evans and Pezdek have presented further evidence of this kind by noting that subjects asked to study maps of a different campus, and then presented with slides of buildings on this campus, showed a similar linear relationship of RT to recognition to that found in experiments with involving mental rotation.

In the current experiment, it is suggested that the nature of this cognitive effort will be in the form of a series of mental rotations. It is further envisaged that subjects will successively acquire spatial knowledge relating to the orientation and location of the landmarks. Those landmarks, initially out of sight, will be integrated sequentially with the contents of the scene either immediately visible or in memory. As the number of landmarks which have to be integrated increases, it is expected that the relationship between the number of landmarks and the time to integrate them will be monotonic in a way which is analogous to the processes studied in experiments on mental rotation (e.g. Shepard and Metzler, 1971).

### 3.1.1 Experiment IV

Firstly, to determine whether there is evidence of orientation-specificity in spatial knowledge acquired from exploring a virtual environment, four virtual mazes of varying complexity, each containing a number of *landmarks* will be explored by the subjects until they are sufficiently familiar with the spatial organisation of the mazes that they are able to make a number of judgements about the angle from one landmark to another (i.e. the inter-landmark angle). This maze condition will be contrasted with a map condition wherein subjects will study paper-based plan views of the virtual mazes, again until they are sufficiently familiar with them, such that they are able to make a similar set of inter-landmark angle judgements.

Four virtual environments (hereafter, *mazes*) were created consisting of monochrome green walls with four different coloured panels forming the landmarks between which subjects were asked to judge the angle - see figures 3-2, 3-3, 3-4 and 3-5. Four monochrome (black and white) maps of the virtual environment were also prepared and printed on sheets of white A3 paper. The different coloured panels being clearly labelled. Secondly, the time it takes to create a cognitive model or map as measured by the free exploration times of the virtual mazes will be recorded.

## 3.1.2 Hypothesis

It is anticipated that the judgements made of inter-landmark angles made in the maze condition will not show any particular orientational bias as measured by the magnitude and direction of the error in judgement, whereas those made in the map condition should (see the table below). Furthermore it is anticipated that the time to learn the mazes will increase monotonically as a function of their increasing complexity, whereas no differences should be observed in the map conditions. Table 3-1 summarises the hypothesis components for this experiment:

| Hypothesis component | Maze conditions | Map conditions |
|---|---|---|
| The accuracy of judgements from different orientations | No differences in accuracy are expected | Judgement aligned with the way in which the map was learned will be the most accurate. Judgements counter-aligned with the learning condition will be least accurate. Judgements which are non-aligned with the learning condition will show a level of accuracy between the aligned and counter-aligned. |
| The free study / exploration times. | Free exploration of the mazes will increase as the number of landmarks visible at any time decreases. | The configuration of the maps should not affect study time. |

*Table 3-1*

As noted at the beginning of this experiment it is not possible to define a canonical 'aligned', 'counter-aligned' and so forth in a virtual environment because although a subject initially does find him or herself a such an environment in a particular orientation this is lost the instant he or she begins to explore. So the following operational definition will be adopted:

- the most accurate judgement should lie at 180° to the least accurate judgement;
- the intermediately accurate judgements should lie at 90° to the most and least accurate judgements.

If such a pattern is found it will then be taken as evidence for the presence of orientation-specificity in spatial knowledge acquired from exploring virtual environments.

### 3.1.3 Method

#### Materials

Four maps for the configuration of figures 3-2, 3-3, 3-4 and 3-5 were printed on sheets of A3 paper (black on white) and the various panels labelled, but not coloured. The actual maps were approximately four times largely than the figures below.

The mazes were again created using ACK3D - a full description of which may be found in appendix B. The walls of the mazes were a uniform monochrome green with four panels which were different from the walls and these were a clock panel, a window panel, a red panel and a purple panel. ACK3D which was run on a PC (at 33MHz with 8Mb of memory and a SVGA graphics card; the card has 1Mb of video memory and a resolution of 800x600 with 256 colours) had been previously installed on the PC's hard disc. Figure 3-2 illustrates conditions 1a and 2a (all four landmarks visible):

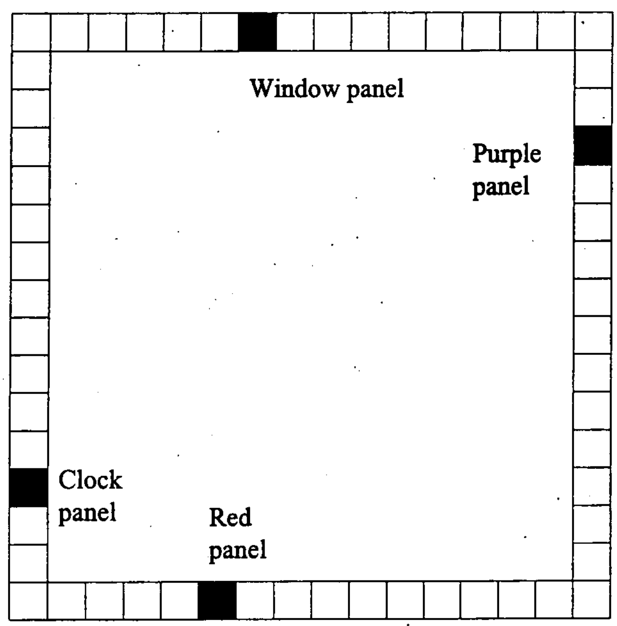



*Figure 3-2*

Figure 3-3 illustrates conditions 1b and 2b (any three landmarks visible from a range of viewing points):

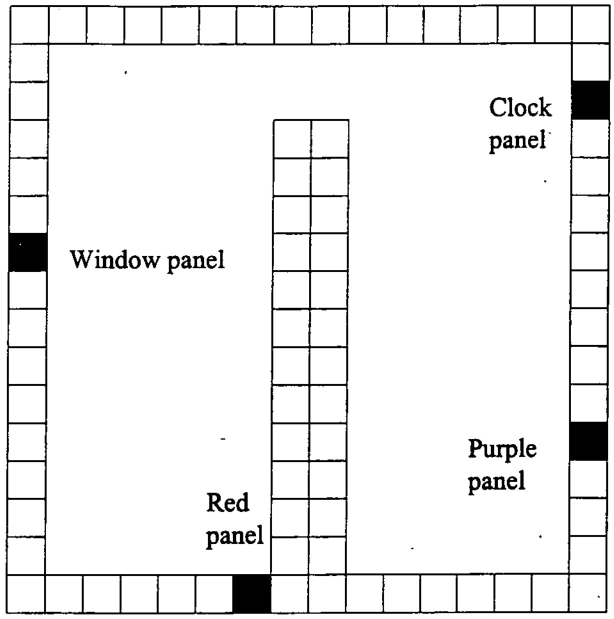
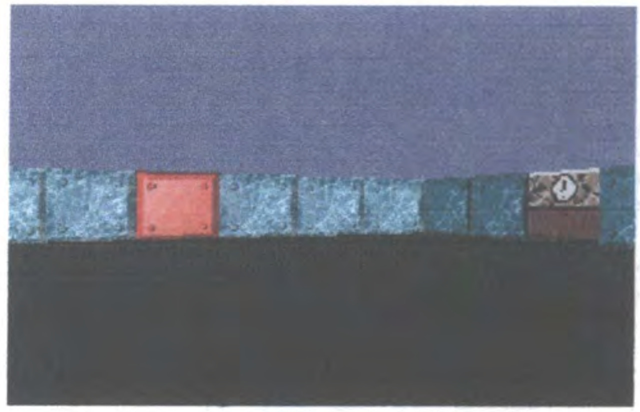



*Figure 3-3*

## Colour Illustrations

The two figures overleaf are screen-shots taken condition 2a looking from the purple panel towards the clock and red panel, and from condition 2b, looking towards the window panel (to the left) and red panel respectively.

This image has been taken from the *four landmarks visible* condition. Here the red panel and the clock panel can be seen.



This image has also been taken from the *four landmarks visible* condition. Here the remaining landmarks are visible, namely, the window and purple panels.

This image has been taken from the *three landmarks visible* condition. Here the red panel and the window panel can be seen.

This image has also been taken from the *three landmarks visible* condition. Here the clock panel and an obscuring are visible.

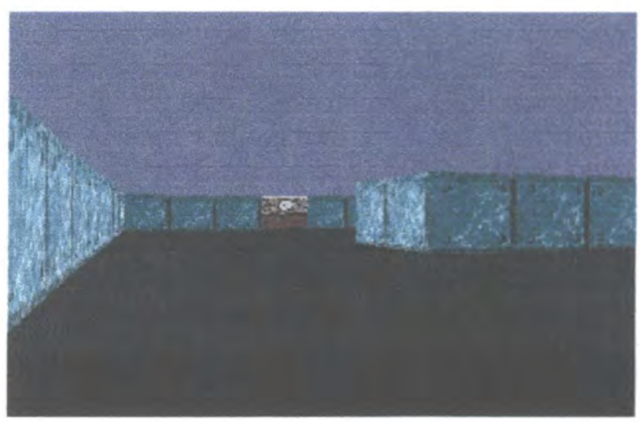


Figure 3-4 illustrates conditions 1c and 2c (any two landmarks visible from a range of viewing points):

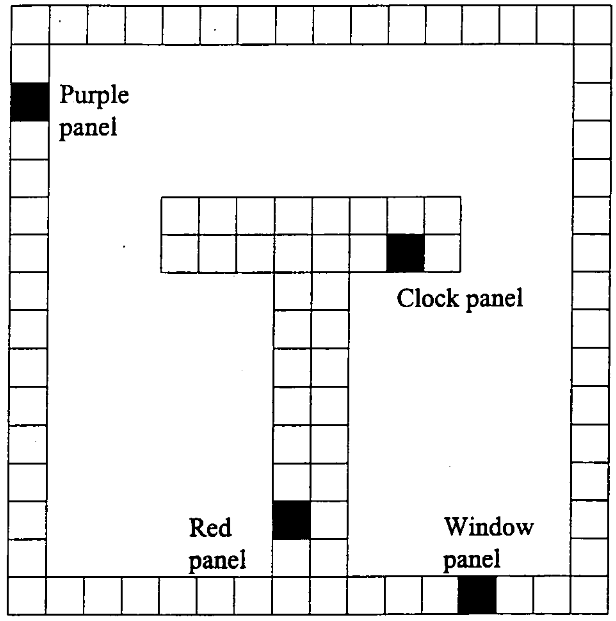



*Figure 3-4*

Figure 3-5 illustrates conditions 1d and 2d (only one landmark visible):

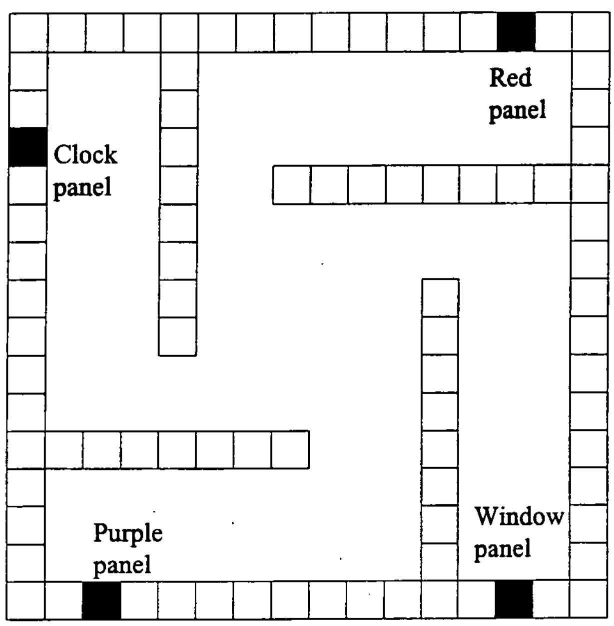
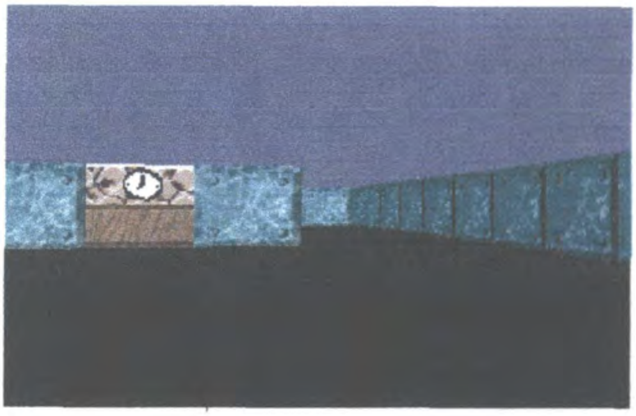



*Figure 3-5*

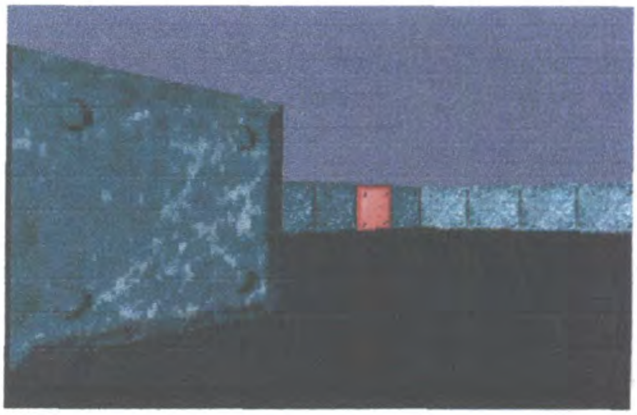
## Colour Illustrations

The two figures overleaf are respectively screen-shots taken from conditions 2c and 2d respectively.

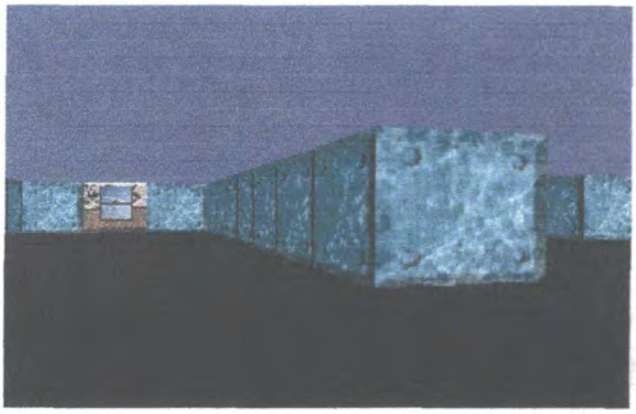
This image has also been taken from the *two landmarks visible* condition. Here the clock panel and an obscuring are visible.



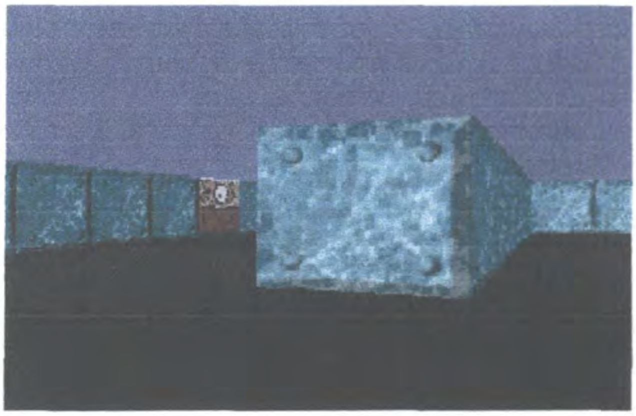
This further image from the *two landmarks visible* condition. Here the clock panel and an obscuring are visible.



This image is from the *one landmark visible* condition. The window panel and an obscuring wall can be seen.



This final image is also from the *one landmark visible* condition. The clock panel and an obscuring wall can be seen.



## Subjects

56 subjects (48 men and 8 women) drawn from the technical and administrative staff at MARI Computer Systems Ltd, agreed to participate in this experiment. All of the subjects use computers on a daily basis, and as such are wholly familiar with the operation of PCs. None was paid.

Subjects were randomly assigned to one of the four maze or four map conditions and given as much time as they required to familiarise themselves with it (for the map conditions) or explore it (for the maze conditions) and learn its spatial arrangements. Study and exploration time were recorded. After the period of exploration, subjects were asked to judge the angles between the landmarks. The judgements were of the form, '... from the A panel, assuming you are facing 0°, what is the angle to the B, C and D panels' - where B, C and D are the other distinct panels.

## Design

An independent measures design was employed with subjects being randomly assigned to the maze and map conditions.

## Procedure

In the map conditions, the following instructions were read to each subject:

*'I am about to show you a map which I would like you to study until you are completely familiar with its features, their location and orientation. There are 4 panels which are different from the walls and these are a clock, a window, a red panel and a purple panel. All panels are labelled. There is no set time limit although I will time you. When you satisfied that you are completely familiar with the map I will ask you a number of questions like this:'*

*'imagine you are standing with your back to the XXX panel facing due North (i.e. 0 degrees). Estimate (i.e. say aloud) the straight-line angle from the XXX panel to the YYY panel. (Where XXX and YYY will be one of the four panels.)'*

After the instructions were read to the subjects they were asked if they understood what was required of them, and if not the instructions were re-read and then they were asked again.

A randomly selected map was then placed on a table so that it lay squarely before them. When the subject indicated that they were satisfied that he / she was sufficiently familiar with the map, it was removed from his / her sight and then either three or four judgements asked of them depending upon condition (see table 3-2). Study times were also recorded (to the nearest second).

For the maze conditions: prior to the experiment each subject was asked if they were colour blind and only those who were not were asked to participate. Each participant was asked to sit before the computer being used for the experiment, instructions were read to them and then one of the four mazes was selected at random and loaded into the computer's memory by typing 'trial *trialnumber*' where the *trialnumber* was either 1, 2, 3 or 4. This command loaded and ran the ACK3D application and the required maze definition file[16].

The instructions were as follows:

*'This is a maze through which I would like you to freely explore until you are completely familiar with its features, their location and orientation. There are 4 panels which are different from the green walls and these are a clock, a window, a red panel and a purple panel. Use the cursor keys to move through the maze. There is no set time limit although I will time you. When you satisfied that you are completely familiar with the maze I will ask you a number of questions like this:'*

*'imagine you are standing with your back to the XXX panel facing due North (i.e. 0 degrees). Estimate (i.e. say aloud) the straight-line angle from the XXX panel to the YYY panel. (Where XXX and YYY will be one of the four panels.)'*

After the instructions were read to the subjects they were asked if they understood what was required of them, and if not the instructions were re-read and then they were asked again. When the subjects indicated that they were satisfied that they were sufficiently familiar with the maze, it was closed down by the experimenter pressing the <ESC> key, which also cleared the screen. Then either three or four judgements were asked of them depending upon condition. Exploration times were also recorded (to the nearest second).

[16] A batch file had been created, called trial.bat, which automated this process.

## The test materials

These are the twelve possible combinations of features rendered as questions (different coloured panels) and are order specific. Yielding...

1. *With your back to the window panel and facing 0° degrees, what is the angle to the clock?*
2. *With your back to the red panel and facing 0° degrees, what is the angle to the clock panel?*

and so forth. Table 3-2 details the actual angles to estimate.

| Source | Destination | 1a / 2a | 1b / 2b | 1c / 2c | 1d / 2d |
|---|---|---|---|---|---|
| window panel | clock panel | 26.0° | -15.0° | -6.0° | -48.0° |
| red panel | clock panel | -60.0° | 35.0° | 114.0° | 78.0° |
| purple panel | clock panel | -32.0° | 90.0° | 11.3° | -8.0° |
| clock panel | window panel | -64.0° | -15.0° | -6.0° | 42.0° |
| red panel | window panel | 4.0° | -38.0° | -149.0° | 0.0° |
| purple panel | window panel | 16.0° | 21.0° | 47.3° | 90.0° |
| clock panel | red panel | 30.0° | -55.0° | 26.6° | -12.0° |
| window panel | red panel | 4.0° | 52.0° | -43.0° | 0.0° |
| purple panel | red panel | -50.0° | -18.0° | 57.5° | 38.0° |
| clock panel | purple panel | -32.0° | -90.0° | 105.3° | 82.0° |
| window panel | purple panel | -16.0° | 22.0° | -41.0° | -90.0° |
| red panel | purple panel | 40.0° | 72.0° | 57.5° | 38.0° |

*Table 3-2*

The orientation of the angles in both the map and maze conditions have been categorised according to the orientation of the angles from <u>the map conditions</u>. Thus the angles have been labelled as being *aligned*, *counter-aligned* and *non-aligned* <u>and</u> *aligned*, *counter-aligned non-aligned-right* and *non-aligned-left* by decomposing the non-aligned data into its constituents.

It should be noted that not all of these conditions have the full range of *aligned*, *counter-aligned non-aligned-right* and *non-aligned-left* judgements. This is due to the difficulty in creating the appropriately configured mazes.

<u>Note</u>: all errors greater than 90° have been excluded on the grounds that such errors are indicative of disorientation.

## 3.1.4 Results

### Analysis of map data

The map data may be analysed to reveal whether the maps differed from condition to condition. Both the signed and unsigned errors have been analysed by means of pairs two-way analyses of variance (aligned, counter-aligned and non-aligned) and (aligned, counter-aligned and the non-aligned judgements being decomposed into non-aligned-right and non-aligned-left). Table 3-3 holds these errors.

| *Signed errors* | | | | *Dividing the non-aligned errors into their constituents* | |
|---|---|---|---|---|---|
| | Aligned | Counter-aligned | Non-aligned | non-aligned-right | non-aligned-left |
| Condition 1a | -0.5° | -29.8° | 16.8° | 12.5° | 21.2° |
| Condition 1b | 12.7° | n/a | 16.2° | 24.2° | 8.2° |
| Condition 1c | 3.2° | -17.8° | -12.2° | -18.9° | -6.9° |
| Condition 1d | 7.7° | 20.5° | 8.5° | 8.5° | n/a |
| *Unsigned errors* | | | | | |
| Condition 1a | 9.5° | 30.5° | 25.2° | 25.5° | 24.8° |
| Condition 1b | 30.0° | n/a | 32.0° | 37.1° | 26.8° |
| Condition 1c | 21.6° | 17.8° | 15.1° | 18.9° | 11.3° |
| Condition 1d | 35.3° | 20.5° | 29.2° | 29.2° | n/a |

*Table 3-3*

### Analysis of the signed errors

Comparing the *signed* aligned, counter-aligned and non-aligned errors with a two-way ANOVA: the magnitude of the errors do not differ with the number of landmarks visible at any time $F(3,6) = 1.75$; or by the orientation of the judgements to be made, $F(2,6) = 1.29$. Further analysis of the *non-aligned-right* and the *non-aligned-left errors* reveals that the magnitude of the errors do not vary reliably: $t(5) = 0.07$.

### Analysis of the unsigned errors

Comparing the *unsigned* aligned, counter-aligned and non-aligned errors with a two-way ANOVA: the magnitude of the errors do not differ with the number of landmarks visible at any time $F(3,6) = 0.39$; or by the orientation of the judgements to be made, $F(2,6) = 0.54$. Further analysis of the *non-aligned-right* and the *non-aligned-left errors* reveals that the magnitude of the errors do not vary reliably: $t(5) = 1.11$.

## Analysis of maze data

The maze error data may be analysed to reveal whether the mazes differed from condition to condition. Both the signed and unsigned errors have been analysed by means of pairs two-way analyses of variance (aligned, counter-aligned and non-aligned) and (aligned, counter-aligned and the non-aligned judgements being decomposed into non-aligned-right and non-aligned-left). Table 3-4 holds these data.

| *Signed errors* | | | | *Dividing the non-aligned errors into their constituents* | |
|---|---|---|---|---|---|
| | Aligned | Counter-aligned | Non-aligned | non-aligned-right | non-aligned-left |
| Condition 2a | 18.2° | 0.0° | 16.9° | 11.8° | 22.0° |
| Condition 2b | 12.7° | n/a | 16.2° | 24.2° | 8.2° |
| Condition 2c | -17.0° | 12.0° | 3.0° | 11.0° | -4.9° |
| Condition 2d | -10.1° | 8.8° | -16.1° | -16.1° | n/a |
| *Unsigned errors* | | | | | |
| Condition 2a | 20.5° | 48.0° | 35.6° | 48.2° | 23.0° |
| Condition 2b | 30.0° | n/a | 22.0° | 37.1° | 6.8° |
| Condition 2c | 23.6° | 25.2° | 21.7° | 23.4° | 20.0° |
| Condition 2d | 21.5° | 31.0° | 22.5° | 22.5° | n/a |

*Table 3-4*

## Analysis of the signed errors

Comparing the *signed* aligned, counter-aligned and non-aligned errors with a two-way ANOVA: the magnitude of the errors do not differ with the number of landmarks visible at any time $F(3,6) = 1.15$; or by the orientation of the judgements to be made, $F(2,6) = 0.13$. Further analysis of the *non-aligned-right* and the *non-aligned-left errors* reveals that the magnitude of the errors do not vary reliably: $t(5) = 0.06$.

## Analysis of the unsigned errors

Comparing the *signed* aligned, counter-aligned and non-aligned errors with a two-way ANOVA: the magnitude of the errors do not differ with the number of landmarks visible at any time $F(3,6) = 1.02$; or by the orientation of the judgements to be made, $F(2,6) = 0.03$. Further analysis of the *non-aligned-right* and the *non-aligned-left errors* reveals that the magnitude of the errors do vary reliably: $t(5) = 1.94$, $p < 0.06$.

## Study Times

Table 3-5 holds the mean free study / exploration times for all four map and maze conditions.

| *Condition* | *1a / 2a* | *1b / 2b* | *1c /2c* | *1d / 2d* |
|---|---|---|---|---|
| Map (study times in seconds) | 47.0 | 62.7 | 75.4 | 27.7 |
| Maze (exploration times in seconds) | 126.7 | 76.8 | 153.1 | 252.0 |

*Table 3-5*

Figure 3-6 illustrates the above data.

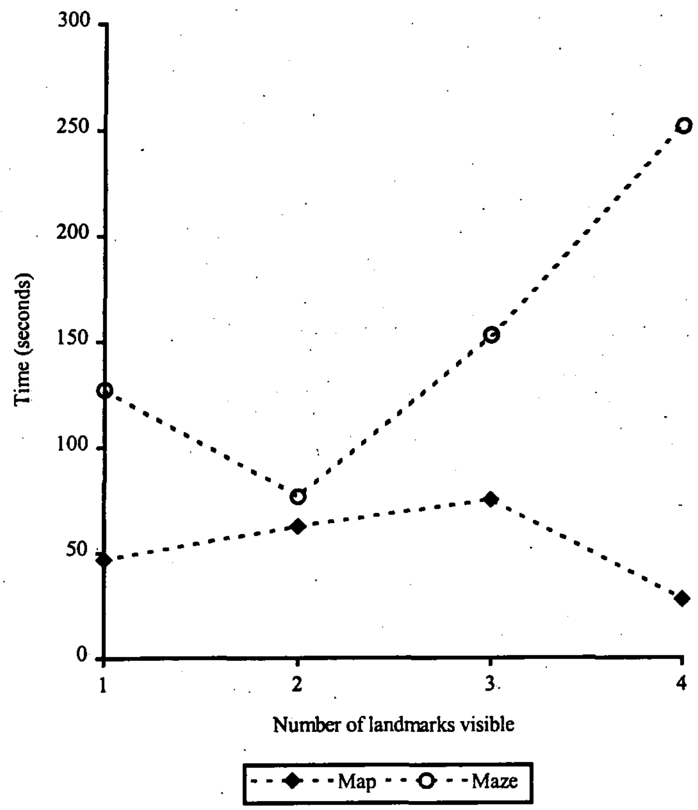



*Figure 3-6*

### Free study times

It is clear that the mean free study times for all four map conditions do not vary reliably. Rank correlating the number of landmarks with the free study times, a value of $r_S = -0.2$ is found. This indicates that the study times do not increase monotonically with the number of landmarks. This finding is unsurprising as all of the landmarks are necessarily equi-available.

### Free exploration times

Clearly the mean free study times for all four virtual mazes conditions do vary reliably. While the free study times for conditions 2a, 2b and 2c do not differ, the free study time for condition 2d is reliably longer than 2c ($p < 0.05$) and 2b ($p < 0.05$) and 2a ($p < 0.06$). Rank correlating the number of landmarks with the free study times, a value of $r_S = 0.8$ is found. While this level of correlation is not statistically reliably it does suggest that free study times *tend* increase monotonically with the number of landmarks.

## 3.1.5 Discussion of results

### The map conditions

The results of the four map conditions may be summarised and compared with the relevant hypothesis components as follows:

1. Judgement aligned with the way in which the map was learned will be the most accurate. Judgements counter-aligned with the learning condition will be least accurate. Judgement which are non-aligned with the learning condition will show a level of accuracy between the aligned and counter-aligned.

   Evidence was found for a broad confirmation of the presence of orientation specificity in judgements made after studying maps. However these effects were not statistically reliable which may be due to the small number of subjects in each condition.

2. The configuration of the maps should not affect study time.

   Free study times did not vary between conditions as expected.

## The maze conditions

The results of the four maze conditions may be summarised and compared with the relevant hypothesis components as follows:

1. The accuracy of judgements from different orientations will not vary.

   Evidence for orientation-specificity was found according to the operation definition given at the very beginning of this chapter, namely, that *orientation-specificity is typified by the pattern of: (i) the smallest error in making a judgement being at 180° to the largest error and (ii) the intermediate errors being at right angles to the smallest and largest errors.*

   Furthermore, while the accuracy of the judgements did not vary between conditions 2a, 2d and 2c, the mean signed errors incurred in making judgements after exploring the virtual maze in condition 2d were very significantly different (they were strongly biased in an anti-clockwise direction) from those in the other three conditions.

2. Free exploration of the mazes will increase as the number of landmarks visible at any time decreases.

   Analysis of the free exploration times suggests a monotonic increase with the number of landmarks.

# 4. Experiment V

Experiment V explores the differences in the nature of the spatial knowledge acquired from maps (which Thorndyke and Hayes-Roth, 1982, describe as 'survey knowledge') and such knowledge acquired from the exploration of non-immersive virtual environments. Experiment V is thus an attempt to parallel some of the central themes of the study by Thorndyke and Hayes-Roth (1982) but substituting a *virtual building* for a real one.

## 4.1 Introduction to Experiment V

Thorndyke and Hayes-Roth aimed to investigate the differences in spatial knowledge acquired from maps and spatial knowledge acquired from free exploration of a particular environment. They selected as their environment the first floor of the Rand Corporation in Santa Monica, USA. The first floor consisted of two buildings separated by an enclosed hall with a 50° dog leg. The building contained a number of distinct and prominent public areas which, with the exception of the hall, were all set at right-angles to each other.

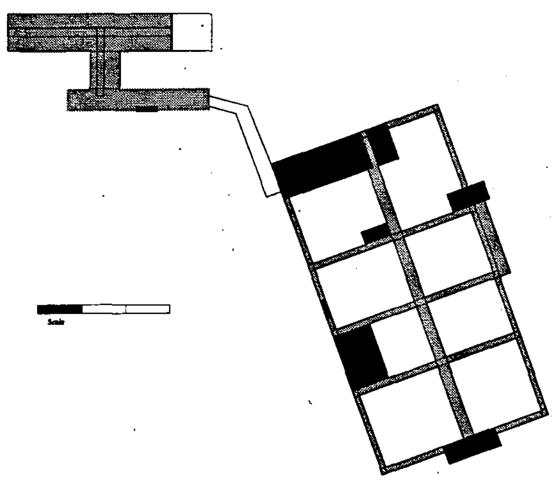


*Figure 4-1*

Figure 4-1, after Thorndyke and Hayes-Roth (1982) p.566, is a representation of the first floor of the Rand Corporation although it is not to scale or in precise proportion.

Their subjects were divided into two groups, those who had previously acquired knowledge of the building by either actually working there (the navigation condition) and those who were requested to acquire such knowledge by studying floor plans of the building (the map knowledge condition). Within each condition, a further subdivision was made. For the map condition, (i) subjects were required to learn a map of the building so that they could reproduce it without error; (ii) as group (i) but with a further 30 minutes of over-learning; and (iii) as (i) but with a further 60 minutes of over-learning.

For the navigation condition, (i) subjects were identified who had worked at the Rand for 1 to 2 months; (ii) for 6 to 12 months; and (iii) for 12 to 24 months.

Both groups were asked to estimate:

- Euclidean (i.e. 'straight line') distances from the centre of one room to another;
- route distances, again from the centre of one room to another;
- orientation, that is, subjects were asked to point to a given location from their current location, and;
- location, that is, to locate a designated location from an incomplete map.

## Results from the map-learning condition

Thorndyke & Hayes-Roth found that the performance of the map learning subjects with regard to distance estimates was characterised as follows:

- the correlation between the Euclidean and route distance estimates was very high (r = 0.82);
- the relative accuracy of the estimates was equally divided between Euclidean and route distance estimates (i.e. for 50% of the sample the correlation between actual and route distance was higher than the correlation between the actual and Euclidean distances).
- more and larger errors were made in estimating route distance than Euclidean distance and these error were not reduced with over-learning.

Thorndyke and Hayes-Roth have argued that subjects who have acquired spatial knowledge from a map generate an image of the map to estimate distances. Subjects are able to estimate distances by scanning from point to point in a manner which is analogous to visually scanning the actual map. When estimating a Euclidean distance, subjects scan the image and estimate the distance by comparing it to the provided scale. However as Euclidean distance estimates do not depend on the route information, the error in subjects' estimates of Euclidean distance will be independent of the number of the legs on the connecting route. Therefore when subjects estimate route distances, they must estimate and sum the lengths of the component legs on the route. This additional processing is thus a potential source of error in the estimation process. The more component legs to be estimated and combined, the greater the opportunity for error. As a consequence, the error in map-learning subjects' estimate of route distances should exceed the error in their estimates of Euclidean distance which indeed it does. This model of generating distance estimates from images created from studying maps is also supported by the image scanning work of Kosslyn, Ball and Reiser, (1978); Denis and Cocudes (1989); and, Kulhavy, Schwartz and Shaha (1983) which has been reviewed in chapter 1.

## Results from the navigation condition

In contrast, the distance estimates made by the navigation subjects were found to be less uniform.

- the judgements of route distances were more accurate than judgements of Euclidean distances, but as the amount of navigation experience increased, the differences in accuracy of judgement between route and Euclidean distances diminished.
- Euclidean judgements were found to become more accurate with extended navigational experience though the accuracy of route distances judgements was unchanged.

Therefore, unlike distance estimation from spatial knowledge acquired from maps there appears to be a clear dependency between the Euclidean and route judgements. Euclidean judgements are derived from route estimates.

## 4.1.1 Experiment V

This experiment necessarily differs from the Thorndyke and Hayes-Roth study in a number of ways. Firstly, as already mentioned, a virtual building will be used in place of a real one. The virtual building differs from a real building in that it is very regular, all angles are right-angles, all surfaces are either horizontal or vertical. There is no outside world to place it in context; and the lighting is uniform. It is, of course, also devoid of people, furniture and a ceiling! The virtual building consists of five empty rooms connected by a corridor. The rooms are distinguished by either their monochromatic colour scheme (i.e. purple, red or green coloured walls) or by means of features 'embedded' in the walls (i.e. clocks or opaque 'windows').

Secondly, this experiment will only address the Euclidean and route distance estimates. The reasons for this are three-fold,

- experiments I, II, III and IV have already provided a body of evidence on the issue of angle estimation in virtual environments;
- there are practical difficulties with the availability of subjects who would be willing to spend a substantial amount of time making additional orientation judgements, and;
- while Thorndyke and Hayes-Roth physically escorted their subjects to specific rooms in the Rand building from which to make judgements this, of course, cannot be reproduced in this experiment. Instead this will be paralleled by making a number of different copies of the virtual building with different starting points specified. Thus subjects can be effectively 'spirited' to specific rooms from which to make the distance estimates.

While the differences between this experiment and Thorndyke and Hayes-Roth's are pronounced, there is no reason to suppose that they affect the validity of the comparison between spatial knowledge acquired from a map of the virtual building and spatial knowledge acquired from exploring the virtual environment itself.

### 4.1.2 Hypothesis

The statement of hypothesis for this experiment is as Thorndyke and Hayes-Roth's:

1. Spatial knowledge acquired from exploring the virtual building will facilitate more accurate route judgements of distance than equivalent Euclidean judgements of distance.
2. Spatial knowledge acquired from a map of a virtual building will facilitate more accurate Euclidean judgements than route judgements of distance.
3. The difference in accuracy between the route and Euclidean judgement will diminish with extended navigational experience.

### 4.1.3 Method

### Materials: the navigation conditions

A virtual building was again created using the PC application ACK3D. ACK3D which was run on a 486SX PC (at 33MHz with 8Mb of memory and a SVGA graphics card with 1Mb of video memory with a resolution of 800x600 with 16 colours) had been previously installed on the PC's hard disc.

## Materials: the map condition

Figure 4-2 is a representation of the map of the virtual building used in this experiment. The map used in this experiment, was printed on a sheet of A4 paper oriented 'landscape' (black on white) and the various rooms labelled as below. As with Thorndyke and Hayes-Roth, a scale was included on the map but the subjects were not explicitly instructed to use it.

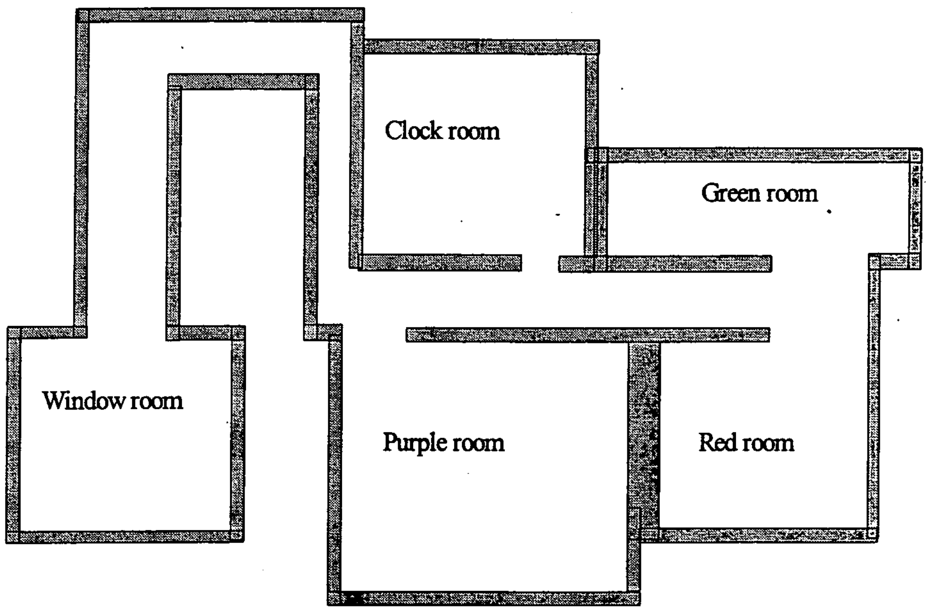


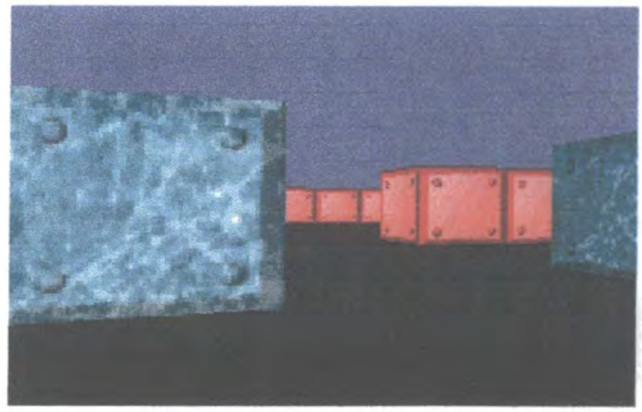

*Figure 4-2*

## Colour Illustrations

The two screen-shots overleaf are taken from the virtual building used in this experiment.

This image has been taken looking towards the window room from the corridor leading to it.

This image has been taken looking towards the red room from the green room.



## Subjects

24 subjects (20 men and 4 women), drawn from the technical and administrative staff at MARI, agreed to participate in this experiment. All of the subjects use computers on a daily basis, and as such are wholly familiar with the operation of PCs. None was paid.

## Design

An independent measures design was employed with a third of the subjects being assigned to each condition (i.e. the map condition and the two navigation conditions).

Unlike the design employed by Thorndyke and Hayes-Roth, the map condition was not further subdivided. In their original experiment Thorndyke and Hayes-Roth had divided the map condition into three sub-groups, two of which involved over-learning the map. However they subsequently found that the map learners' spatial knowledge did not improve with extended exposure to the map as measured in terms of the accuracy of judgements made of inter-room, Euclidean and route distances. Consequently Thorndyke and Hayes-Roth conflated the map condition's data, using it as a single control condition. Given this finding, this experiment will employ a unitary map condition.

In contrast, the navigation condition has been divided into two sections; a *one period of exploration* condition consisting of free exploration for two minutes starting in a randomly chosen room, and a *three periods of exploration* condition consisting of three periods of free explorations for two minutes, punctuated by rest periods of 30 seconds, starting afresh from a randomly selected room. The duration of the periods of exploration were determined by means of two pilot trials where subjects explored a similar virtual building until they were confident they had learned its organisation and dimensions. Subjects typically took 2 to 3 minutes to explore this virtual building, and when pressed to spend more time doing so, complained of boredom.

## Procedure

Subjects were tested individually. The experimenter informed each subject that the purpose of the study was to assess the accuracy of people's spatial knowledge given different amounts and kinds of learning experience. The distinction between Euclidean (described as the 'the straight line' distance) and route distances was also explained after they had completed the exploration or study phase.

## The map condition instructions

The following instructions were read to each subject:

*'I am about to show you a map of an imaginary building which I would like you to study for two minutes. After that time I will ask you to draw the building on a blank sheet of paper. Any mistakes in your drawing will be pointed out to you, and the process of study followed by drawing will continue until you have been able to draw a full and correctly labelled map of the building on two consecutive occasions. Afterwards there will be a number of questions about the spatial organisation of the virtual building.'*

After the instructions were read to the subjects they were asked if they understood what was required of them, and if not the instructions were re-read and then they were asked again. The map was then placed on a table so that it lay squarely before them, and the study-recall cycle repeated until the subject had drawn a correctly labelled map (a drawing was judged to be veridical if the rooms were correctly proportioned with no gross metric distortion) on two consecutive trials.

## Instructions for the exploration conditions

Prior to the experiment each subject was asked if they were colour blind and only those who were not were asked to participate. Each participant was asked to sit before the computer being used for the experiment, the instructions read to them and then the file containing the definition of the virtual building loaded. The instructions were as follows:

*'This is a virtual building which I would like you to explore for 2 minutes (or, for 2 minutes on three occasions with a brief rest period between sessions). The building has a number of different rooms characterised either by the colour of their walls (i.e. red, green and purple) or by the objects embedded in them (i.e. clocks and windows). Use the cursor keys to move through the virtual building. Afterwards there will be a number of questions about the spatial organisation of the virtual building.'*

After the instructions were read to the subjects they were asked if they understood what was required of them, and if not the instructions were re-read and then they were asked again. Those subjects participating in the single exploration phase were also told that, 'two minutes is quite a short time for this task, so I will let you know when one minute has passed'.

## The distance judgements

After the subjects in both the map and navigation conditions had carried out the first phase of the instructions they were invited to estimate both the Euclidean and route distance between the centres of 5 rooms of the virtual building. This was effected by loading five different configurations of the virtual building in which the starting position was moved from room to room. The experimenter then rotated the view of the each room in turn so as both to aid the subjects' sense of orientation and to mimic the likely behaviour of the subjects in Thorndyke and Hayes-Roth's experiment. Then 'standing' at the centre of each of the five rooms the subject were asked to estimate the Euclidean and route distances to the other four rooms. The subjects were provided with a proforma, as an extract (below) illustrates:

| 3 | red room | clock room | window room | purple room |
|---|---|---|---|---|
| Estimate the straight-line distance from the centre of the Green room to the... | | | | |

Each set of questions were administrated randomly (i.e. a list of 10 non-repeating, random numbers was generated, and those numbers used to reference the questions). As each set of estimates were completed they were covered so as to prevent the subject comparing one set with another.

## Test materials

The distances between the rooms are in standard units of distance where a unit corresponds to the width of a graphical block used in the construction of the virtual environment. The scale on the map was also divided into units corresponding to the graphical blocks.

| From | To | Route distance | Euclidean distance |
|---|---|---|---|
| Red room | Green room | 11 | 8.06 |
| Clock room | Green room | 18 | 11.66 |
| Window room | Green room | 43 | 20.62 |
| Purple room | Green room | 24 | 12.73 |
| Clock room | Red room | 20 | 8.06 |
| Window room | Red room | 45 | 18.11 |
| Purple room | Red room | 25 | 7.07 |
| Window room | Clock room | 38 | 13.04 |
| Purple room | Clock room | 20 | 11.05 |
| Purple room | Window room | 37 | 10.44 |

## 4.1.4 Results

The raw data for this experiment may be found in appendix A. The data from the three experimental conditions consists of two sets of judgements namely the route and Euclidean inter-room estimates. Furthermore each inter-room estimate is judged twice, that is, room A ⇨ room B and room B ⇨ room A. The overall mean of these estimates has been used throughout the analyses which follow.

## 4.1.5 One period of exploration results

### 4.1.5.1 Comparison of signed and unsigned errors

Table 4-6 holds the signed and unsigned mean errors incurred by subjects in making both route and Euclidean judgements.

| | Mean signed error | Mean unsigned error |
|---|---|---|
| Route judgements | -11.8 | 11.9 |
| Euclidean judgements | 0.4 | 4.8 |

*Table 4-6*

Analysing the signed errors with a one-tailed *t*-test: $t(7) = -9.93$, $p < 0.001$, which indicates that the route errors are very reliably larger than the Euclidean errors. Repeating this procedure for the unsigned errors: $t(7) = 4.09$, $p < 0.0025$, which indicates that the unsigned route errors are again very reliably larger than the unsigned Euclidean errors.

These two results fail to support the first hypothesis component, namely, *spatial knowledge acquired from exploring the virtual building will facilitate more accurate route judgements of distance than equivalent Euclidean judgements of distance.*

### 4.1.5.2 Comparison of errors: by judgement

Analysing the signed errors with a two-tailed *t*-test: $t(9) = 5.47$ $p < 0.001$, which indicates that the mean errors associated with the route judgements are significantly larger than the corresponding Euclidean errors. Again with the unsigned errors, $t(9) = 4.47$ $p < 0.001$, which indicates that the mean errors associated with the route judgements are significantly larger than the corresponding Euclidean errors.

4.1.5.3 Correlating the actual distances and the corresponding errors

There is a reliable negative correlation between actual distance and the mean signed route errors, $r(9) = -0.83$, $p < 0.01$. Figure 4-3 illustrates the line of best fit for the above route errors plotted against the actual distance.

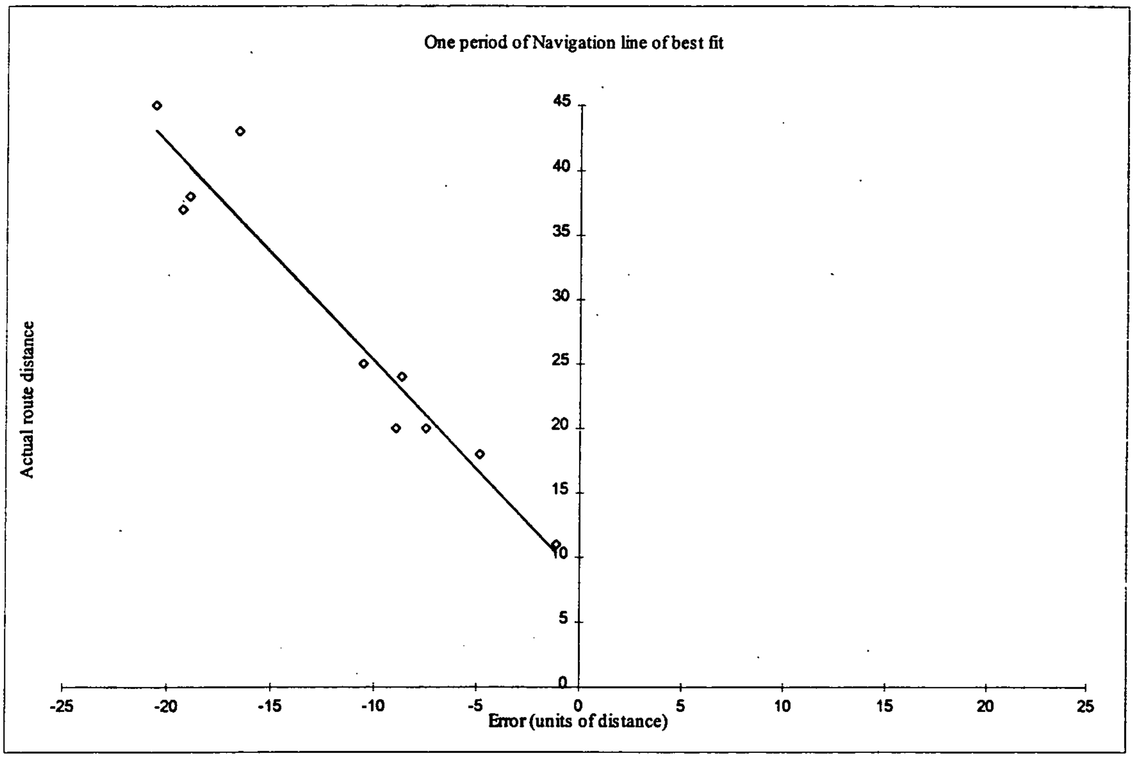



*Figure 4-3*

From this figure it is clear that there is a linear relationship between the magnitude of the errors and the actual distance, and that there are two major groups of errors (and a singleton).

In contrast the mean unsigned errors do not appear to vary in a systematic way, an observation which is substantiated by the absence of a reliable correlation between actual distance and the size of the error, $r(9) = 0.55$. Given the low level of correlation, the line of best fit for the unsigned errors has not been calculated.

## Euclidean errors

The mean signed Euclidean errors do not appear to vary with the magnitude of the actual Euclidean distance, $r(9) = -0.41$, likewise the mean unsigned Euclidean errors, $r(9) = -0.02$. Given these low levels of correlation, the lines of best fit have not been calculated.

### 4.1.5.4 One period of exploration: in summary

Subjects made significantly larger signed errors in estimating route distances than the corresponding Euclidean distances, $t(7) = 9.93$ $p < 1.2E\text{-}05$, similarly for the unsigned errors, $t(7) = 4.09$, $p < 0.0025$. These findings fail to support following hypothesis component, namely, *spatial knowledge acquired from exploring the virtual building will facilitate more accurate route judgements of distance than equivalent Euclidean judgements of distance.*

Furthermore the magnitude of the signed route errors was found to increase as a function of the magnitude of the actual distance, $r(9) = -0.834$, $p < 0.015$, this did not hold for the unsigned route errors or either of the Euclidean judgements.

## In conclusion

These results have failed to replicate the findings of Thorndyke and Hayes-Roth. The Euclidean judgements have proved to be significantly more accurate than the route judgements which is the complete reverse of what was expected. Thorndyke and Hayes-Roth's model of distance estimation predicts that the Euclidean estimates are dependent upon the route estimates. Inaccurate route estimates as observed in this condition should have produced inaccurate Euclidean estimates but this has not been observed. It would appear that the two sets of judgements are independent.

### 4.1.6 Three periods of exploration results

#### 4.1.6.1 Comparison of signed and unsigned errors

Table 4-7 holds the signed and unsigned mean errors incurred by subjects in making both the route and Euclidean judgements.

| | Mean signed error | Mean unsigned error |
|---|---|---|
| Route error | -10.1 | 10.3 |
| Euclidean error | 3.5 | 6.2 |

*Table 4-7*

Analysing the signed errors with a one-tailed *t*-test: $t(7) = -4.59$, $p < 0.002$, which indicates that the route errors are very reliably larger than the Euclidean errors. Repeating this procedure for the unsigned errors: $t(7) = 1.81$, $p < 0.06$, which indicates that the unsigned route errors are again reliably larger than the unsigned Euclidean errors.

These two results fail to support the first hypothesis component, namely, *spatial knowledge acquired from exploring the virtual building will facilitate more accurate route judgements of distance than equivalent Euclidean judgements of distance.*

#### 4.1.6.2 Comparison of errors: by judgement

Analysing the signed errors with a two-tailed *t*-test: $t(9) = 5.13$, $p < 0.001$ which indicates that the mean errors associated with the route judgements are significantly larger than the corresponding Euclidean errors. Analysing the unsigned errors with a one-tailed correlated *t*-test: $t(9) = 7.24$, $p < 0.001$ which again indicates that the mean unsigned errors associated with the route judgements are significantly larger than the corresponding Euclidean errors.

4.1.6.3 Correlating the actual distances and the corresponding errors

There is a reliable negative correlation between actual distance and the mean signed route errors, $r(9) = -0.951$, $p < 0.01$. Figure 4-4 illustrates the line of best fit for the above route errors plotted against the actual distance.

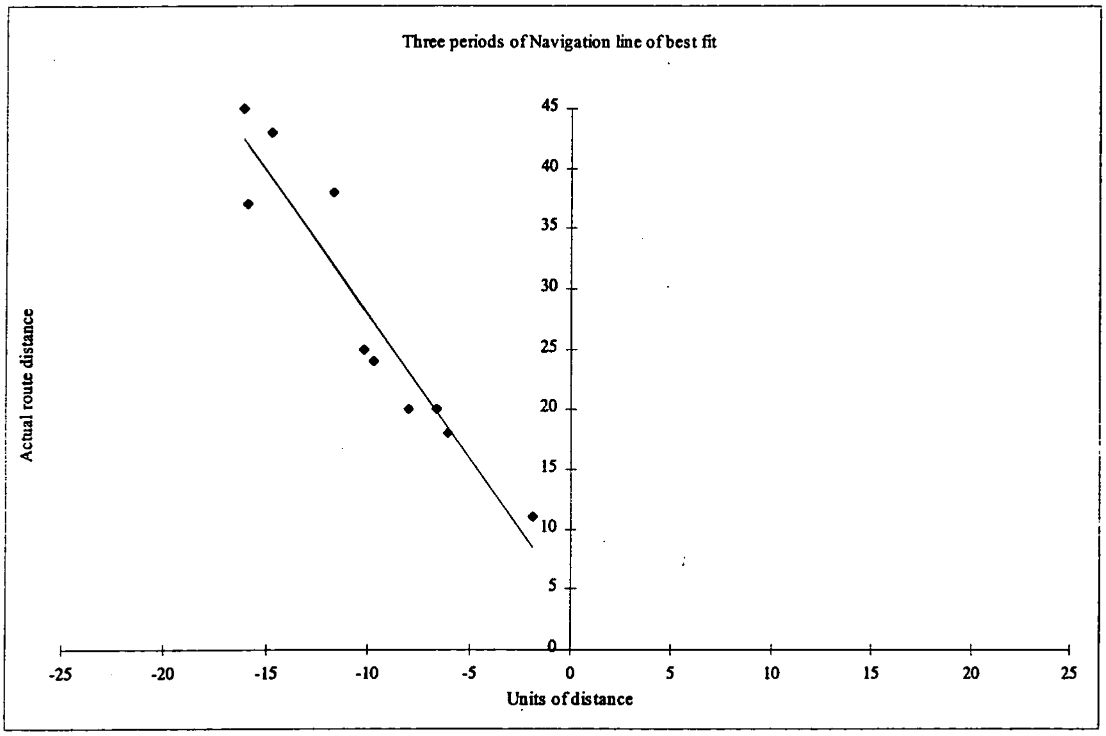



*Figure 4-4*

From this figure it is clear that there is a linear relationship between the magnitude of the errors and the actual distance, and that there are two major groups of errors (and a singleton).

In contras the mean unsigned errors does not appear to vary in a systematic way, an observation which is substantiated by the absence of a reliable correlation between actual distance and the size of the error, $r(9) = 0.43$. Given the low level of correlation, the line of best fit for the unsigned errors has not been calculated.

## Euclidean errors

The mean signed Euclidean errors do not appear to vary with the magnitude of the actual Euclidean distance, $r(9) = -0.41$, likewise the mean unsigned Euclidean errors, $r(9) = -0.30$. Given these low levels of correlation, the lines of best fit have not been calculated.

#### 4.1.6.4 Three periods of exploration: in summary

*The relative accuracy of judgements.* Subjects made significantly larger signed errors in estimating route distances than the corresponding Euclidean distances, *t*-test: $t(7) = -4.59$, $p < 0.002$, similarly for the unsigned errors: $t(7) = 1.81$, $p < 0.06$. These findings fail to support following hypothesis component, namely, *spatial knowledge acquired from exploring the virtual building will facilitate more accurate route judgements of distance than equivalent Euclidean judgements of distance.*

Furthermore the magnitude of the signed route errors was found to increase as a function of the magnitude of the actual distance, $r(9) = -0.951$, $p < 0.001$, this did not hold for the unsigned route errors or the Euclidean judgements.

## In conclusion

These results have failed to replicate the findings of Thorndyke and Hayes-Roth. The Euclidean judgements have proved to be significantly more accurate than the route judgements which is the complete reverse of what was expected. Thorndyke and Hayes-Roth's model of distance estimation predicts that the Euclidean estimates are dependent upon the route estimates. Inaccurate route estimates as observed in this condition should have produced inaccurate Euclidean estimates but this has not been observed. It would appear that the two sets of judgements are <u>independent</u>.

### 4.1.7 Map condition results

#### 4.1.7.1 Comparison of signed and unsigned errors

Table 4-8 holds the signed and unsigned mean errors incurred by subjects in making both the route and Euclidean judgements.

| | Mean signed error | Mean unsigned error |
|---|---|---|
| Route error | -0.20 | 11.46 |
| Euclidean error | 6.60 | 8.04 |

*Table 4-8*

Analysing the signed errors with a one-tailed *t*-test: $t(7) = -3.04$, $p < 0.01$, which indicates that the route errors are very reliably larger than the Euclidean errors. Repeating this procedure for the unsigned errors: $t(7) = 1.64$ $p < 0.08$, which indicates that the unsigned route errors are again larger than the unsigned Euclidean errors.

The difference in accuracy between the route and Euclidean errors fails to support the second hypothesis component, namely, *spatial knowledge acquired from a map of a virtual building will facilitate more accurate Euclidean judgements than route judgements of distance.*

#### 4.1.7.2 Comparison of errors: by judgements

Analysing the signed errors with a two-tailed *t*-test (i.e. Euclidean errors should be smaller than route errors): $t(9) = 4.41$, $p < 0.001$ which indicates that the Euclidean errors are significantly larger than the route errors. Analysing the unsigned errors with a two-tailed *t*-test (i.e. Euclidean errors should be smaller than route errors): $t(9) = 3.76$, $p < 0.005$ which indicates that the Euclidean errors are significantly smaller than the route errors.

4.1.7.3 Correlating the actual distances and the corresponding errors

There is a reliable negative correlation between actual distance and the size of the mean signed route errors, $r(9) = -0.78$, $p < 0.01$. Figure 4-5 illustrates the line of best fit for the above route errors plotted against the actual distance.

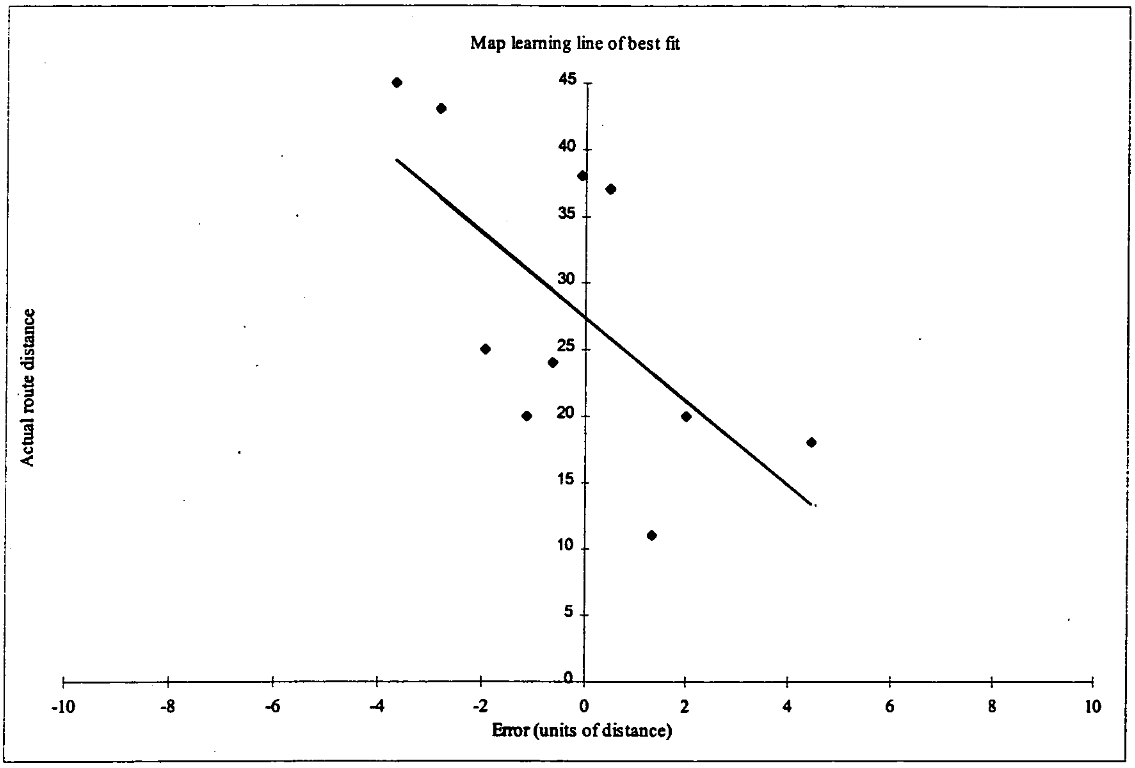



*Figure 4-5*

No such correlation is found between the actual distance and the size of the mean unsigned errors: $r(9) = 0.21$, and given the low level of correlation, the line of best fit for the unsigned errors has not been calculated.

## Euclidean errors

The magnitude of the signed Euclidean errors do not appear to vary with the magnitude of the actual Euclidean distance, $r(9) = -0.20$. Correlating the unsigned errors with the actual Euclidean distance, $r(9) = 0.29$, given this low level of agreement the line of best fit has not been calculated.

4.1.7.4 Map condition: in summary

*The relative accuracy of judgements.* Subjects made larger errors in estimating Euclidean distances than route distances, $t(14) = -1.25$, $p < 0.12$. However analysis of the unsigned errors revealed that the route errors were significantly larger than the Euclidean errors, $t(9) = 3.76$, $p < 0.005$ which indicates that the Euclidean errors are significantly smaller than the route errors. These findings therefore offer only equivocal support to the hypothesis component s*patial knowledge acquired from a map of a virtual building will facilitate more accurate Euclidean judgements than route judgements of distance.*

Furthermore, the magnitude of the signed route errors was found to increase as a function of the magnitude of the actual distance, $r(9) = -0.78$, $p < 0.01$, this did not hold for the unsigned route errors or the Euclidean judgements.

## In conclusion

These results have failed to replicate the findings of Thorndyke and Hayes-Roth. The route judgements have proved to be more accurate than the Euclidean judgements which is the reverse of what was expected. However, Thorndyke and Hayes-Roth did report very significant positive correlations between both sets of judgements and the actual distances, which have also been observed here. The high levels of correlation between the pairs of distance estimates in both the route and Euclidean suggests that the cognitive representations from which the subjects were making their judgements were internally consistent. This consistency suggests a map-like cognitive representation of the spatial relations within the virtual environment.

## 4.1.8 Comparing conditions: the signed errors

Table 4-9 holds the mean signed errors for the route and Euclidean estimates.

| | Mean signed route mean | Mean signed Euclidean mean |
|---|---|---|
| one period of exploration | -11.75 | 0.43 |
| three periods of exploration | -10.14 | 3.51 |
| map learning | -0.21 | 6.60 |

*Table 4-9*

Analysing the signed route and Euclidean data with a two-way analysis of variance: for type of judgement (i.e. route or Euclidean), $F(1,14) = 41.37$, $p < 0.001$ indicating that the route errors are very significantly larger than the Euclidean errors. Analysing for the effect of the learning condition (i.e. map versus navigation), $F(2,28) = 6.15$, $p < 0.007$, indicating a significant learning effect. There is no evidence for an interaction between type of judgement and learning condition, $F(2,28) = 0.56$, $p < 0.58$.

### Analysis of the signed route data

Analysing the signed route data with an ANOVA: $F(2,21) = 5.56$, $p < 0.01$ indicating that there are reliable differences among learning conditions.

The one period of navigation errors are reliably larger than the map errors, $t(14) = 2.61$, $p < 0.02$ (two-tailed); the three periods of navigation errors are reliably larger than the map errors, $t(14)=2.14$, $p < 0.05$ (two-tailed); while the signed navigation errors do not differ in magnitude.

### Analysis of the signed Euclidean data

Analysing the signed Euclidean data with an ANOVA: $F(2,21) = 1.55$ which indicates that there are no reliable differences among learning conditions.

## 4.1.9 Comparing conditions: the unsigned errors

Table 4-10 holds the mean unsigned errors for the route and Euclidean estimates.

| | Mean unsigned route mean | Mean unsigned Euclidean mean |
|---|---|---|
| one period of exploration | 11.86 | 4.78 |
| three periods of exploration | 10.28 | 6.20 |
| map learning | 11.46 | 8.04 |

*Table 4-10*

Analysing the signed route and Euclidean data with a two-way analysis of variance: for type of judgement (i.e. route or Euclidean), $F(1,14) = 13.66$, $p < 0.002$ indicating that the route errors are significantly larger than the Euclidean errors. Analysing for the effect of the learning condition (i.e. map versus navigation), $F(2,28) = 0.50$ suggesting no differences among learning conditions. There is also no evidence for an interaction between type of judgement and learning condition.

Taking these analyses further: analysing the unsigned route data with an ANOVA: $F(2,21) = 0.62$ indicating that there are no reliable differences among learning conditions, similarly for the unsigned Euclidean data: $F(2,21) = 1.00$ again indicating that there are no reliable differences among learning conditions.

### 4.1.10 Discussion of results

The results from this experiment are unequivocal: Thorndyke and Hayes-Roth's findings have not been reproduced.

1. Map learning: this experiment employed a more realistic paradigm to that of Thorndyke and Hayes-Roth in that subjects studied a map until they could accurately reproduce it. There was no deliberate or prolonged over-learning. Unlike Thorndyke and Hayes-Roth who found that more and larger errors were made in estimating route distance than Euclidean, this experiment found the reverse.
2. Free exploration: Thorndyke and Hayes-Roth found that free exploration of a building gave rise to more accurate route distance estimates than Euclidean estimates but with extended exposure both improved and tended to become equally accurate. In contrast, this experiment found the Euclidean estimates were more accurate than route estimates and while extended exposure made no difference to the accuracy of the route estimates, the Euclidean estimates declined in accuracy.
3. However the correlations between the route judgements errors and the actual route distances for all conditions proved to be statistically reliable but negative. This indicates that the size of the error incurred in judging route distances increases with distance to judge. In contrast, no reliable correlations were found between the Euclidean judgements errors and the actual Euclidean distances.
4. The independence of the Euclidean estimates from route estimates is another striking feature of these results. Thorndyke and Hayes-Roth argue that route judgements plus 'mental algebra' are used to produce estimates of Euclidean distances. Yet as the route judgements have proved to be so systematically inaccurate and the Euclidean judgements so relatively accurate this relationship cannot hold. As accurate Euclidean judgements cannot be made from inaccurate route judgements they must have been arrived at independently.
5. No improvement in accuracy was found in the route judgements with increased exploration, and evidence was found for increased exploration producing poorer Euclidean distance estimates. Given these findings this component of the hypothesis cannot be supported.

# 5. Experiments VI, VII and VIII

Experiment VI is an investigation into whether the *clutter* phenomenon is a feature of virtual space. Clutter has been suggested as the cause of the frequently observed phenomenon of people over-estimating distances when the intervening route is filled with objects, landmarks or turns (e.g. Cohen, Baldwin and Sherman, 1978; Byrne, 1979; Sadella and Staplin, 1980, Thorndyke 1981; Thorndyke and Hayes-Roth, 1982).

Experiment VII further examines the role of *clutter* in distance estimation and Moar and Bower's (1983) observation that judgements of angles tend to systematicity, that is, angles tend to be judged closer to a multiple of 90° than their true value. Finally, having both estimates of distance and angles the resultant vectors can be compared with the actual vector.

Experiment VIII is an examination of the rôle of imagery in making distance estimates from memory of recently explored virtual environments.

This chapter ends with a general discussion of the findings of these final three experiments.

## 5.1 Introduction to experiment VI

This experiment has two principle objectives: firstly, to obtain a baseline measure of the accuracy of subjects judgements of Euclidean distance from within virtual environments in the presence and absence of obstacles, the presence of which should give rise to the *clutter* phenomenon. Secondly, to compare *direct* exploration with *indirect* exploration of such environments. Exploration of virtual environments in the experiments reported in this volume has required subjects to use the keyboard to manipulate the perspective or view of the virtual environment (i.e. facilitate the appearance of moving through virtual space) which may termed *direct exploration.* In contrast, *indirect exploration* for the purposes of this experiment consists of the subject instructing the experimenter to move for him or her. The subject will be able to instruct the experimenter to, for example, move to the left then stop, turn right and stop and so forth. In this way the subject experiences exploration at a remove.

### Distance estimation

Thorndyke and Hayes-Roth's (1982) model of distance estimation which has been discussed at length in the literature review (chapter 1 section 3), suggests that people employ 'mental algebra' using estimates of the length of component legs of the route, together with the angles turned through, to produce an estimate of total distance. They further suggest that increasing the number of computations required for an estimate increases the likelihood of error, noting that the absolute error is probably greater than evidence suggests as some of the subject's computational errors will cancel each other out, reducing the overall error. Thorndyke and Hayes-Roth believe that people estimate the distance between two points by mentally simulating a trip from the start point to the destination. When estimating route distances, they estimate and sum the lengths of the component legs on the route. When estimating Euclidean distances, they must estimate the angles at which they turn between different legs on the route. They must then perform some mental algebra using the legs and the angle estimates to estimate the Euclidean distance between the points. However, this model largely ignores the following factors which are thought to affect the accuracy of distance estimates:

- evidence suggests that remembered routes and angles tend to be 'normalised'; that is, for example, streets that in reality deviate from being straight tend to be remembered as being straight (e.g. Norman and Rumelhart, 1975; Chase and Chi, 1980[17]) and that estimated angles tend to be recalled as being closer to right-angles than their true value Moar and Bower (1983); and,
- the effect of clutter which is discussed below.

## Evidence for the effect of clutter

Byrne (1979) found that subjects' distance estimates for routes with many turns are reliably greater than for equally long routes with fewer turns. He suggested that distance along a route is estimated using the processing heuristic based on a function of the number of intervening obstacles or features - the more features / locations to remember between two points, the greater the apparent distance between those points. Byrne has further proposed that the cognitive representation of distance information is in terms of a network of topological information which is encoded, in the case of route information, as ordered strings of locations with information relating to the angle turned through. Similar evidence for the clutter illusion has been found by Cohen, Baldwin and Sherman (1978); while Sadella and Staplin (1980) found that people in a shopping mall over-estimated distances between two equi-distant locations as a function of intervening intersections, time to travel there, and how crowded the route was. Sadella and Staplin went on to identify the main contributory factor in over-estimating distances as being the number of intersections encountered. Kosslyn, Pick and Fariello (1974) have also found that both children's and adults' memory judgements of the

[17]Cited in Levine, Jankovic and Palij, 1982

distance between two objects in a room increased when barriers were interposed between the objects. Studies of subjects' use of visual imagery have demonstrated that the time to scan across a visual image increases linearly with scan distance and with the number of objects on the scanned path (Kosslyn, 1973, 1978; Kosslyn, Ball and Reiser, 1978). Sadella, Staplin and Burroughs (1980) also describe a variant of the distance distortion: the distance from a well-known landmark (which they call a spatial reference point) to a less well-known landmark is estimated 7% shorter than the reverse distance (from the less well-known landmark to the well-known landmark).

## Other forms of clutter

Numerous studies from environmental psychology have demonstrated that people's experiences in their locale influence their perception of point-to-point distance. These environmental influences include the relative attractiveness of locations as destinations, their centrality (i.e. their proximity to frequently visited areas), the familiarity of the paths connecting the locations, the direction of paths (towards or away from central locations), and the length of time the subject has resided in the locale. Finally, Sadella, Staplin and Burroughs (1979) have reported that a route containing high frequency names was estimated as being longer than one containing low frequency names.

## Evidence to the contrary

Cohen, Weatherford, Lomenick and Koeller (1979) assessed distance estimation ability of second and sixth graders and adults in a novel environment consisting of seven identical stimulus locations and three barriers. The space encountered and the paths walked by the subjects were designed such that each subject experienced the factorial combination of barriers (present versus absent) and route (travelled versus not travelled) across each of the three inter-location distances (4, 6 and 8 feet). For all ages, estimates of travelled routes containing barriers were <u>more accurate</u> than barrier-present routes that had not been travelled. Thus, though the studies described above have shown that barriers to direct travel lead to distortions in spatial representations, it would appear that walking can help subjects compensate for these potentially distorting effects.

## 5.1.1 Experiment VI

Two virtual rooms were created for this experiment. The first virtual room had walls which measured 12x12 panels (units) externally and 10x10 internally and were coloured monochromatic green, except for a red, window and clock panel. The walls of the second virtual room measure 16x16 panels (units) externally and are coloured a monochromatic green. This room also had a distinguishing red, window and clock panel. The second room also had a number of internal walls which were intended to add an element of *clutter*.

The two rooms were complemented by two modes of exploration, namely, *the free exploration condition* (hereafter the *hands-on* condition) in which subjects were asked to make judgements of Euclidean distances while actively exploring the virtual rooms and to *the indirect exploration condition* (hereafter the *hands-off* condition). The *hands-off* mode of exploration had the subjects ask the experimenter to move for them within the virtual rooms, that is, the subjects were not required to use the keyboard directly. Instead they instructed the experimenter to move in the following way, e.g. go left - stop - forward - stop. Neither condition was time limited.

## 5.1.2 Hypothesis

Firstly, active exploration of virtual environments (*hands-on condition*) will produce the more accurate estimates of Euclidean distance estimation than by subject-directed exploration. Secondly, the presence of obstacles will tend to produce (i.e. *clutter*) less accurate judgements in that subjects will tend to over-estimate the actual distances.

## 5.1.3 Method

### Materials

Two virtual rooms were again created using the PC application ACK3D full detail of which may be found in appendix B. ACK3D which was run on a 486SX PC (at 33MHz with 8Mb of memory and a SVGA graphics card with 1Mb of video memory with a resolution of 800x600 with 256 colours) had been previously installed on the PC's hard disc.

Figure 5-1 is a plan view of the smaller, uncluttered virtual room.

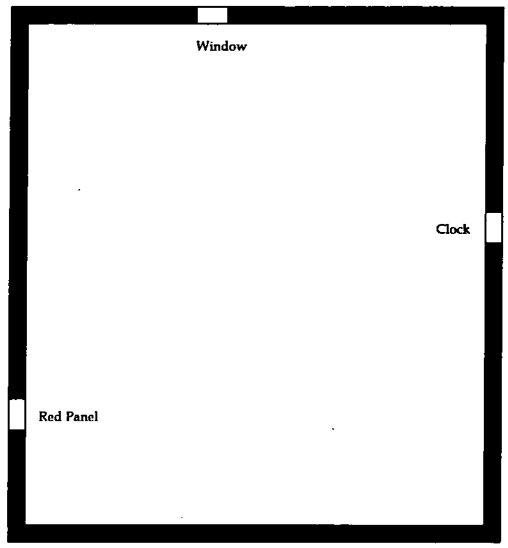



*Figure 5-1*

Figure 5-2 is a plan view of the larger, cluttered virtual room.

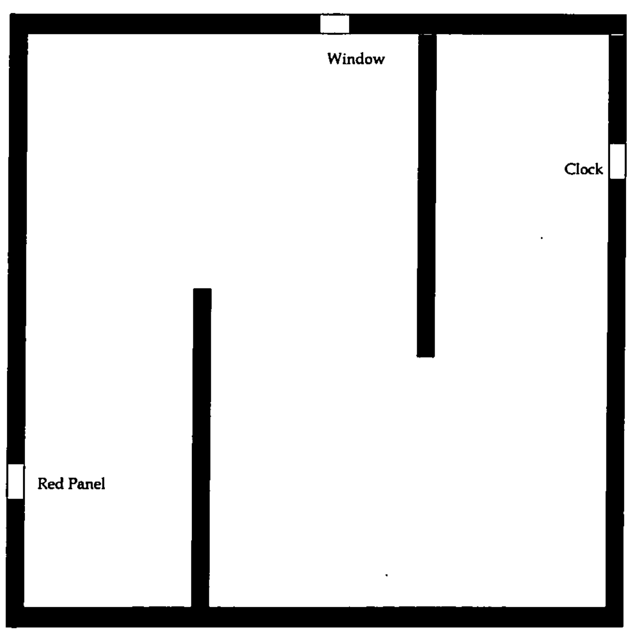



*Figure 5-2*

## Colour Illustrations

The two screen-shots overleaf are taken from the two virtual rooms used in this experiment.

## Subjects

16 subjects drawn from staff at MARI Computer Systems Ltd. agreed to participate in this experiment. All of the subjects used computers on a daily basis, and as such were wholly familiar with the operation of PCs. None was paid.

## Design

A 2x2 factorial design was employed with a half of the subjects being randomly assigned to either the free exploration condition (the *hands-on* condition) or indirect exploration condition (the *hands-off* condition). Within each of these conditions, subjects made judgements about both the cluttered and uncluttered virtual environments.

## Procedure

Subjects were tested individually. The experimenter informed each subject that the purpose of the study was to investigate the accuracy of people's spatial knowledge in a virtual room.

The following instructions were then read aloud.

> *'I would like you the estimate the Euclidean, that is, the straight line distance between a number of panels in the two virtual rooms I am about to show you. The rooms are essentially green in colour but have one red panel, one window panel and one clock panel and it is these panels I will ask you to estimate the straight line distance between in units, where a unit is the width of one panel. Finally, I would like you to make these judgements of distance while you are within the virtual room.'*

After the instructions were read to the subjects they were asked if they understood what was required of them, and if not the instructions were re-read and then they were asked again.

## The test materials

Table 5-1 holds the inter-feature distances to be judged and their distances.

| | Judgement | Feature | Feature | Actual Euclidean distance |
|---|---|---|---|---|
| Condition 1 | J1 | Clock panel | Window panel | 9.92 |
| (uncluttered) | J2 | Window panel | Red panel | 12.21 |
| | J3 | Clock panel | Red panel | 12.65 |
| Condition 2 | J4 | Clock panel | Window panel | 9.43 |
| (cluttered) | J5 | Window panel | Red panel | 15.81 |
| | J6 | Clock panel | Red panel | 18.36 |

*Table 5-1*

## 5.1.4 Results

The raw data for this experiment may be found in appendix A. The data from this experiment have been analysed in terms of the errors incurred in making the judgements of Euclidean distance allowing the errors to be easily compared across conditions. Table 5-2 holds the mean signed and unsigned errors incurred in making estimates of both cluttered and uncluttered distances from both modes of explorations.

| Signed errors | Clutter | No-clutter |
|---|---|---|
| Direct exploration | -0.8 | -0.9 |
| Indirect exploration | -3.5 | -2.3 |
| Unsigned errors | | |
| Direct exploration | 3.0 | 2.7 |
| Indirect exploration | 4.0 | 2.4 |

*Table 5-2*

Analysing the signed errors with a two-way analysis of variance: $F(1,14) = 0.63$ indicates that the presence or absence of clutter has no significant effect on the accuracy of the judgements; however, a value of $F(1,14) = 5.42$, $p < 0.04$ indicates that the mode of exploration has a significant effect on the accuracy of the judgements, direct exploration being the more accurate. There is no evidence of an interaction between clutter and mode of exploration.

Analysing the unsigned errors with a two-way analysis of variance: $F(1,14) = 4.79$ indicates that the presence or absence of clutter has a significant effect on the accuracy of the judgements; whereas, a value of $F(1,14) = 0.40$, indicates that the mode of exploration has no significant effect on the accuracy of the judgements. Again there is no evidence of an interaction between clutter and mode of exploration.

### 5.1.5 Discussion

#### The effects of clutter

There are two key findings with respect to the effect of clutter on distance estimation in virtual environments. Firstly, the presence of obstacles (intervening walls) does not induce the over-estimation of Euclidean distance which is characteristic of *clutter*. Instead it appears to induce slight under-estimation. Secondly, the presence of *clutter* tends to produce less accurate Euclidean distance estimates compared with estimates made from uncluttered virtual environments.

#### Modes of exploration

The results of this experiment are very much in line with the brief review of active versus passive acquisition of spatial knowledge outlined in section 1.2.2. Introducing a level of indirection into the experience of a virtual environment tends to result in less accurate estimates of inter-feature distances. This finding is congruent with the reports of a number of researchers have reported more error prone or less accurate spatial judgements when spatial knowledge has been acquired passively (e.g. Appleyard, 1970; Beck and Wood, 1976; Feldman and Acredolo, 1979; Golledge and Spector, 1978).

#### A confounding error

Post-experimentally it was noticed that a design error had occurred in this experiment. The panels used as landmarks in the cluttered condition had been inadvertently moved with respect to the no-clutter condition. Despite this error it is not anticipated that this will have had a significant effect on the results as the landmarks had only been moved by a panel or two's width. This error could have been avoided had the design of the virtual environments been properly reviewed before the experiment was conducted.

## 5.2 Introduction to experiment VII

The unexpected findings of experiment VI that Euclidean distances in cluttered environments tend to be under-estimated is here further explored. Furthermore the claims by Lee (1970) and Sadalla and Magel (1980) that right-angle turns (*in lieu* of the 'walls' of experiment VI) can induce the clutter illusion are also examined.

In addition to the examination of the effects of clutter in virtual environments Moar and Bower's (1983) observation that judgements of angles tend to systematicity, that is, angles tend to be judged closer to a multiple of 90° than their true value is also tested.

Finally, as subjects are for the first time being asked to estimate both angle and distance it is possible to calculate the resultant vectors from the estimates of Euclidean and route distances and inter-feature angles and compare them with the actual vector.

### 5.2.1 Experiment VII

In this experiment, the effect of clutter has been isolated by creating three red monochrome virtual corridors. All three corridors have a fixed unit length of 60 units (i.e. graphic panels) but have either:

- no turns (the control condition);
- five right-angle turns with connecting corridors of varying lengths; or,
- eight right-angle turns again with connecting corridors of varying lengths.

The choice of five and eight turns for the experimental conditions reflect, in part, the limitation of the application used to generate the corridors. Specifically, the maximum length of a straight corridor was 60 units and the choice of five or eight turns is a balance between ensuring that a reasonable number of turns and that the connecting corridors are, again, of a reasonable length. Clutter in this experiment will be instantiated in the form of an increasing number of right-angle turns (either no turns, or five, or eight turns) along the virtual corridors being used.

### 5.2.2 Hypothesis

Judgements of distance traversed will tend to be over-estimated with the increasing amounts of clutter there is *en route*. Clutter should produce similar effects for both route and Euclidean judgements. Finally, after Moar and Bower (1983) it is expected that there will be a tendency to systematicity in that judgements of inter-feature angles will tend to be estimated to be closer to the nearest multiple of 90° than they actually are. The inter-feature angles to be judged are the angles from one end of the virtual corridor to the other - the 'start-to-end' angle.

### 5.2.3 Method

#### Materials

The virtual corridors were again created using the PC-based applications ACK3D (details of which may be found in appendix B). ACK3D which was run on a PC (at 33MHz with 8Mb of memory and a SVGA graphics card; the card has 1Mb of video memory and a resolution of 800x600 with 256 colours) had been previously installed on the PC's hard disc.

#### Subjects

16 subjects (all men), drawn from the technical staff at MARI Computer Systems Ltd., agreed to participate in this experiment. All of the subjects use computers on a daily basis, and as such were wholly familiar with the operation of PCs. None was paid.

#### Design

A repeated measures design was employed. Subjects were assigned to each of the five conditions in a random order. Although there were five conditions, strictly, only three corridors were used. This fact was concealed from the subjects.

- The control condition consisted on a straight corridor 60 units long. Each subject traversed this only once.
- Figure 5-3 illustrates conditions 1a and 1b which used the same corridor. As can be seen this virtual corridor is not symmetrical, and by reversing the starting point with the end point, the subjects moved through the corridor either in a clockwise or anti-clockwise manner. Each subject traversed the virtual corridor once in each direction.
- Figure 5-4 illustrates conditions 2a and 2b. As (ii), each subject traversed the virtual corridor once in each direction.

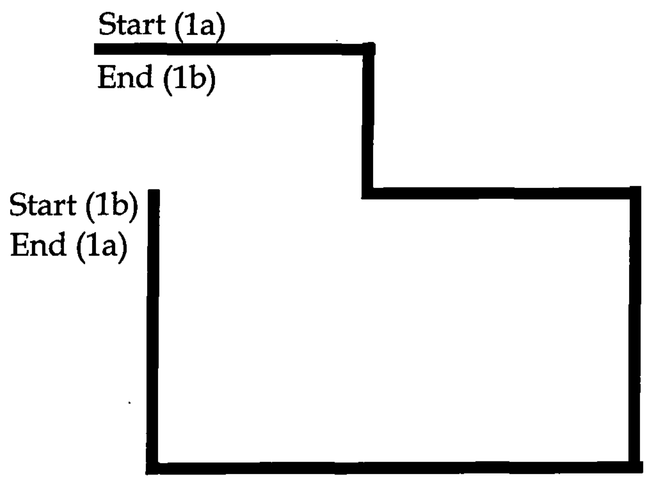



*Figure 5-3*

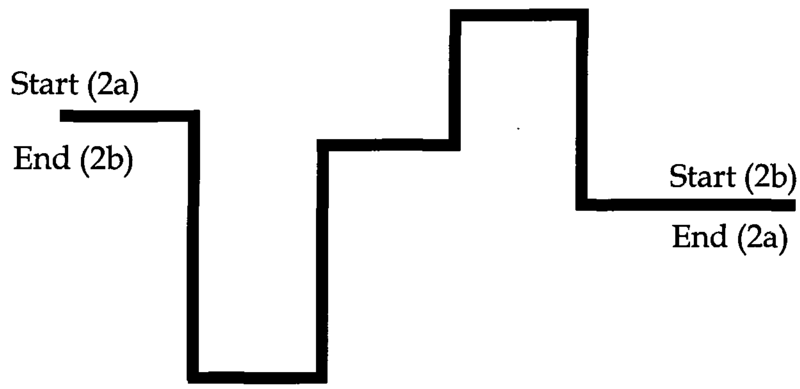


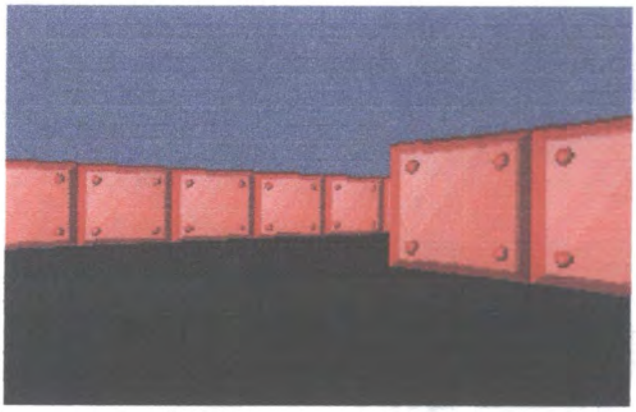

*Figure 5-4*

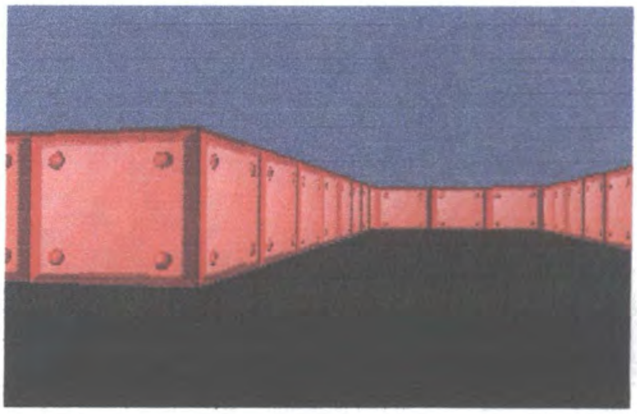
As can be seen the two corridors have two major differences: firstly, figure 5-7 has only 5 right-angle turns whereas figure 5-8 has eight; and secondly, figure 5-7 turns back on itself, in contrast figure 5-8 follows an overall East-West progression. All corridors were 60 units long and three units wide. The central line was taken to be the route distance.

## Colour Illustrations

The two screen-shots overleaf are taken from the two virtual corridors used in this experiment.

This image and the one below have been taken from the featureless monochrome virtual corridors used in this experiment.





## Procedure

The subjects were told that the experiment was concerned with understanding how accurate their judgements of distance and angles were in virtual space. Each subject was then asked to sit before the computer being used for the experiment and then one of the 5 corridors was selected at random and loaded. The following instructions were then read aloud.

*'This is a corridor along which I would like you to move until you reach the end. Each panel of the corridor equals 1 unit of distance. Use the cursor keys to move. When you have done so I will ask you the following questions:*

- *estimate the distance you actually travelled in units allowing for the twists and turns you make, that is, the route distance;*
- *estimate the straight line distance from the starting point to the end of the corridor, that is, the 'as crow flies distance'; and,*
- *imagine you are standing with your back to the starting panel of the corridor facing due North (i.e. 0°). Estimate (i.e. say aloud) the angle from this point to the end of the corridor*

*There are a total of 5 corridors.'*

In addition to the corridors being presented in random order, the order in which the above questions were to be asked was also randomised.

## 5.2.4 Results

The raw data for this experiment may be found in appendix A.

## Treatment of results

The overall means of the two pairs of 5-turns and 8-turns judgements have been taken, and used in the analysis, which in turn have been translated into mean errors. Errors rather than judgements have been used for two reasons: firstly, to permit the different Euclidean judgements to be compared with each other, and secondly, to allow the route and Euclidean estimates to be compared directly.

## Signed distance judgements

Table 5-3 holds the mean signed route and Euclidean errors for the three conditions - one data set has been excluded due to the subject's inability to complete all of the required judgements. Only the signed errors have been analysed as the clutter effect is a signed error.

| | Mean signed route errors | Mean signed Euclidean errors |
|---|---|---|
| no clutter | 5.87 | 4.9 |
| 5-turns | -7.83 | 11.05 |
| 8-turns | -5.67 | -0.13 |

*Table 5-3*

Comparing the **route** errors with the no-bias condition (i.e. zero error) reveals that two of these data sets do not differ from zero (i.e. the no clutter condition, $t(14) = -0.84$ and the 8-turns condition, $t(14) = 1.03$). While the errors in the 5-turns condition do reliably differ from zero, $t(14) = 1.93$, $p < 0.05$. However further analysing these errors by means of a series of (paired) *t-tests* failed to reveal any reliable differences between the pairs of judgements.

Comparing the **Euclidean** errors with the no-bias condition (i.e. zero error) indicates that two of these data do not differ from zero (i.e. the no clutter condition, $t(14) = -0.84$ and the 8-turns condition, $t(14) = 1.03$). While the errors in the 5-turns condition do reliably differ from zero, $t(14) = 1.93$, $p < 0.05$. Further analysing these errors by means of a series of (paired) *t-tests*:

- 5-turns errors compared with 8-turns errors, $t(14) = 5.88$ $p < 0.001$, indicating that the 5-turns errors are reliably larger than the 8-turns errors;
- control condition errors compared with 8-turns errors, $t(14) = 0.51$ indicating no reliable difference between conditions;
- control condition errors compared with 5-turns errors, $t(14) = -1.98$ $p < 0.05$ indicating that the 5-turns errors are reliably larger than the control condition errors.

Although there is some evidence for reliable over-estimation in both the route and Euclidean estimates in 5-turn condition, the hypothesis component that a cluttered virtual environment would tend to produce over-estimates of distance <u>cannot be unequivocally supported</u>.

## 5.2.5 Evidence for systematicity in the judgements of angles

The final component of the hypothesis relates to evidence for systematicity in the judgements of angles. Moar and Bower's (1983) evidence for systematicity is based upon the use of a series of *t*-tests, comparing the differences between the error in judgement and 90° with the difference between the actual angle and 90°. Their evidence for systematicity is then based on the finding that the judged angles were significantly closer to a multiple of 90° than the actual angle. This procedure has been used on the angle judgements from this experiment. For each condition the judged angles and the actual angle, the absolute difference from the nearest multiple of 90° (including 0°) has been derived. This gives two sets of differences which have been compared by way of independent *t*-tests, in which pair-wise comparisons of the difference between the error in judgement and the difference between the actual angle and 90°.

| Condition | Actual angle | Actual 'error' | Mean signed errors |
|---|---|---|---|
| 1a | 70° | 20° | -5.1 |
| 1b | 160° | 20° | -38.1 |
| 2a | 7° | 7° | 18.0 |
| 2b | 7° | 7° | 0.5 |

Comparing the signed errors: $t(4) = -1.59$, $p < 0.09$ suggesting the presence of some evidence for systematicity. (The unsigned errors have not been analysed as systematicity refers to a directional bias only).

### 5.2.6 Vectors

## Control condition: route estimates

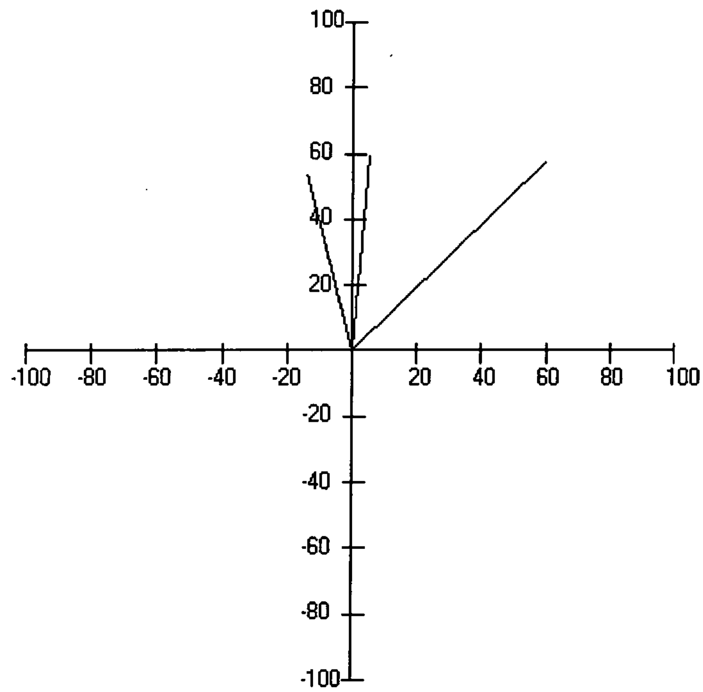



Figure 5-5 illustrates the vectors for the control condition route distance and angle estimates. The dotted line (obscured by the y-axis) indicates the actual vector running from the origin to 0,60. Both axes are in units of distance. This figure is a little unrevealing in that all but three of the vectors are obscured by the y-axis, however, it does show that the angle was correctly estimated.

Figure 5-5

## Condition 1a: route estimates

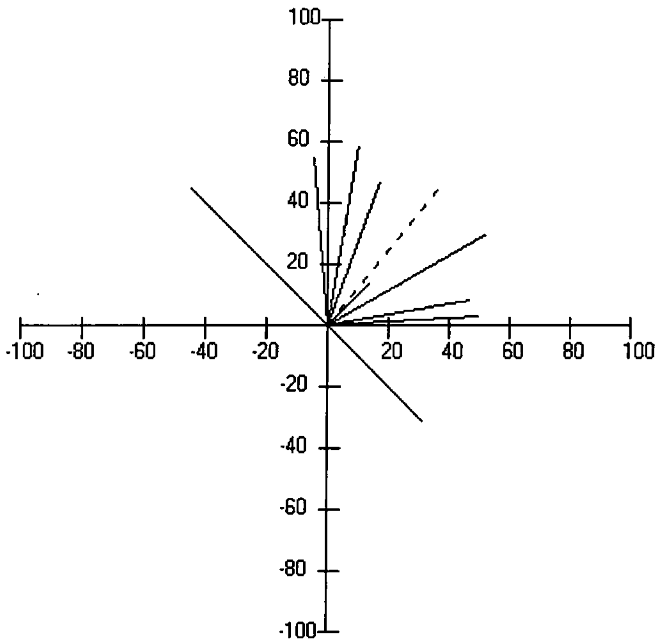



Figure 5-6 illustrates the vectors for route distance and angle estimates for condition 1a. Both axes are in units of distance. The dotted line indicates the actual vector running from the origin to 38,47. All but three of the vectors are in the correct quadrant and from inspection the remaining vectors appear to be fairly equally distributed either side of the actual vector.

Figure 5-6

## Condition 1b: route estimates

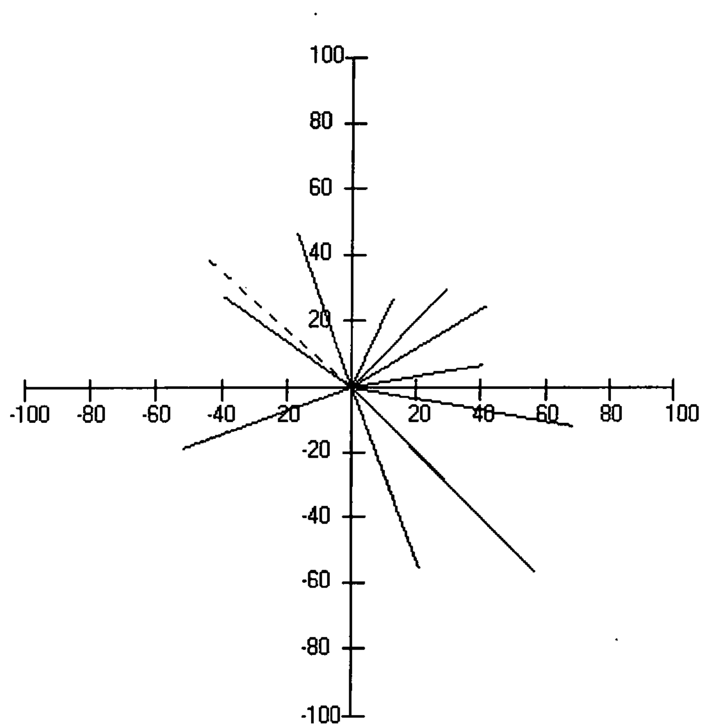



Figure 5-7 illustrates the vectors for route distance and angle estimates for condition 1b. The dotted line indicates the actual vector running from the origin to -45,39. Both axes are in units of distance. The 'star-burst' appearance of this figure suggests that many of the subjects were disoriented with most vectors lying in different quadrants to that of the actual vector,

Figure 5-7

## Condition 2a: route estimates

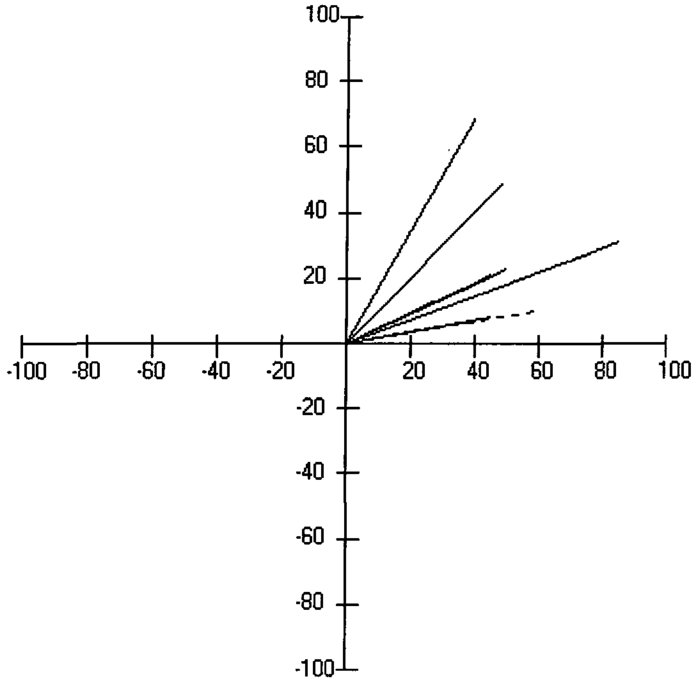



Figure 5-8 illustrates the vectors for route distance and angle estimates for condition 2a. The dotted line indicates the actual vector running from the origin to 59,10. Both axes are in units of distance. All of the vectors are in the same quadrant as that of the actual vector but most demonstrate an anti-clockwise bias.

Figure 5-8

## Condition 2b: route estimates

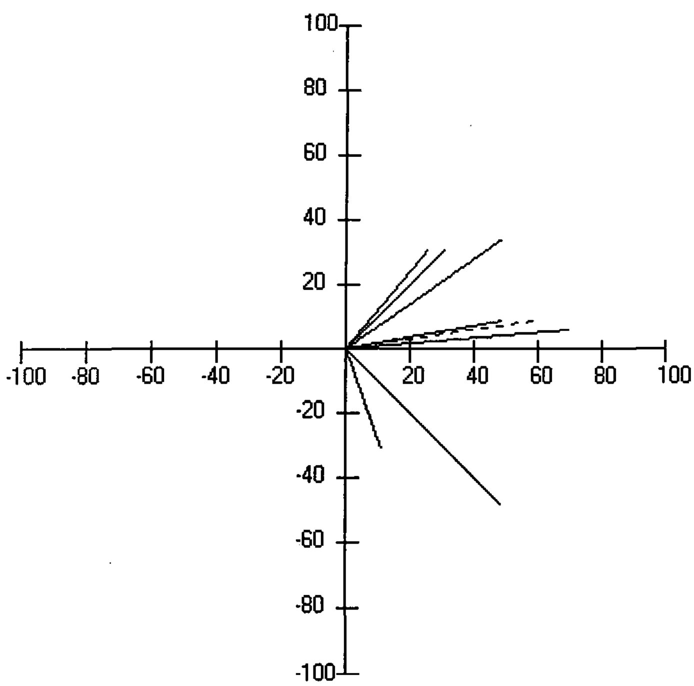



Figure 5-9 illustrates the vectors for route distance and angle estimates for condition 2b. The dotted line indicates the actual vector running from the origin to 59,9. Both axes are in units of distance. From this figure it is clear that most vectors are clustered about the actual vector.

*Figure 5-9*

## Control Condition: Euclidean estimates

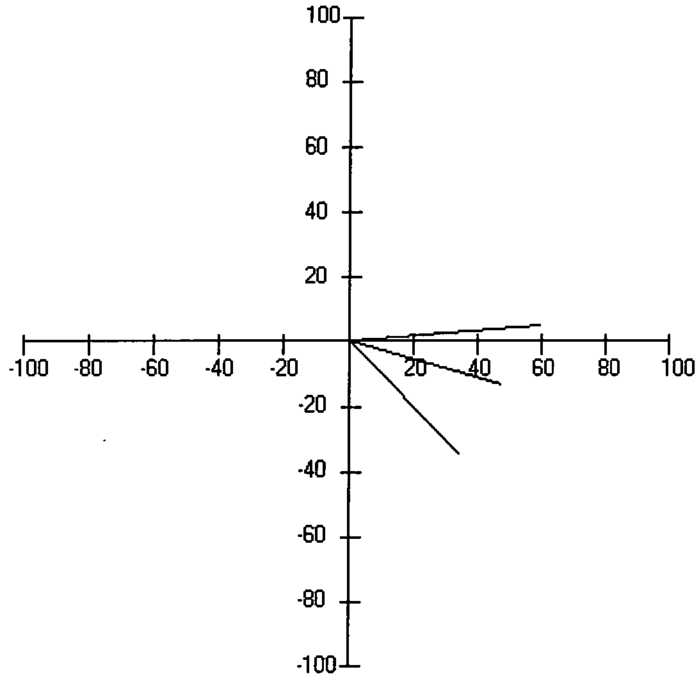



Figure 5-10 illustrates the vectors for route distance and angle estimates for the control condition. The dotted line (obscured by the y-axis) indicates the actual vector running from the origin to 60,0 Both axes are in units of distance. From this figure it is clear that most vectors are clustered about the actual vector with only three vectors being noticeably different.

*Figure 5-10*

## Condition 1a: Euclidean estimates

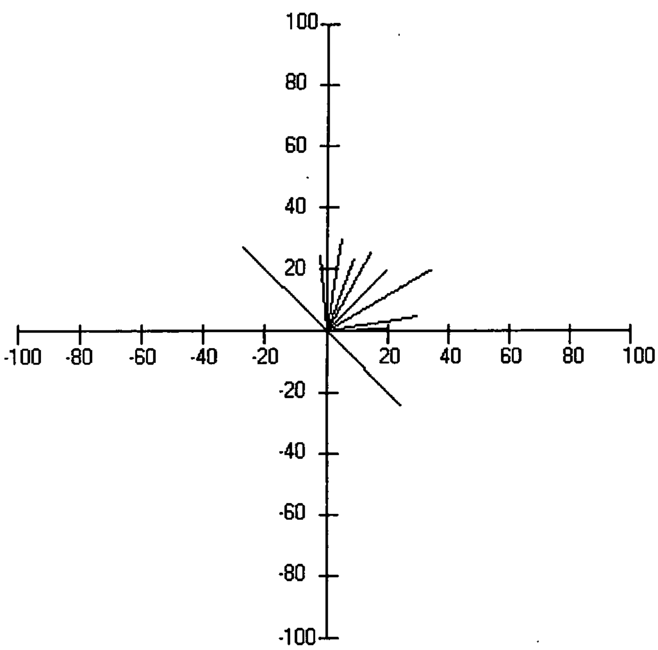



Figure 5-11 illustrates the vectors for route distance and angle estimates for condition 1a. The dotted line (obscured) indicates the actual vector running from the origin to 4,4 Both axes are in units of distance. All but three of the vectors are in the correct quadrant and from inspection appear to be fairly equally distributed either side of the actual vector.

*Figure 5-11*

## Condition 1b: Euclidean estimates

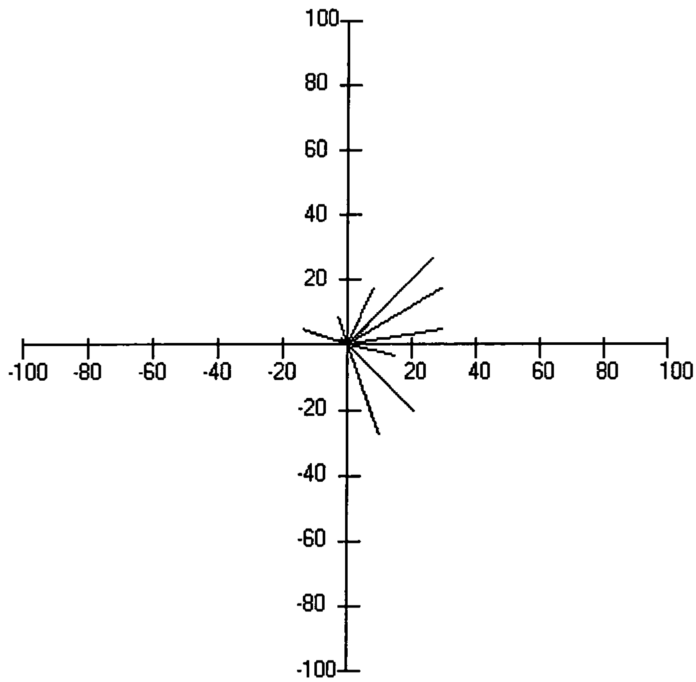



Figure 5-12 illustrates the vectors for route distance and angle estimates for condition 1b. The dotted line (obscured) indicates the actual vector running from the origin to -4,4. Both axes are in units of distance. This figure shows evidence of the 'star-burst' pattern of vectors noted in condition route judgements 1b which suggests that many of the subjects were disoriented.

*Figure 5-12*

## Condition 2a: Euclidean estimates

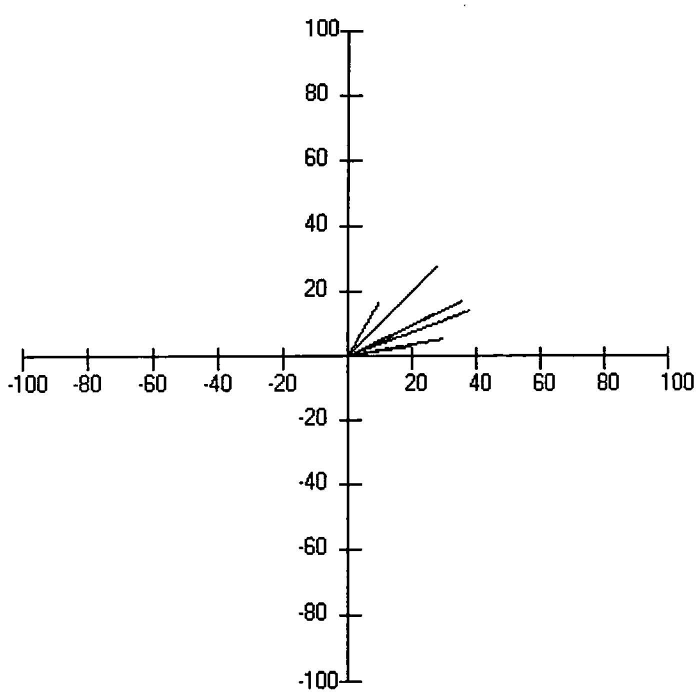



Figure 5-13 illustrates the vectors for route distance and angle estimates for condition 2a. The dotted line (obscured) indicates the actual vector running from the origin to 30,5. Both axes are in units of distance. Clearly all of vectors lie in the same quadrant as the actual vector.

*Figure 5-13*

## Condition 2b: Euclidean estimates

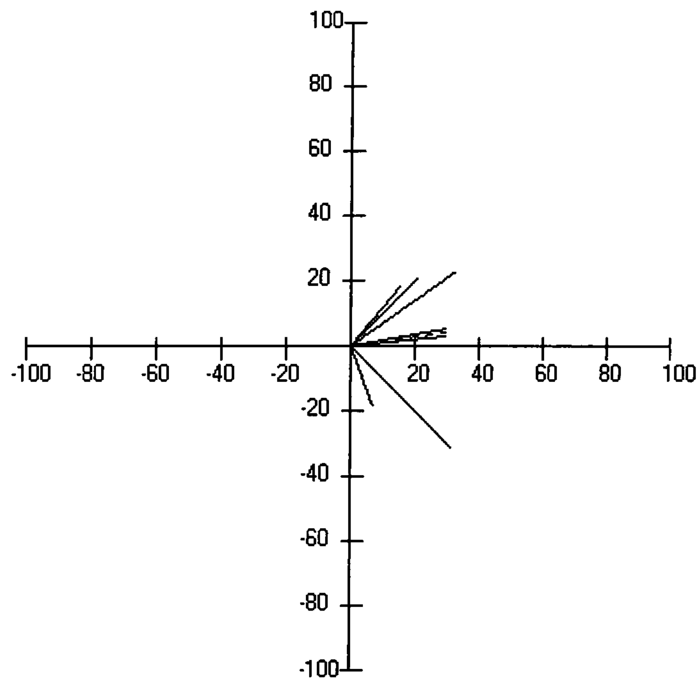



Figure 5-14 illustrates the vectors for route distance and angle estimates for condition 2b. The dotted line indicates the actual vector running from the origin to 30,4. Both axes are in units of distance. From this figure it is clear that most vectors are clustered about the actual vector.

*Figure 5-14*

## 5.2.7 Discussion

Firstly, with only one exception, the participants in this experiment were able to make the judgements requested of them, although from informal observation their confidence in the accuracy of the judgements was low.

## The distance estimates

While the mean route judgements for the 8-turn condition proved to be accurate, a statistically reliable under-estimate was found in the 5-turn condition. In all, this clearly does not provide evidence for the presence of the clutter illusion. The position with the Euclidean estimates is less clear. The estimates in the 5-turn condition produced evidence of reliable over-estimations of the actual distances ($p < 0.05$), while the 8-turn condition did not. This finding runs contrary to expectations, given that the clutter effect is taken to be related to the number of turns (or obstacles) in a route. Overall, these findings do not suggest that clutter is a contributory factor in the errors made in estimating distances in virtual environments.

## Evidence for systematicity

Some evidence systematicity was found in the judgements of angles in the four conditions. However further work is required to determine whether this finding holds across a range of configurations.

## 5.3 Introduction to experiment VIII

The genesis of this experiment lies with, firstly, elements of Thorndyke and Hayes-Roth model of distance estimation discussed at the beginning of this chapter. It will be recalled that they argued that people who have acquired spatial knowledge from a map generate an image of the map which they can subsequently scan to produce distance estimates.

The second stimulus for this experiment comes from the informal observation of, and post-experimental reports from, subjects who participated in experiments I, II, IV and V indicated that the preferred means by which judgements of distance and angle are made from memory is by way of imagery. A number of the subjects[18] described creating an image of the virtual environment they had recently explored and then performing some cognitive manipulation of that image be it 'mental rotation' or 'image scanning'.

Experiment VIII, then, is an explicit test of the rôle of imagery in making distance estimates from memory of recently explored virtual environments.

### Image scanning

Thorndyke and Hayes-Roth (1982) have sought to show that when learning maps intentionally, the individual acquires an *image* of the depicted space, and that the mental representation of a map and the physical map are isomorphic. Image scanning then permits the individual to identify the exact and relative location of particular objects. Evidence of image scanning processes in cognition are extensive and include Kosslyn, Ball and Reiser's (1978) seminal study where they presented subjects with a map of an imaginary island on which seven different locations were identified. These locations, a beach, a lake, a hut and so forth were so placed as to ensure that the distances between them were all different. The subjects were asked to study the map until they could accurately reproduce it on a blank proforma. They were then asked to form an image of the island focusing on a particular feature. A second feature was then named and subjects were asked to scan their image and depress a button when they had located the second named object. The results showed a linear relationship between latency and the distance of the second named object from the first. However, it should be noted that Kosslyn *et al* found that the absence of explicit instructions to generate and consult an image (of the map previously studied by subjects) resulted in the disappearance of the linear

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18 It must be stressed that no formal records were taken of these reports.

relationship between time to scan the image from feature to feature (the verification latency) and the distance separating those features.

### 5.3.1 Experiment VIII

A simple regular virtual environment was created consisting of monochrome green walls with two different coloured panels, and three free standing objects forming the *objects* between which subjects were asked to estimate the distance. Subjects were assigned to either the explicit imagery condition or the implicit imagery condition and then given three minutes in which to explore the virtual environment and learn its spatial arrangement. After the period of exploration, subjects were either asked to visualise the virtual environment and then to fix their attention on the first of two named objects or to simply fix their attention on the first of two named objects. When a second object was named the subjects were either asked to explicit scan across the visualised image or to 'locate' the second object. Scanning and locating times were recorded, as was the time to estimate the distance and finally the distance estimate itself. As can be seen from this brief outline of the experiment, there are a number of critical differences between this and Kosslyn *et al*'s original experiment. These are:

- Kosslyn *et al* employed a verification paradigm as the *raison d'être* for the image scanning. More specifically, they asked their subjects to locate a first object, and then to scan for a second which may or may not have been present. Furthermore, the range of objects suggested by Kosslyn *et al* were all plausible, in that it was not unreasonable to expect them to be found on an island or a map of an island, and as such subjects were required to scan the image of the island they had generated to verify the existence or otherwise of those objects. In contrast as no such set of objects could reasonably exist for the rather minimalist virtual environment employed in this experiment (please see figure 4-13). Therefore replacing the verification paradigm, subjects were instead explicitly requested to estimate inter-object distances.
- In a pilot study which was conducted prior to the experiment proper in order to determine a reasonable estimate for the exploration time, it became clear from observation of the participants that they were capable of generating and then scanning an image of the virtual environment that had just explored but estimating the inter-object distances was very clearly a separate process. This finding was also wholly consistent with the earlier experiments in this series where subjects were seen to be engaged in the actual process of performing a range of computations, and were observed to vocalise their calculations, and so forth. Given this evidence a distinct measurement of the time the subjects took to estimate inter-object distances was also recorded.

- This experiment has an implicit imagery condition. This condition has adopted what is judged to be a imagery-neutral term namely 'locate' as the alternative to 'scan'. Although the image-neutrality of the term 'locate' was not established it did prove to be meaningful to all of the subjects in the imagery implicit condition.
- The number of inter-object distances has been reduced from 84 to 20 (namely, 10 x 2, that is, ten judgements from A ⇨B, where 'A' and 'B' stand for objects in the virtual environment, and then another 10 judgements from B ⇨A. The order of presentation was random.

## The differences between this experiment and Kosslyn *et al*

In their original experiment, Kosslyn, Ball and Reiser used a tape recorder to name the starting location, followed a delay of 4 seconds, and then named a second location. Presentation of the second location started a clock, which was used to measure the RT for verification. As Kosslyn, Ball and Reiser did not provide precise instruction on how the tape recorder and timer were interfaced, the current experiment has adopted a variation on this, which is as follows. A program written in a mixture of C and C++ was created to replace Kosslyn *et al*'s apparatus. The program worked by:

i. reading a text file containing the randomised pairs of locations to be identified;

ii. displaying those words; and

iii. managing the delays between words.

The displayed words were read from the screen by the experimenter (in lieu of the tape recorder) to the subject. In addition to managing the timed display of the stimulus material, the program also recorded the scan times (or time to locate, if image scanning was not involved), the 'time to estimate', that is, the time to estimate the inter-object distance, and then wrote all of this data to file. A sample of the contents of the output files is as follows:

| source | destination | scan time | time to estimate |
|---|---|---:|---:|
| purple panel | ceiling light | 3.24 | 6.20 |
| ceiling light | purple panel | 1.50 | 4.23 |
| red panel | treasure chest | 4.61 | 5.82 |
| ceiling light | treasure chest | 5.93 | 7.76 |

## 5.3.2 Hypothesis

As discussed above, Kosslyn, Ball and Reiser found a linear relation between the inter-object distance and time to scan from a named location to another, but only when the subjects were explicitly instructed to employ imagery. When subjects were left to their own devices no such relationship was found. It is, therefore, hypothesised that if the preferred medium of making judgements of distance is an image (rather than any other cognitive representation) then a linear relationship between the inter-object distance and time to scan from a named location to another will be observed in both the presence and absence of explicit instructions to form such an image.

## 5.3.3 Method

### Materials

A virtual environment was again created using the PC application ACK3D full details of which may be found in appendix B. ACK3D, which was run on 486SX PC (at 33MHz with 8Mb of memory and a SVGA graphics card with 1Mb of video memory with a resolution of 800x600 with 256 colours), had been previously installed on the PC's hard disc. Figure 5-15 is a plan view of the virtual room.

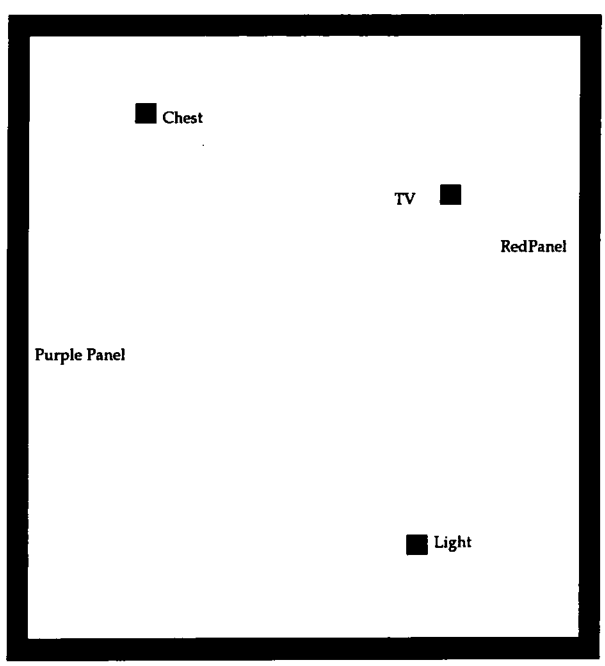


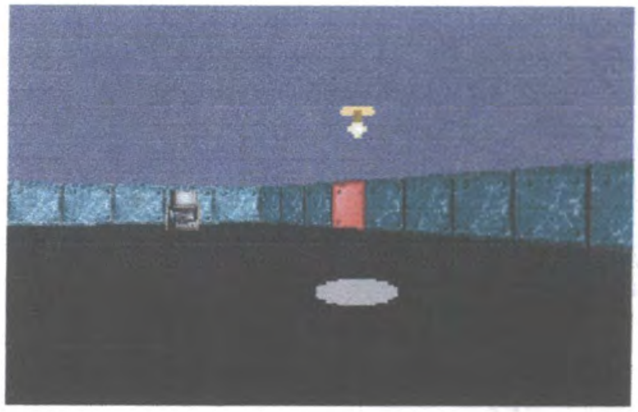

*Figure 5-15*

The walls of this virtual room measured 14x14 panels (units) and were coloured a monochromatic green. Two of the panels in the walls were coloured purple and red respectively. In addition to these two panels, three free standing objects were included, these were a treasure chest, a ceiling light and a television - the choice of objects, as before, is limited by the ACK3D application.

## Colour Illustrations

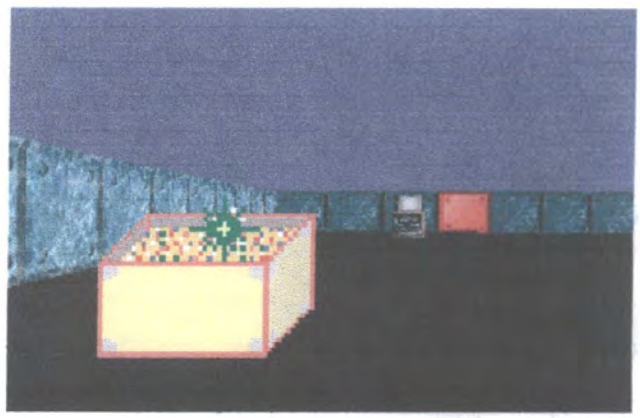
The screen-shots overleaf are from the virtual room used in this experiment.

The following four images have been taken from the virtual environment employed in this experiment. In this image are visible, the ceiling light, the TV and the red panel.

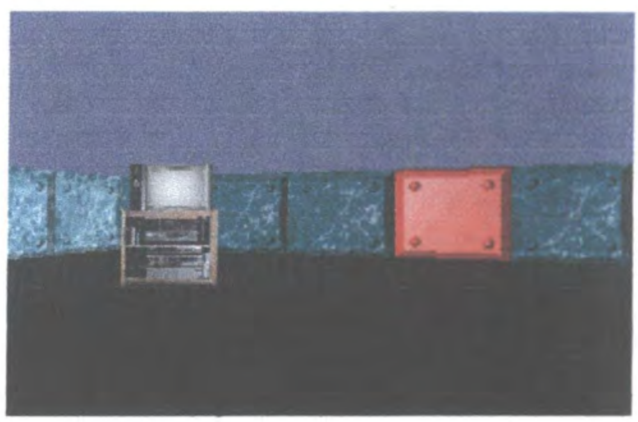


In this image the treasure chest may be seen.

The treasure chest and the TV can be seen in this image.



The TV and the red panel are visible in this image.



## Subjects

10 subjects (all men) drawn from the technical staff at MARI Computer Systems Ltd. agreed to participate in this experiment. All of the subjects used computers on a daily basis, and as such were wholly familiar with the operation of PCs. None was paid.

## Design

An independent measures design was employed with a half of the subjects being randomly assigned to each condition. The two conditions are:

- the condition wherein explicit instructions to use imagery are made, hereafter 'the explicit imagery' condition and
- the condition wherein no explicit instructions to use imagery are made, hereafter 'the implicit imagery' condition.

## Procedure

Subjects were tested individually. The experimenter informed each subject that the purpose of the study was to investigate the accuracy of people's knowledge of distances in a virtual environment.

## Initial instruction

The subjects in both the explicit imagery and the no-imagery conditions were asked if they were for colour blind and only those who were not were asked to participate. Each participant was asked to sit before the computer being used for the experiment, the instructions were read to them and then the file containing the definition of the virtual building loaded. Both groups were either one of read the following:

## Instructions (explicit imagery condition)

*'This is a virtual room which I would like you to explore for 3 minutes. The room has a number of different objects located within it and some differently coloured panels. Please study the relative locations of the objects and panels. Use the cursor keys to move around the virtual room. Afterwards there will be a number of questions about the spatial organisation of the objects.'*

- When I say 'ready' please close your eyes and visualise the virtual room you have just explored. I will give you a few seconds to fix the image.
- Then I will say name a starting location, for example the television set. I would like you to fix your attention on the named starting location and then when I name a second location I would like you to imagine a black speck moving as quickly as possible from the starting location to the second location.
- As soon as you get there press the spacebar.
- Then as soon as you have estimated the distance (in units, where one panel = one unit) between the two locations please press the spacebar again, and state the distance.
- After as short delay, the whole process will begin again from point 2.

## Instructions (implicit imagery condition)

*'This is a virtual room which I would like you to explore for 3 minutes. The room has a number of different objects located within it and some differently coloured panels. Please study the relative locations of the objects and panels. Use the cursor keys to move around the virtual room. Afterwards there will be a number of questions about the spatial organisation of the objects.'*

- When I say 'ready' please close your eyes.
- Then I will say name a starting location, for example the television set. I would like you to fix your attention on the named starting location and then when I name a second location.
- As soon as you have located the second location press the spacebar.
- Then as soon as you have estimated the distance (in units, where one panel = one unit) between the two locations please press the spacebar again, and state the distance.
- After as short delay, the whole process will begin again from point 2.

After the instructions were read to the subjects they were asked if they understood what was required of them, and if not the instructions were re-read and then they were asked again. The subjects were then invited to explore the virtual room for 3 minutes - a figure which had been arrived at being timing two subjects, not included in the experiment proper, to explore the virtual room until they felt confident they knew the spatial organisation of the objects contained therein. After this period of exploration the subjects were then asked to locate a second object in the virtual room according to the above instructions starting their search from a (first) named location within the virtual room.

## Timings

After the exploration phase of the experiment, and using the same computer as above, but with the display moved out of sight of the subject, the timing program was used to drive the data collection phase of the experiment.

At the beginning of every trial, the subjects were told, 'ready' which was followed by a delay of eight seconds. Thereafter the name of the starting location appeared on the screen of the computer, which was immediately read by the experimenter, then followed a delay of four seconds and the name of the target location, which again was read by the experimenter. The names of all the objects in the virtual room consisted of two words were as closely matched for length (i.e. number of syllables) as was practical, so, for example, 'light' became 'ceiling light'. As soon as the second word had been displayed, a centi-second clock was started. The subjects had been instructed to position their preferred hand lightly on the keyboard, with their thumbs immediately above the spacebar which was being used in lieu of a button. Pressing the spacebar stopped the timer. As the instructions (above) indicate, two sets of times were recorded, the first is the time to locate / scan to the second object from the first object, and the second is the 'time to estimate'. In all, the subjects were asked to locate and scan between (or 'locate') 20 pairs of objects, which they had observed in the virtual room. The order of presentation of the pairs of objects was random.

## 5.3.4 Results

The raw data for this experiment may be found in appendix A.

## Test materials

Table 5-4 contains the judgements asked of the subjects and the actual inter-feature distances in 'units' where a unit corresponds to the width of a graphical block used in the construction of the virtual environment. All distances referenced hereafter are also in units.

| Judgements | From | To | Distance (units) |
|---|---|---|---|
| J1 | television set | treasure chest | 2.83 |
| J2 | television set | red panel | 2.83 |
| J3 | red panel | ceiling light | 5.66 |
| J4 | television set | ceiling light | 6.32 |
| J5 | treasure chest | purple panel | 6.71 |
| J6 | ceiling light | purple panel | 9.22 |
| J7 | treasure chest | ceiling light | 10.00 |
| J8 | treasure chest | red panel | 10.77 |
| J9 | television set | purple panel | 11.70 |
| J10 | red panel | purple panel | 13.15 |

*Table 5-4*

In all of the three pairs of measurements taken in this experiment, namely,

- the scan time / time to locate;
- the time to estimate; and
- the distance estimates themselves, two sets of judgements were required of the subjects, that is, for example, judging from the red panel to the purple panel (i.e. from A ⇨ B - hereafter the 'set1'), and then from the purple panel to the red panel (i.e. from B ⇨A - hereafter the 'set 2').

For each type of measurement these pairs of values are reported together with their mean, referred to as the 'overall' mean.

## Scan times for the explicit imagery condition

Table 5-5 holds the mean of the two pairs of image scanning times (in seconds) together with the actual inter-object distance in units (as above).

| | J1 | J2 | J3 | J4 | J5 | J6 | J7 | J8 | J9 | J10 |
|---|---|---|---|---|---|---|---|---|---|---|
| mean scan time | 2.88 | 2.57 | 3.78 | 3.18 | 3.49 | 3.53 | 4.13 | 3.62 | 4.51 | 3.11 |
| distance | 2.83 | 2.83 | 5.66 | 6.32 | 6.71 | 9.22 | 10.00 | 10.77 | 11.70 | 13.15 |

*Table 5-5*

A Spearman's rank correlation on the mean image scanning times and the actual distance, produces a value of $r_S = 0.512$, which is a little short of the critical value ($r_S = 0.56$, $N = 10$) and as such indicates a *fairly* reliable correlation. However, if the last pair of data are excluded, the correlation is more pronounced, $r = 0.80$, $p < 0.05$. A possible justification for excluding the final set of data is that these times and distances refer to a pair of boundary features. That is, they form part of the walls of the virtual environment being the red panel and purple panel and as such subjects may have been moving from wall to wall in a ballistic manner without scanning the intervening distance. Baum and Jonides (1977) have also observed that the time required to compare two distances decreased with the magnitude of the difference between the distances on both perceptual and memorial tasks, and this may be the case here.

## Regression analysis (i)

Figure 5-25 illustrates the line of best-fit for the above data.

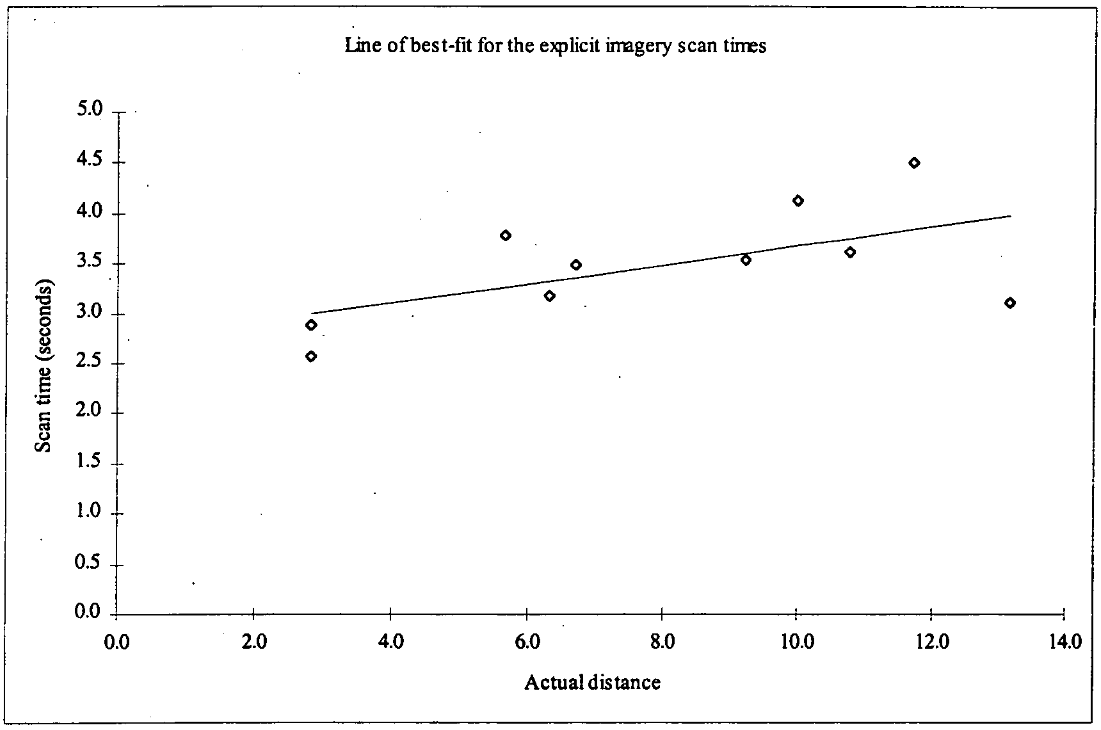



*Figure 5-16*

<u>These findings compared with Kosslyn *et al* (1978)</u>. The first observation to be made is that there is a clear linear relationship between distance to scan and time to scan when subjects are explicitly instructed to form and image. However, the above figure stands in contrast to Kosslyn *et al*'s findings in that it appears to take a relatively longer time to scan the image of the virtual room. Kosslyn found (judging from his graph) that subjects could scan a distance of 18 cm in under 2 seconds. In contrast, these subjects are unable to scan the shortest virtual distance in anything less than 2 seconds[19]. This may mean that the apparent depth of the virtual environment employed in this experiment suggests minimum apparent distances of 18+ centimetres.

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[19] The equation of the line is y = 2.72 + 0.1*x, that is, scan_time = 2.72 + 0.1*units_of_distance.

## Regression analysis (ii)

Figure 5-17 illustrates the line of best fit for the explicit imagery condition excluding the final data point.

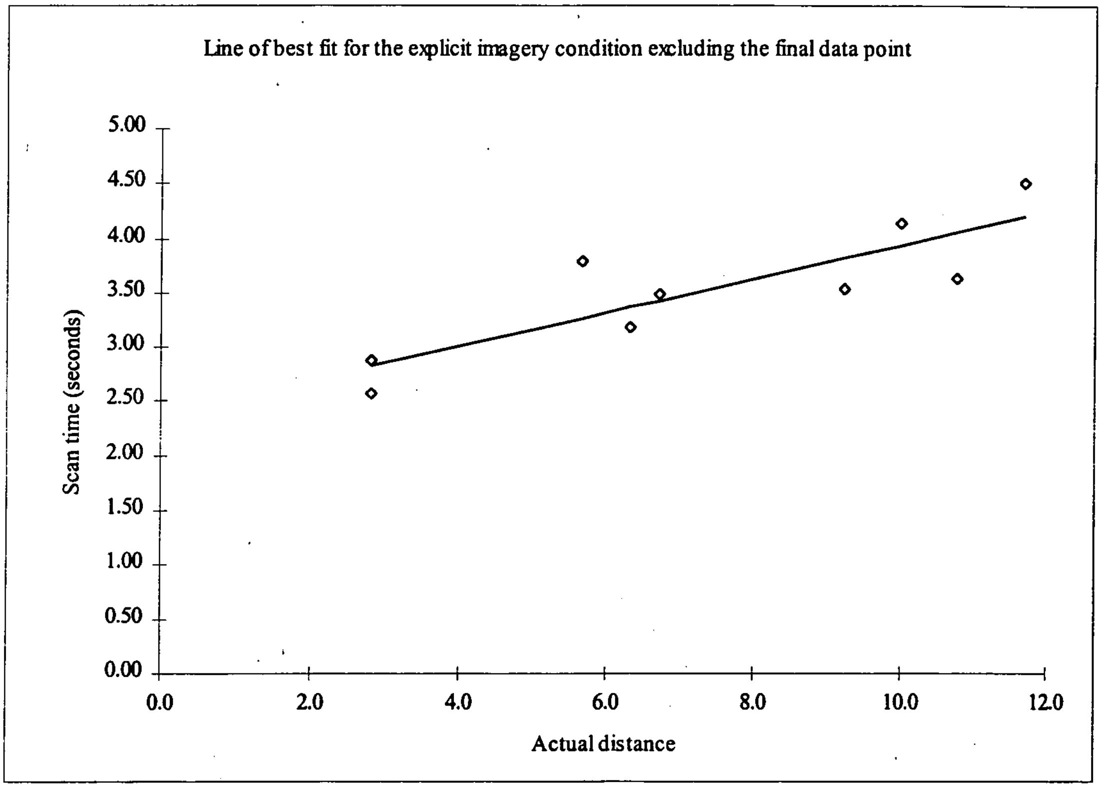



*Figure 5-17*

Again there is a clear linear relationship between the *distance to scan* and *time to scan* although the line of best fit is steeper when the final data point is omitted[20].

[20] The equation of the line being y = 2.38 + 0.16*x, that is, scan_time = 2.38 + 0.16*units_of_distance,

## Time to locate for the implicit imagery condition

Table 5-6 holds the mean times to 'locate' (in seconds) together with the actual object to object distance in units.

| | J1 | J2 | J3 | J4 | J5 | J6 | J7 | J8 | J9 | J10 |
|---|---|---|---|---|---|---|---|---|---|---|
| mean time | 3.4 | 2.8 | 4.0 | 3.0 | 2.1 | 2.8 | 2.9 | 3.7 | 2.8 | 2.6 |
| distance | 2.83 | 2.83 | 5.66 | 6.32 | 6.71 | 9.22 | 10.00 | 10.77 | 11.70 | 13.15 |

*Table 5-6*

A Spearman's rank correlation on the overall mean time to locate and the actual distance, produces a value of $r = -0.17$ which indicates the absence of a correlation[21] between the time to locate and inter-object distance. This finding does not support the hypothesis that imagery is the preferred medium for making judgements of distance within virtual environments.

These finding compared with Kosslyn *et al.* It is clear from these data, that the overall time to locate the second named object from the first does not monotonically increase with the increased distance between objects. Furthermore, this is also consistent with Kosslyn *et al*'s findings that in the absence of explicit instructions to use imagery, that a faster, non-imagery based cognitive manipulation is employed by subjects.

[21] For the sake of completeness, if like the imagery condition, the last data pair is omitted and the correlation recalculated a value of $r = -0.034$ is found, which again indicates an absence of a correlation between the distance to estimate and the time to locate the second object from the first.

## Verbal reports

After each experiment in the no-imagery condition, subjects were asked to describe how they had carried out that their tasks. A summary of their replies are as follows:

| Subject | Protocol |
|---|---|
| $S_1$ | Subject 1 employed image scanning using the purple panel as focus and frame of reference Distance estimates were just that, not being informed by a conscious calculation. |
| $S_2$ | Subject 2 did not form an image. Instead the subject knew the relative location of each objects in the form, 'A is to the right of B'. |
| $S_3$ | Subject 3 employed image scanning as (Subject 1). |
| $S_4$ | Subject 4 described using a picture formed in his head, facing the red panel and then moving from the red panel to the first, named object. Distance estimates involved Pythagorus' theorem and then estimating square roots. |
| $S_5$ | Subject 5 knew the relative position of each object with respect to the immediately adjacent wall. Subject 5 also formed an image. |

Interestingly in four of the five post-experiment debriefings, subjects claim to have used imagery. Either, their reports are in error, or are post-experiment rationalisation or the images formed of virtual environment are non-veridical.

## Scan times for the explicit versus implicit imagery conditions

Comparing mean times in both conditions with an independent *t*-test: $t(18) = 1.897$, $p < 0.075$ which indicates a possible (though not statistically reliable) difference between conditions. This results suggests that the implicit imagery group are faster at locating the second named object from the first than the explicit imagery group. This may also be taken as further evidence that the implicit imagery group, despite their post-experimental reports to the contrary, are *probably* not using imagery to locate objects 'within' their cognitive representation of the virtual space they have explored. These results are again consistent with Kosslyn *et al*'s findings.

## In summary

This experiment has found evidence that when subjects are explicitly instructed to construct an image of the virtual environment they have just explored that they do so, and are able to scan across the image from feature to feature. Whether this is used to estimate distances within that virtual environment remains equivocal. However, if subjects are not so instructed, despite their post-experimental claims to the contrary, they employ some other means of locating one object from another. These results broadly agree with reported experimental evidence, namely, that e.g. Kosslyn *et al*, and other have been able to show a simple linear relation between image scanning times and distance to scan. However it is not clear whether this linear relationship holds for all distances scanned across such an image especially at extremes or boundary conditions.

## Distance estimates for the explicit and implicit imagery condition

Table 5-7 holds the mean signed and unsigned errors incurred in judging the inter-object distances.

| | Mean explicit signed error | Mean implicit signed error | Mean explicit unsigned error | Mean implicit unsigned error |
|---|---|---|---|---|
| Subjects | 1.47 | 1.79 | 1.38 | 1.56 |

*Table 5-7*

Comparing the explicit with the implicit signed errors: $t(8) = -0.45$, for the signed errors, $t(8) = 0.30$. These results clearly indicate the absence of reliable differences between the magnitude of the errors.

## The 'time to estimate' for the explicit imagery condition

Table 5-8 holds the mean time to estimate inter-object distances. All times are in seconds, and distances are in 'units of distance'.

| | J1 | J2 | J3 | J4 | J5 | J6 | J7 | J8 | J9 | J10 |
|---|---|---|---|---|---|---|---|---|---|---|
| mean time | 2.90 | 3.68 | 3.56 | 3.26 | 4.38 | 4.39 | 4.55 | 4.25 | 4.52 | 3.17 |
| distance | 2.83 | 2.83 | 5.66 | 6.32 | 6.71 | 9.22 | 10.00 | 10.77 | 11.70 | 13.15 |

*Table 5-8*

A Spearman's rank correlation on the mean image scanning times and the actual distance, produces a value of $r_S = 0.391$, which indicates a low level of correlation and as such does not merit regression analysis. Table 5-9 holds the sum of the mean scan times <u>and</u> the time to estimate and the actual distance:

| | J1 | J2 | J3 | J4 | J5 | J6 | J7 | J8 | J9 | J10 |
|---|---|---|---|---|---|---|---|---|---|---|
| combined time | 2.9 | 3.7 | 3.6 | 3.3 | 4.4 | 4.4 | 4.6 | 4.3 | 4.5 | 3.2 |
| distance | 2.83 | 2.83 | 5.66 | 6.32 | 6.71 | 9.22 | 10.00 | 10.77 | 11.70 | 13.15 |

*Table 5-9*

A Spearman's rank correlation on the combined times and the actual distance, produces a value of $r_S = 0.561$, which is *very nearly* statistically reliable (critical value = 0.564), and if the final data point is omitted, a value of $r_S = 0.81$ which is statistically reliable, $p < 0.05$. Such a high level of correlation does merit regression analysis.

Figure 5-18 illustrates the line of best-fit omitting the final data point.

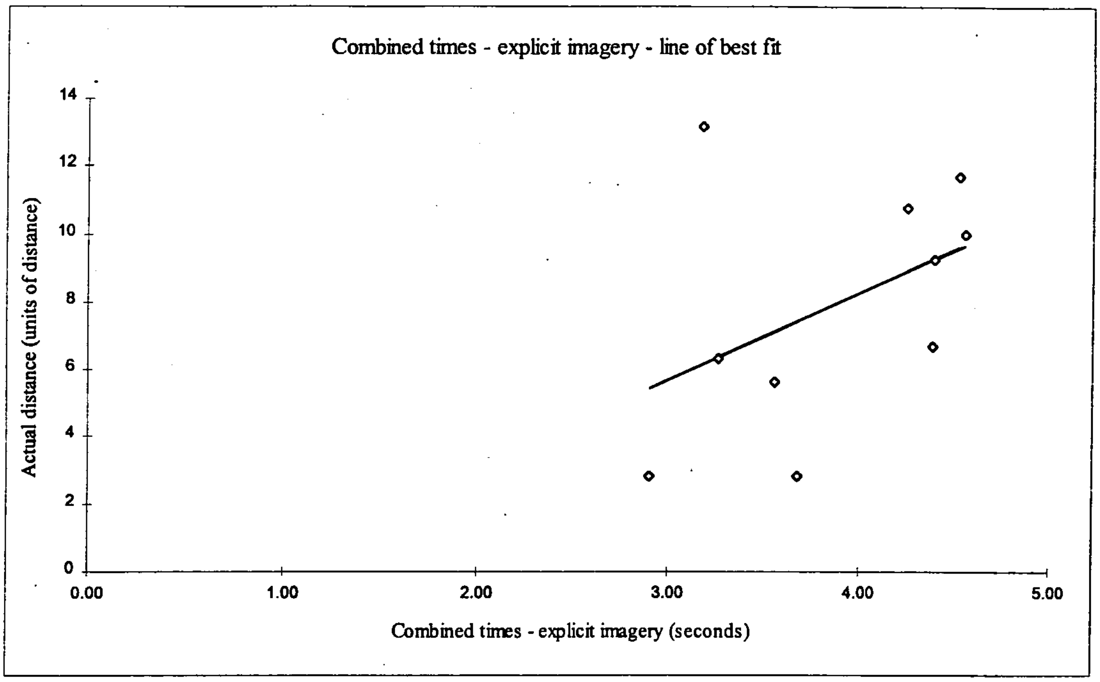



*Figure 5-18*

From this figure it is quite clear that there is evidence of a linear relationship between the combined scan time and time to locate and the actual distance[22].

## The 'time to estimate' for the implicit imagery condition

Table 5-10 holds the mean time to estimate inter-object distances. All times are in seconds, and distances are in 'units'.

| | J1 | J2 | J3 | J4 | J5 | J6 | J7 | J8 | J9 | J10 |
|---|---|---|---|---|---|---|---|---|---|---|
| mean time | 4.4 | 4.0 | 3.4 | 3.6 | 4.3 | 4.9 | 5.0 | 5.7 | 4.6 | 3.8 |
| distance | 2.83 | 2.83 | 5.66 | 6.32 | 6.71 | 9.22 | 10.00 | 10.77 | 11.70 | 13.15 |

*Table 5-10*

A Spearman's rank correlation on the mean image scanning times and the actual distance, produces a value of $r = 0.40$, which again indicates a low level of correlation and as such does not merit regression analysis.

22 The equation of the line of best fit is: overall_time = -9.97 + 4.39* distance_scanned.

### Comparing the 'time to estimate' for the two imagery conditions

Comparing these times with an ANOVA, a value of $F(1,18) = 4.41$ is found. This result indicates that the mean times to estimate distance are not reliably different between conditions.

## 5.3.5 Discussion of results

In all, despite subjects' post-experimental protocols to the contrary, and the informal observation of prior experiments, these results agree with Kosslyn *et al*'s findings sufficiently well to suggest that when subjects are instructed to use imagery in these circumstances, they do so, but left to their own devices they do not. Not only is there a linear relationship between time to scan and distance to estimate, but the use of imagery is more time consuming than employing a non-imagery based strategy. However, the separation of scanning time from distance estimation time appears to have been meaningful, and there is no reliable difference between the groups, further suggesting a cognitive dislocation between image scanning and the process of distance estimation. Finally, irrespective of how individuals estimate distances, both groups are equally accurate.

## 5.4 General discussion of experiments VI, VII and VIII

### Direct and indirect exploration

Introducing a level of indirection into the experience of an environment produces less accurate distance estimation of inter-feature distances. It is not clear why this should be necessarily so as the exploration of non-immersive virtual environments consists of manipulating the viewing point rather than moving the explorer / observer. The two differences between the direct and indirect conditions were firstly, in the latter condition the subjects were required to vocalise their instruction to move the point of view on the virtual environment. However this, if anything, may have assisted the subjects (possibly as verbal labels, e.g. Maki and Braine, 1985) in remembering spatial locations. Secondly, it seems very unlikely that the kinaesthetic feedback from pressing the cursor keys on the PC's keyboard in the direction exploration condition would have contributed very much information to, say, the subjects' sense of inertial navigation.

### Whither clutter?

Both experiments VII and VIII failed to find evidence for the role of clutter either in the form of obstructing walls (experiment VI) or a series of right-angle turns (experiment VII) in producing reliable over-estimations of distances. To the contrary, evidence was found for distinct but not statistically reliable under-estimation of distance. This finding is consistent with the pattern of distance estimation presented in chapter 4, experiment 5. However some evidence was found for over-estimation of distance when routes had not have a general linear East-West progression and instead turned back on themselves (experiment VII).

### Image scanning

Analysis of the data from experiment VIII lends support to the following:

- People can form images of explored virtual environment if explicitly told to do so and are able to scan them. This adds virtual environments to the list of media which can give rise to images - Kosslyn *et al* (1978) - pictures and maps, Denis and Cocude (1989) - textual descriptions.
- If people are explicitly instructed to form and then scan an image generated from exploring a virtual environment, there is a linear relationship between distance to scan and time taken to scan, again replicating the findings of, for example, Kosslyn *et al* (1978).

- Distance estimation and image scanning are not necessarily synonyms. The pre-experiment pilot suggested that distance estimation and image scanning, at least for virtual environments, were separate operations, and this suggestion was confirmed in the experiment proper.

# 6. Discussion

## 6.1 Introduction

The eight experiments reported in the preceding chapters were conducted with the aim of answering the question, 'Is spatial knowledge acquired from exploring virtual environments more like spatial knowledge acquired directly from the environment (i.e. primary spatial knowledge) or rather does it have the characteristics of spatial knowledge acquired from maps and figures (i.e. secondary spatial knowledge)?'. The methodology adopted was one of distance and angle estimation.

## 6.2 The estimation of angles in virtual environments

### Angle estimation in experiments I, II, III, IV and VII

The first four experiments[23] investigated the nature of the spatial representation acquired from exploring a virtual environment by requiring of subjects a series of judgements of angles between features in that environment. Throughout these four experiments the subjects had been required to adopt an imagined ego-centric frame of reference when making judgements of inter-feature angles. An ego-centric frame of reference is usually defined as one which is based about the representing individual. This is a three-dimensional co-ordinate system wherein objects are located in terms of *in front of, to the right or left,* or *above or below* the individual (e.g. Bryant and Tversky, 1992). An imagined ego-centric frame of reference is at a remove in that the subject is required to generate an image of the virtual environment and then adopt a view point from within that image which resembles a true ego-centric frame of reference.

To ensure the adoption of this frame of reference by the subjects the following instructions were common to these four experiments (minor variants permitting):

*'imagine you are standing with your back to the XXX panel facing due North (i.e. 0°). Estimate (i.e. say aloud) the angle from the XXX panel to the YYY panel. (Where XXX and YYY will be one of the n panels.)*

The one exception to this was experiment III, which involved subjects making judgements of angles while actively exploring virtual environments, so that the instruction to *imagine* was

[23] Together with a part of experiment VII.

omitted. Therefore in addition to the ego-centric frame of reference, the use of imagery in these experiments has been quite explicit.

## Experiment I

Experiment I was a pilot in that it attempted to establish the feasibility of a series of experiments based around the theme of investigating spatial cognition derived from exploring virtual environments. To this end it employed a virtual reality game - *Doom*. Subjects were asked to explore the first level of *Doom*. Subsequent to this exploration they were asked to make a number of judgements of inter-feature angles from this first level of *Doom*. The judgements were from two different starting points to four other locations. The accuracy of the judgements of angles were compared and not found to be reliably different. In addition to this finding there was clear, though not statistically reliable, evidence for an anti-clockwise bias in the judgements of angles which was unexpected. Experiment I also compared the incidental and intentional learning of the spatial configuration of the virtual environment. Again no differences were found in the accuracy of the judgements which is consistent with other comparisons of incidental and intentional spatial learning (e.g. Kozlowski and Bryant, 1977; Mandler, Seegmiller and Day, 1977; Brewer and Treyens, 1981).

The two key findings from this pilot experiment, namely the viability of this approach to the estimation of inter-feature angles and the anti-clockwise bias, then formed the basis of the remaining three experiments of this first half of the investigation.

## Experiment II

Experiment II further investigated the finding that the judgements of angles in a virtual environment appear to have an anti-clockwise bias. In contrast to the first experiment, experiment II and all subsequent experiments employed a virtual reality construction kit - ACK3D - which enabled especially designed 'three dimensional' non-immersive virtual environments to be created.

Experiment II did find evidence for a reliable ($p < 0.06$) anti-clockwise bias in the judgements of inter-feature angles for one of the two virtual environments explored, namely the 'left-oriented' but not in the 'right-oriented' virtual environment. However this effect was greatly reduced when errors greater than 90° were excluded.

## Experiment III

Experiment III was designed to investigate the accuracy of judgements of inter-feature angles while actively exploring virtual environments and thus establish a baseline against which the judgements of angles made from memory could be compared. The experiment had two conditions. The first of which was so designed that one set of judgements were made of features which were *in the line of sight* of each other. The second condition was designed so that the features were *out of the line of sight* of each other being obscured by an intervening 'wall', thus the judgements made of features which were *out of the line of sight* of each other required the subject to remember the location of at least one of the obscured features. In contrast judgements which were made of features which were *in the line of sight* of each other did not require the use of memory to make the estimate.

The results of this experiment indicated that the signed errors in the *out of the line of sight* condition proved to be slightly larger than those errors made in the *in the line of sight* condition, as expected, but this effect was not statistically reliable. However this effect was also observed in the unsigned errors which did prove to be statistically reliably, $p < 0.05$.

## Experiment IV

Experiment IV addressed the question of whether spatial knowledge acquired from exploring a virtual environment shows the same orientation specificity as knowledge acquired from studying maps or figures. Orientation-specificity has been usually defined thus: judgements of angle made in the same orientation as the orientation in which the spatial knowledge was acquired are made more accurately (e.g. Levine, Jankovic and Palij, 1982; Presson and Hazelrigg, 1984) and more quickly (e.g. Loftus, 1978; Evans and Pezdek, 1980) than those which are counter-aligned or non-aligned with the learning orientation. However for this experiment the orientation-specificity was operationally defined in terms of a distinctive pattern of errors: *(i) the smallest error in making a judgement being at 180° to the largest error and (ii) the intermediate errors being at right angles to the smallest and largest errors.*

Upon analysis, evidence for this pattern of errors and thus orientation-specificity in the cognitive representation of the spatial configuration of the virtual environments was found in a number of the conditions.

Experiment IV also considered the integration of multiple view points in virtual space to form a perceptual / conceptual whole. It was suggested that subjects would construct an overall model or map of a virtual environment by integrating the orientation and location of the landmarks in turn by a series of mental rotations. Those landmarks, initially out of sight, would be integrated sequentially with the contents of the scene either immediately visible or in memory. This component of the experiment recorded the free exploration time and compared it with the number of landmarks visible at any one time. It was found that rank correlating the number of landmarks with the free study times obtained a value of $r_S = 0.8$, which while not being statistically reliable[24] does suggest that free study times *tend* to increase monotonically with the number of landmarks to integrate.

## Experiment VII (second hypothesis component)

Although experiment VII's principal focus was an examination of the role of clutter in distance estimation, it also tested Moar and Bower's (1983) observation that judgements of angles tend to systematicity, that is, angles tend to be judged closer to a multiple of 90° than their true value. In this experiment subjects were asked to traverse a number of virtual corridors and then judge the 'start-to-end' angle.

Evidence was found for systematicity in those corridors which turned in on themselves but no such evidence was found in those corridors which had an East-West linear progression.

24 The number of data pairs was only 4.

## 6.3 The findings: angle estimation

### 6.3.1 Angle estimation: an anti-clockwise bias

Experiments I, II, and III reported evidence for an anti-clockwise bias in the direction of the judgements of inter-feature angles out of sight, although when errors greater than 90° were excluded the magnitude of this bias greatly diminished. In contrast it was found in experiment III that when subjects were asked to judge the angle between two features which were in plain view of each other, they tended to bias their judgements in a clockwise direction by approximately 20°.

These results point to two key questions. Firstly, 'How big is the anti-clockwise bias?' and secondly, 'What is the role of memory in this anti-clockwise bias?'. As to the first question, the range of the mean signed errors in experiment I - III was -7.6° to -22.1° - see table 6-1 below. (It should be noted that the data from experiment III condition *in the line of sight* have not been included as these judgements were not made from memory.) Yet this range may be an under-estimate of the strength of the effect given that there appears to be an inherent clockwise bias in making judgements of angles when the features are in plain view. If this is so, the effect may then be as strong as 25° - 45°. This clearly needs further investigation. As to the second question and the role of memory in this apparent anti-clockwise bias:

### Symmetry

Tversky (1981) has reported that remembering one spatial location with respect to another can lead to distortions of direction. Tversky has found alignment errors, that is, features were both recalled and recognised as being more closely aligned than they actually were in a range of spatial tasks including judgements of directions between cities; judgements in subjects' local environment; in memory for Tversky attributes these errors to two heuristics found in models of perceptual organisation. The first is alignment whereby figures are lined up relative to one another due to their mutual proximity. The second is rotation where the natural axes induced by a figure converge with frame axes (North-South, East-West, or horizontal-vertical), a phenomenon which Tversky believes is related to the Gestalt 'law' of perceptual organisation by common fate, artificial countries and maps, and in memory for blobs not interpreted as maps. However despite this evidence it does not seem to offer an account of the systematic directional distortion reported here.

## Systematicity

Systematicity (e.g. Moar and Bower, 1983) which is the reported tendency to recall angles as being nearer a multiple of 90° and appears to be essentially a variant on the above observations and may be ruled unlikely for the same reasons. However it should be noted that some evidence for systematicity was found in experiment VII but in slightly unusual circumstances. In experiment VII subjects were asked to judge the 'start-to-end' angle after traversing a number of virtual corridors. In the conditions where there was some evidence of systematicity those corridors turned in on themselves like a half-uncurled spiral, and it is perhaps this unusual feature which differentiates these results from a more typical linear judgement.

## Availability

There is some evidence to suggest that some judgements of orientation and angle are more *available* than other, and this differential availability of spatial information may be account for the anti-clockwise bias. For example, right-left, East-West has been shown in many experiments to be more difficult to discriminate than up-down, front-back (e.g. Farell, 1979; Just and Carpenter, 1975; Maki, Maki and Marsh, 1977; Maki and Braine, 1985). Loftus (1978) found that if directions were presented as a simple number (e.g. 310°), then a monotonic increase in reaction time to draw the direction was observed as the value increased; however, if the directions were presented visually, angles close to North and South (±10°) were significantly more quickly responded to / processed than angles close to East and West. Similarly Maki *et al* (1977) have demonstrated the effects on reaction time for both memorised familiar (e.g. maps of the US states), abstract locational (e.g. 'left of', 'above', etc.) and orientational (vertically versus horizontally oriented) stimuli. Furthermore Franklin and Tversky (1990) have found that reaction times for reporting the location of objects which had been described in a body of text which the subjects had read depended upon the orientation of their bodies. When subjects were standing, reaction times were fastest for reporting objects which were located beyond the subject's head / feet, yet when the subjects were reclining front / back were fastest.

While there is no doubt that right-left, East-West judgements do take longer than front-back, North-South and do appear to be less available to subjects, this does not offer a full account of why there should be a difference between clockwise and anti-clockwise.

Finally, returning briefly to point to Maki (1979) who has argued that whatever causes right and left to be difficult to discriminate also causes East - West to be difficult (and perhaps by extension clockwise and anti-clockwise directions). Maki goes on to assume that the difficulty of discriminating right-left is related to the right-left symmetry of the body, citing Corballis and Beale, 1976; Nicoletti *et al*, 1988 as evidence.

## Handedness

Of the pool of approximately 50 people who participated in these experiments only two were found to be left-handed, and none were ambidextrous (this information was sought informally some time after the experiments had been conducted). It is not unreasonable to suppose that this predominance of right-handed subjects may have been a factor in the observed anti-clockwise bias and is certainly worthy of further research.

## Mental rotation

It will be recalled that subjects were explicitly instructed to make use of imagery in making their judgements of angles and while it is recognised that it cannot be stated with absolute confidence that this was the sole means by which subjects made judgements and that if imagery was employed it was not supplemented by some other form of representation or mechanism, subjects did informally report that they had formed images. Given that imagery was being used then mental rotation is the prime suspect for the source of this directional bias (e.g. Shepard and Metzler, 1971; Shepard and Hurwitz, 1983). For example, Denis (1991, p.57) has observed that in the standard Cooper and Shepard mental rotation experiments that the natural direction of mental rotation appears to be anti-clockwise. This feature of mental rotation may then account for, or contribute to, the above observation in that there may be something inherent in the mechanism of mental rotation itself which produces an anti-clockwise bias. Furthermore the presence of an anti-clockwise bias is consistent with Kozlowski and Bryant's (1977) findings that when subjects are asked to point at familiar building which is out of sight they tend to point to the left of (that is, *anti-clockwise of*) the actual locations of the buildings. They also found that the magnitude of these anti-clockwise errors tend to increase if made by individuals who, by self-report, had a poor sense-of-direction.

## In conclusion

On the balance of evidence the mechanism of mental rotation is the most likely cause of the anti-clockwise biases reported in experiments I, II and III.

### 6.3.2 Angle estimation: orientation-specificity

Experiment IV presented some evidence for the pattern of errors associated with orientation-specificity in judgements made after exploring virtual environments. It will be recalled that orientation-specificity has been operationally defined by the pattern of: (i) the smallest error in making a judgement being at 180° to the largest error and (ii) the intermediate errors being at right angles to the smallest and largest errors. As the presence of orientation-specificity is taken to be characteristic of secondary spatial knowledge, that is, spatial knowledge acquired from representations of space (for example, Evans and Pezdek, 1980; Levine, 1982; Levine, Jankovic, and Palij, 1982; Presson and Hazelrigg, 1984; Presson, McAdams and DeLange, 1987[25]; Rossano and Warren, 1989), a conclusion might be that spatial knowledge acquired from virtual environments indeed has the characteristics of secondary spatial knowledge.

### Orientation-specificity and *preferred direction*

In practice, however, it has proved to be very difficult to distinguish between orientation-specificity and what Shepard and Hurwitz (1983) and Sholl (1987) describe as the *preferred direction* which is a characteristic of (primary) spatial knowledge which has been acquired from exploring the real world. It therefore may then be concluded that although the issue of orientation-specificity initially appeared to be a useful way of determining whether spatial knowledge acquired from exploring virtual environments is more like that which is acquired from the environment or from representations of the environment in practice it is very difficult to say whether the pattern of errors observed in experiment IV are more properly associated with orientation-specificity or *preferred direction.*

### 6.3.3 Angle estimation: comparing errors

The errors incurred in these experiments may be compared in a number of ways. Firstly, the percentage of errors falling within 10° of the actual value which have been operationally defined as 'accurate' could be compared with other empirical evidence; secondly, the percentage of errors greater than 90° of the actual value which have been operationally defined as 'inaccurate' could again be compared with other reported evidence; and finally, the mean signed and unsigned errors could be similarly compared. However as discussed in chapter 1, section 1.3.6 there are only a very small number of studies of the accuracy of judgements of

[25] Cited in Presson *et al*, 1989, p. 896.

angles[26]. Of such studies those that there are tend to report directly or indirectly mean errors incurred in making judgements of angles and these will be compared with the findings from experiments I, II, III, IV and VII.

Table 6-1 holds a summary of the signed and unsigned mean errors from experiments I, II, III, IV and VII. Table 6-2, in contrast, holds data from experiments conducted by Kozlowski and Bryant (1977); Thorndyke and Hayes-Roth (1982); and Moar and Bower (1983).

| Source | Mean signed errors | Mean unsigned errors |
|---|---|---|
| Experiment I | | |
| – Intentional learning condition | -14.5° | 35.4° |
| – Incidental learning condition | -14.6° | 37.2° |
| Experiment II | | |
| – Right-oriented environment condition | 1.3° | 27.9° |
| – Left-oriented environment condition | -27.2° | 43.5° |
| Experiment III | | |
| – In the line of sight condition | -6.0° | 43.3° |
| – Out of the line of sight condition | 9.1° | 41.7° |
| Experiment IV | | |
| – 4 landmarks visible (condition 2a) | 11.7° | 34.7° |
| – 3 landmarks visible (condition 2b) | 14.5° | 26.0° |
| – 2 landmarks visible (condition 2c) | -0.7° | 23.5° |
| – 1 landmark visible (condition 2d) | -5.8° | 25.0° |
| Experiment VII | | |
| – condition 1a | -5.1° | n/a |
| – condition 1b | -38.1° | n/a |
| – condition 2a | 18.0° | n/a |
| – condition 2a | 0.5° | n/a |

*Table 6-1*

The following data has been gleaned from the very few published studies which tabulate their results. However it should be noted that only the data from Moar and Bower can reliably taken as being signed, and as to the other data it is impossible to say whether it is signed or unsigned.

[26]Levine (1980) reports that when *you-are-here* maps are inverted people go off in directions that were incorrect by in excess of 90° more than 25% of the time, and Goldin and Thorndyke (1982) have found that subjects in simulated navigation condition (subjects were shown a film) made significantly more errors in excess of 90° than those subjects in the real navigation condition.

| Source | mean errors |
|---|---|
| Kozlowski and Bryant, 1977 | |
| – good sense of direction | 10.79° |
| – poor sense of direction | 25.71° |
| | |
| Thorndyke and Hayes-Roth, 1982 | map learning |
| – judging orientation | 39.3° |
| – judging location | 16.9° |
| – judging orientation for simple routes | 41.5° |
| – judging orientation for complex routes | 38.5° |
| | navigation (free exploration) |
| – judging orientation | 22.1° |
| – judging location | 24.9° |
| – judging orientation for simple routes | 17.4° |
| – judging orientation for complex routes | 30.9° |
| | |
| Moar and Bower, 1983 | -11.4° - 37.5° |

*Table 6-2*

As statistical tests would be inappropriate on the above data, inspection alone must be relied upon. From inspection it is apparent that the magnitude of the signed errors incurred in making judgements from memory of inter-feature angles from virtual environments do not appear to differ from angle estimation in the real world. The only apparent difference is in the preponderance of anti-clockwise biased errors from experiments I - III, however this may be an artefact of the reporting practice in that only signed errors rather than both signed and unsigned errors appear to be more generally reported.

Turning to the unsigned errors, it was found that the mean errors varied between 25° and 45°. However a more interesting observation is that range of the mean signed errors in experiment I (both conditions), experiment II (left-oriented environment condition), experiment III (*out of the line of sight* condition), experiment IV (all conditions) and experiment VII (conditions 1a and 1b) is 31.6°- 45.1°, a window of only 13.5°. Such a narrow window of judgements[27] 31.6°-45.1° indicates that these results are very similar to those reported by Thorndyke and Hayes-

[27] The reasons for the exclusion are that:

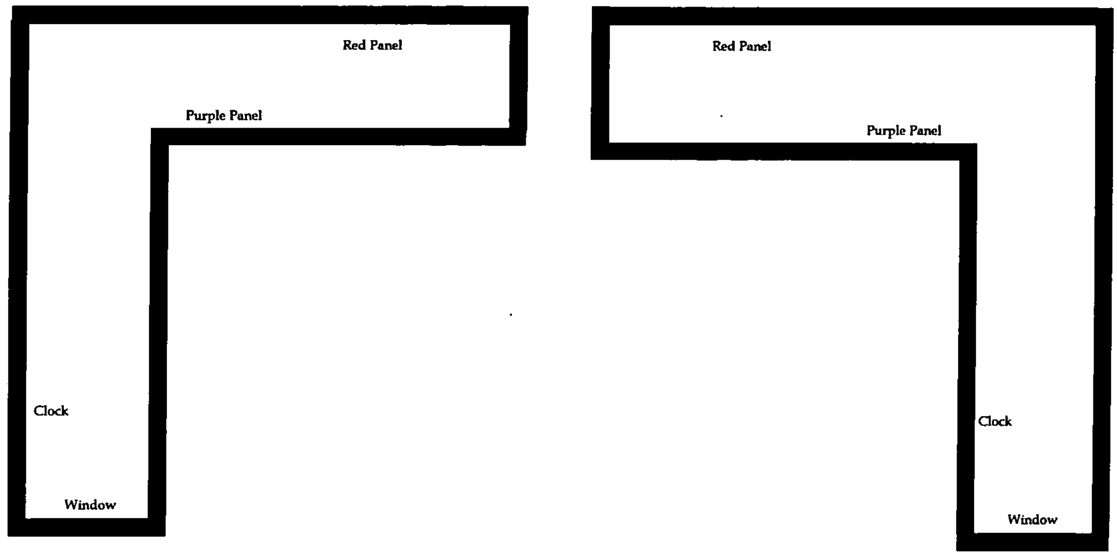
- experiment III (*in the line of sight* condition) the judgements are not made from memory;
- experiment II (right-oriented environment condition), the $F_2$ analysis of the judgements themselves revealed that they are not generalisable, and
- experiment VII (conditions 2a and 2b) the virtual corridors involved in these conditions turned back on themselves which is not a feature of the other experimental conditions.

Roth (1982) in their *simulated orientation task.* Thorndyke and Hayes-Roth found that when subjects were asked to imagine a pair of locations and to judge the angle between them, the mean errors were approximately 50° falling to approximately 25° with increasing experience. These errors were also found to be larger by 5° - 10° than when the subjects made the judgements while they were actually physically located in one of the pairs of rooms. Both sets of judgements were again found to improve in accuracy with increasing experience.

However, in conclusion, it must be noted that as the variety of different judgements from both the real and virtual environments is so great, further work is required in this area is required before any degree of confidence can be attached to the above observations.

### 6.3.4 Angle estimation: study and free exploration times

The free exploration times for the virtual maze conditions in this experiment were significantly larger than the free study times for the map conditions, a finding paralleling Taylor and Tversky (1992a). Taylor and Tversky found that found that it took subjects significantly longer to study and comprehend a route description of an environment than a survey description. The spatial information from the maps is immediately available: in contrast the virtual maze required exploration which necessarily takes longer but it may be that the route information acquired from this free exploration takes longer to learn that the corresponding survey knowledge. Indeed, exploration times rose with the increasing number of discrete landmarks to assimilate. Further work is again required to resolve this issue.




A plan view of the right-oriented virtual room. A plan view of the left-oriented virtual room.

*Figure 6-1*

However (anticipating the next section of this chapter) no such differences were found in experiments V, VI, VII or VIII where subjects were faced with distance estimation tasks.

### 6.3.5 The estimation of angles: in conclusion

These first four experiments have demonstrated that:

- asking subjects to judge inter-feature angles while adopting an imagined ego-centric frame of reference proved to be meaningful.
- subjects are at times prone to disorientation in that errors of 90° or more, which are taken to be indicative of disorientation, occur with a frequency of approximately 30% of all judgements. This is consistent with Goldin and Thorndyke's (1982) finding that subjects making judgements of angle in a simulated navigation condition (i.e. watching a film of a tour through an environment) tend to make more errors of 90° or more than subjects who had actually taken the tour.
- in excluding those errors in excess of 90°, the pattern and magnitude of the remaining errors are indistinguishable from the size of the errors reported elsewhere, excepted that (next point):
- there is a pronounced, and unexpected, anti-clockwise bias in the direction of the judgements for which mental rotation is an unproven but implicated mechanism.
- in trying to determine whether spatial knowledge acquired from exploring virtual environments showed evidence of orientation-specificity revealed that the boundaries between orientation-specificity and *preferred* direction are blurred. This test for orientation-specificity has failed to determine whether spatial knowledge acquired from exploring virtual environment is more like that which is acquired from maps or the real environment.

## 6.4 The estimation of distance in virtual environments

### A brief reprise of the findings

Complementing the four experiments which addressed the issue of the accuracy of angle estimation in a variety of different virtual environments, the final four experiments investigated distance estimation. Experiment V was a detailed investigation into inter-feature distance estimation; experiment VI examined the effects on distance estimation of direct and indirect exploration of virtual environments; experiment VII considered the effects of judging distances in cluttered environments, and finally experiment VIII contrasted distance estimation and image scanning.

### Experiment V

Experiment V paralleled part of Thorndyke and Hayes-Roth's (1978) investigation into the differences in spatial knowledge acquired from maps and from the environment, substituting virtual space for real space. Very briefly, Thorndyke and Hayes-Roth reported evidence that spatial knowledge acquired from exploring a building initially produced judgements of route distances between features (in practice these were rooms) which were more accurate than the equivalent Euclidean judgements but with experience both types of judgements improved and converged in accuracy. In contrast, spatial knowledge acquired from studying a map of the building produced more accurate Euclidean than route judgements, a difference which persisted despite over-learning.

Experiment V only *paralleled* certain aspects of Thorndyke and Hayes-Roth's experiment in that a virtual environment replaced a physical building, and that the map learning condition was modified. Of course, another fundamental difference lies with the free exploration conditions. Thorndyke and Hayes-Roth's subjects in these conditions were employees working in the building in question. The subjects in the current experiment were, necessarily, fleeting visitors to a virtual building which they explored either once or three times for a short period of time. The results of this experiment are then in three parts, (i) estimates from the map learning condition; (ii) from one period of exploration and (iii) from three periods of exploration of the virtual environment.

Thorndyke and Hayes-Roth reported that free exploration of an environment gave rise to more accurate route estimates than Euclidean estimates but that with extended exposure to the environment these difference to the accuracy tended to disappear. In contrast Thorndyke and

Hayes-Roth found that map learning gave rise to accurate Euclidean distance estimates and relatively inaccurate route distance estimates.

On the whole this experiment found evidence for the reverse of these patterns. Free exploration of a virtual environment gave rise to strikingly inaccurate route estimates (significant under-estimates) and relatively accurate Euclidean distance estimates. Repeated exposure to the virtual environment made no difference to this. As to the map learning condition only equivocal support could be found for the Thorndyke and Hayes-Roth position (their findings were confirmed by the analysis of the unsigned errors and contradicted by the signed errors).

## Experiment VI

Experiment VI investigated the accuracy of inter-feature judgements of distance while actively and passively exploring a *cluttered* virtual environment. To this end two virtual environments were designed one of which was cluttered thus obscuring a number of distinctive features. The clutter was implemented in the form of 'walls' around which subjects were required to manoeuvre. In the uncluttered room all features were in plain view of each other. Further to this the subjects explored the virtual environments in one of two ways: they either moved themselves around the virtual environments (the active, *hands-on* condition) or did so indirectly by issuing instructions to the experimenter to either move forwards, stop, back, to the right and so forth (the *passive, hands-off* condition).

There were two key findings with respect to the effect of clutter on distance estimation in virtual environments. Firstly, the presence of obstacles (intervening walls) does not induce the over-estimation of Euclidean distance which is characteristic of *clutter*. Instead it appears to induce under-estimation. Secondly, the presence of *clutter* tends to produce less accurate Euclidean distance estimates compared with estimates made from uncluttered virtual environments.

As to the modes of exploration, it was found that introducing a level of indirection into the experience of a virtual environment tends to result in less accurate estimates of inter-feature distances.

## Experiment VII[28] (first hypothesis component)

Experiment VII further investigated whether the *clutter* phenomenon produces over-estimations of both route and Euclidean distance judgements in virtual environments. To this end five virtual corridors were designed, two of which had five 90° turns, and a further two had eight 90°, the 90° turns were intended to produce *clutter* and finally a fifth completely linear control condition was included. The two corridors further differed in that one progressed in a East-West direction, the other turned in on itself. Subjects traversed all five corridors and were asked to estimate the route and Euclidean distances of each.

Evidence was found that while the mean route judgement for the 8-turn condition proved to be accurate, a statistically reliable under-estimate was found in the 5-turn condition. This result does not provide evidence for the presence of the clutter illusion. The position with the Euclidean estimates was less clear. The estimates in the 5-turn condition produced evidence of reliable over-estimations of the actual distances ($p < 0.05$), while the 8-turn condition did not. This finding runs contrary to expectations, given that the clutter effect is taken to be related to the number of turns (or obstacles) in a route. Overall, these findings did not suggest that clutter is a contributory factor in the errors made in estimating distances in virtual environments.

## Experiment VIII

Experiment VIII paralleled experiment 2 of Kosslyn, Ball and Reiser's (1978) image scanning study. Kosslyn *et al*'s seminal experiment is of particular interest as distance estimation has been assumed by some (e.g. Thorndyke and Hayes-Roth) to be intimately related to image scanning. Replacing Kosslyn *et al*'s picture of an island, a virtual room was designed which had two distinctive coloured panel and three free standing objects being these a treasure chest, a ceiling light and a television. Subjects explored this room and then were asked to estimate distances between features by whatever means they so chose or by constructing an image of the room and scanning from feature to feature.

Evidence was found that people can form images of explored virtual environments if explicitly told to do so and are able to scan them. This adds virtual environments to the list of media which can give rise to images - Kosslyn *et al* (1978) - pictures and maps, Denis and Cocude (1989) - textual descriptions. If people are explicitly instructed to form and then scan an image generated from exploring a virtual environment, then a linear relationship between distance to scan and time taken to scan holds, again replicating the findings of, for example, Kosslyn *et al* (1978). However if subjects are not explicitly instructed to form an image, no such relationship is found between the distance to estimate and the time it takes to estimate that distance. This

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[28] It should be noted that the second part of this experiment is discussed in section 6.2.

again is similar to Kosslyn *et al*'s findings. Distance estimation and image scanning are thus not necessarily synonyms.

Furthermore a pre-experiment pilot strongly suggested that distance estimation and image scanning, at least for virtual environments, were separate operations, and this suggestion was subsequently confirmed in the main experiment.

## 6.5 The findings: distance estimates

### 6.5.1 Distance estimation: the independence of the Euclidean estimates

The independence of the Euclidean estimates from route estimates is the most striking feature of the results from experiment V. Thorndyke and Hayes-Roth had suggested that route judgements plus 'mental algebra' are used to produce estimates of Euclidean distances, clearly arguing for the dependence of Euclidean estimates on route estimates. Yet results from experiment V have demonstrated that route judgements are systematically inaccurate (increasingly so as the distance to estimate increase) while the Euclidean judgements are relatively accurate and appear to be affected by the distance to judge. As accurate Euclidean judgements cannot be consistently made from inaccurate route judgements they must have been arrived at independently. Furthermore, as there is abundant evidence to suggest that routes are learned first and are later integrated into a more map-like representation (e.g. Cohen and Cohen, 1985), it is difficult to understand how the Euclidean judgements are more accurate than the route judgements.

Accurate Euclidean judgements and inaccurate route distance judgements are consistent with map learning, and this further suggests that when subjects make judgements of Euclidean distances they do so by generating an image of the virtual environment and scan that image to 'read off' the Euclidean distance. Judgements of route distances, in contrast, may be made by adding together the legs of virtual distance traversed. Why different strategies are used is not clear and is worthy of further investigation.

As to the cognitive representation of distance information: if Euclidean distance information can be read off an image it may then be assumed to be stored as an analogue of the actual distance whereas route distance information may be stored as a series of propositions. However, the arguments over whether imagery is one or two modes of representation (Paivio, 1975, 1977); whether it is a mode of representation at all (Pylyshyn, 1973) or whether it is an integral part of representation (Kosslyn *et al*, 1977) must be recognised, though it will not pursued here. Nonetheless this is also clearly worthy of further research.

### 6.5.2 Distance estimation: correlations

Statistically reliable negative correlations between the signed route judgements errors and the actual route distances were found for both free explorations of the virtual environment and the map condition. Furthermore when the lines of best fit were plotted for the signed errors against the actual distances the clear linear nature of their relationship was found. These relationships did not hold for the unsigned errors. In contrast, no such reliable correlations or linear agreements were found between the signed and unsigned Euclidean judgements errors and the actual Euclidean distances.

These findings are further confirms the independence of the process by which route and Euclidean judgements are made. However, they also pose a difficulty. Studies of subjects' use of visual imagery have demonstrated that the time to scan across a visual image increases linearly with the length of the scanned path (Kosslyn, 1973, 1978; Kosslyn, Ball and Reiser, 1978). This finding is clearly consistent with the route errors but not the Euclidean errors, despite the belief that Euclidean judgements are made by this very mechanism (e.g. Thorndyke and Hayes-Roth, 1982).

### 6.5.3 Distance estimation: No improvement in accuracy with practice

Experiment V failed to find the improvement in the accuracy of judgements of distance predicted by Thorndyke and Hayes-Roth. Indeed while no evidence was found in the route judgements with increased exploration, the accuracy of Euclidean distance estimates actually decreased. Although both findings are counter-intuitive, support for the findings of this experiment comes from a series of experiments reported by Kozlowski and Bryant (1977)[29] - experiment 3 specifically. In this experiment they led subjects through a windowless maze, measuring 3 metres high by 2 metres wide, illuminated by lights every 2 - 3 metres. The subjects had been misleadingly told that this was a time-estimating exercise, but on being led back to the beginning of the maze were asked to make a number of estimates including draw an arrow leading back to the end of the maze and both the Euclidean and route distance travelled. The route was travelled a further four times and a further three measures taken. Kozlowski and Bryant noted that the error in both Euclidean and route distance estimates <u>did not significantly differ as a function of trials</u>.

### 6.5.4 Distance estimation: comparing errors

Unlike the estimation of angles there is a much wider range of distance estimate data available for comparison with the results of experiments V, VI, VII and VIII. However the issue of which of these data to use for a comparison is not clear cut. Distance estimation has been variously studied in the laboratory using psycho-physical methodologies (e.g. Kerst and

[29] A component of this experiment, the angle estimation, has already been cited in experiment I.

Howard, 1978; Baum and Jonides, 1979; Nelson and Chailkin, 1980); estimates have been elicited from memory of environments directly familiar to the subjects (e.g. Thorndyke, 1980; Thorndyke and Hayes-Roth, 1982); and from memory of maps and other sources of information (e.g. Kerst and Howard, 1978; Tversky, 1993). So given this diversity it is difficult to determine which is the most appropriate data set to use as a basis for comparison. However: data from the study of maps (and other sources such as TV, film, textual descriptions and so forth) will not be used because of the multi-modal nature of this information, that is, Tversky's *cognitive collage* observation. This leaves the psycho-physical data and estimates have been elicited from memory of environments directly familiar to the subjects. However even given these potential sources none are suitable as a basis for comparison.

### 6.5.5 Distance estimation: little evidence for the effects of clutter

Both experiments VII and VIII failed to find evidence for the role of clutter either in the form of obstructing walls (experiment VI) or a series of right-angle turns (experiment VII) in producing reliable over-estimations of distances. To the contrary, evidence was found for distinct but not statistically reliable under-estimation of distance. This finding is consistent with the pattern of distance estimation presented in chapter 4, experiment V. However some evidence was found for over-estimation of distance when routes had not have a general linear East-West progression and instead turned back on themselves (experiment VII).

### 6.5.6 Distance estimation: image scanning

Analysis of the data from experiment VIII lends support for the following:

- People can form images of explored virtual environment if explicitly told to do so and are able to scan them. This adds virtual environments to the list of media which can give rise to images - Kosslyn *et al* (1978) - pictures and maps, Denis and Cocude (1989) - textual descriptions.
- If people are explicitly instructed to form and then scan an image generated from exploring a virtual environment, there is a linear relationship between distance to scan and time taken to scan, again replicating the findings of, for example, Kosslyn *et al* (1978).
- Distance estimation and image scanning are not necessarily synonyms. The pre-experiment pilot suggested that distance estimation and image scanning, at least for virtual environments, were separate operations, and this suggestion was confirmed in the experiment proper.

space. This point may be worthy of further research but it is outwith the scope of this discussion.

### 6.6.2 Generalising to other *non-immersive* virtual reality implementations

As interesting as these results are of most use if they can be generalised to other *non-immersive* virtual reality implementations. While it recognised that non-immersive virtual realities are highly diverse phenomenon by virtue of the differences in their implementation, they may all be characterised in the following key ways:

#### Non-immersive virtual reality as a picture

Figure 6-3 is an image taken from ACK3D which has been employed in most the experiments reported in this volume, and as can be seen presents the potential user with an interactive, self-luminous picture.

*Figure 6-3*


Figure 6-4 is an image from Superscape (a PC-based commercial virtual reality system) which again presents the user with an interactive self-luminous picture. Indeed it must necessarily be the case that all non-immersive virtual reality implementations have the same characteristic of an inter-active self-luminous picture displayed on a monitor screen or equivalent.

*Figure 6-4*

## Depth information

While the various instantiation of non-immersive virtual reality may monotonically preserve relative distances along the $x$ and $y$ axes, the $z$ axis remains hopelessly shallow.

## View points

Non-immersive virtual reality differs from plans, maps, projected images and other representations of space in that the view point on the virtual environment can be manipulated by means of an input device (such as cursor keys or a mouse) to produce different perspectives of the scene. Different instantiation of non-immersive virtual reality will, of course, differ along a number of key variables such as the type and sensitivity of the input device, the amount of detail and realism of the virtual environment, the display resolution, its refresh rate and physical size and so forth.

## Interaction with non-immersive virtual reality

Expanding on the last point, interaction with non-immersive virtual reality requires the person to be effectively motionless while the scene moves in response to the person's commands. This, of course, differs from Euclidean space where the person moves or is moved (in, for example, a vehicle) and the scene changes as a consequence. It also differs from studying a representation of space such as a map, when both the scene and the person are more or less static. And finally, interaction with non-immersive virtual reality differs from watching television or a motion picture where the scene does not respond to the watcher (not withstanding the promise of inter-active television).

## Virtual reality as a non-ecological environment

Finally unlike the real environment, virtual reality cannot, by definition, be perceived in an *ecological* manner (Gibson, 1961, 1979). As virtual reality is artificially generated it does not (but perhaps necessarily, cannot) contain information-bearing structured light which is central to Gibson's position. Instead non-immersive virtual reality systems relies upon a limited range of techniques to give the impression of depth:

- for position - texture, size and linear perspective;
- for parallax - binocular perspective;
- motion perspective; and so forth.

## In conclusion

From the above points it is clear that there is sufficient commonalities among current non-immersive virtual reality systems to conclude that it may be expected that interaction with such systems must be broadly similar.

### 6.6.3 *Immersive* virtual reality implementations

Having discussed whether the results of the experiments reported in this volume are generalisable to other implementations of non-immersive virtual reality it is worth briefly considering whether they can be further generalised to immersive virtual reality. Immersive virtual reality differs from the non-immersive variety in a number of important ways which are too numerous to review here but two of these differences may be considered.

- The style of interaction with immersive virtual reality is dramatically different from non-immersive virtual reality, *flying* being a favoured method with the former. Indeed the differences are so great that some users of such systems have experienced motion sickness.
- Immersive virtual reality requires the user to wear a HMD - a head mounted display which necessarily removes much of the information being received from the real world, so much so that a representation of the real world must be included in the virtual environment.

Given these difference it would be unwise to assume that the results can be generalised to immersive virtual reality.

## In conclusion

Therefore, from the above points it is clear that there are may not be sufficient commonalities among immersive virtual reality systems to conclude that these results are generalisable.

## 6.7 Further work

There are four broad and overlapping areas of interest with respect to further work in this area. Firstly, there is the need to address the issues arising from the eight experiments reported here. Secondly, there is the very important issue as to whether these results are generalisable across other *non-immersive* virtual reality implementations. Thirdly, which is an extension of the last point, is the question of whether these results are generalisable across *immersive* virtual reality implementations and finally, there remains the untested proposition raised in the last section as to whether there is a continuum from maps, relief maps, non-immersive virtual environments, immersive virtual reality, restricted Euclidean environments and the real world.

### 6.7.1 Issues arising

The following issues have been either arisen from the results of the experiments reported here or immediately suggest themselves as being relevant to this enquiry.

#### The anti-clockwise bias

There are a number of key questions with respect to this finding:

- the role of mental rotation in estimating angles, if any, needs to be tested and made explicit. Can estimates of inter-feature angles be made without recourse to mental rotation? Or is the bias an artefact of mental rotation coupled with an ego-centric frame of reference? Would instructing subjects to adopt an allo-centric frame of reference produce the same results?
- as the size of the anti-clockwise bias diminished when errors greater than 90° were excluded, is the bias primarily a function of disorientation?

#### Orientation-specificity or preferred direction

Although differentiating between orientation-specificity and preferred direction has proved to be very difficult if not impossible, it nonetheless remains an interesting field for further research. It would be useful to know whether a range of other media give rise to this phenomenon, particularly immersive virtual reality.

## De-coupling route and Euclidean distance estimation

There are perhaps three issues here, firstly, can the finding that Euclidean distance estimates are independent of route distance estimates be reproduced in other virtual environments and using other virtual reality implementations? Secondly, is route information being stored in a different (cognitive) format to Euclidean distance information and if so how? Finally, if route and Euclidean distance information are different and / or independent what are the consequences for the generally held models of the acquisition and sequence of spatial information?

## Relating real world spatial ability to virtual environments

Although evidence has been presented for subjects being able to estimate route and Euclidean distance and the angle between features after exploring a wide variety of virtual environments it cannot be taken as conclusive evidence for the role of spatial cognition proper. These results could, instead, be taken for evidence of mental arithmetic (plus some trigonometry) given that the virtual environments were very regular or alternatively these data could reflect a series of manipulations upon images generated by subjects of the environments they had explored. For example, Parker and Deborah (1992) have suggested that development of the ability to perform mental rotation maybe important for adaptation to many immersive virtual environments. They have found some evidence that training people to work in immersive virtual environments to perform mental rotation may enhance their performance both by increasing their ability to *locomote in* (their expression) and manipulate features of the environment and by reducing motion sickness associated with transitions between virtual and normal environments. Thus a promising avenue for further work would be to determine if there is a correlation between the various measures of spatial ability (e.g. the Guildford-Zimmerman Spatial Orientation test) with subject performance in a virtual reality system. While there is no agreed definition of spatial ability and it does remains to some extent an ill-defined concept, what is agreed upon is that spatial ability consists of a number of dimensions. The major dimensions and their definitions are as follows (after Satalich):

- Spatial orientation: involves the ability to move, manipulate or transform stimuli. These operations involve the cognitive manipulation of the representation of the stimuli centric frame of reference.
- Spatial visualisation: this refers to the manipulation of the relationships within a stimulus.
- Spatial relations: consists of the ability to form an image of an object from different perspectives.

If a strong positive correlation was found to hold between some or all of these various dimension it could then be concluded that it really is spatial cognition at work in a virtual environment.

### 6.7.2 Experimental design issues

Unhappily a number of design error were discovered in the experiments reported in this volume. Without exception they were the result of moving what should have been fixed landmarks between conditions. The key question to be addressed is then: 'what effect has this had?' The answer is relatively slight. None of the landmarks were moved by more than a graphic unit or two the effect of which being that the angles to be judged were changed by perhaps as much as 20°-30° at maximum. No angles differed by as much a quadrant which may well have had a distinct effect on the results.

How could this have been avoided? The simplest means would have been a careful, third-party review of the experimental design prior to running the experiment itself. A further compounding issue has been the use of automation in the analysis of the data. Judgements of angle and distance were entered directly into spreadsheets wherein the errors were automatically calculated and initial analyses performed. This 'distance' from the raw data may well have contributed to the late detection of the design errors described in chapters 2 and 5.

## 6.8 In conclusion

The key findings from these eight experiments are:

- estimates of inter-feature angles made from memory after exploring virtual environments tend to be biased in an anti-clockwise direction, although the size of the errors do not appear to differ from those made in the real world.
- the pattern of errors associated with estimates of inter-feature angles show some evidence of orientation-specificity or *preferred direction*.
- estimates of route distance tend to be systematic under-estimates and relatively inaccurate when compared with corresponding estimates of Euclidean distance. Route and Euclidean estimates also proved to be independent of each other.
- imagery may have an important role in the spatial cognition of virtual environments.

These findings suggest that non-immersive virtual environments may lie on a continuum. Figure 6-4 is one possible continuum wherein non-immersive virtual environments form a *bridge* between static representations of the environment and the environment itself.

maps

⇩

relief maps

⇩

non-immersive virtual environments

⇩

immersive virtual environments

⇩

restricted Euclidean environments

⇩

unrestricted Euclidean environments

*Figure 6-4*

Thus non-immersive virtual environments offer a potentially rich research environment for spatial cognition.

# 7. References

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# 8. Appendix A: experimental data

# 8.1 Experiment I

## Judgements (degrees)

| *Subject* | *Learning condition* | *1a* | *1b* | *1c* | *1d* | *2a* | *2b* | *2c* | *2d* |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Intentional | 0 | 0 | 43.5 | 90 | -180 | -90 | 225 | 0 |
| 2 | Intentional | -27 | 56 | 80 | 130 | 94.5 | -90 | 90 | 0 |
| 3 | Intentional | -90 | -90 | 43.5 | 137.5 | -146 | 179 | 235 | 0 |
| 4 | Intentional | | 0 | 43.5 | 180 | 180 | -137.5 | 138 | 0 |
| 5 | Intentional | 12.5 | 75 | 76 | 70 | -105 | -90 | 270 | 0 |
| 6 | Intentional | -90 | 0 | 0 | 45 | | | | |
| 7 | Intentional | -46 | | | | 122 | -60 | 180 | 0 |
| 8 | Intentional | 45 | 30 | 56 | 127 | -144 | -165 | 180 | 0 |
| 9 | Intentional | 180 | -90 | 0 | 0 | -90 | 90 | 180 | 0 |
| 10 | Intentional | -37 | -142 | -34 | | | | | |
| 11 | Incidental | -134 | -108 | -32 | 0 | 180 | -90 | -60 | 0 |
| 12 | Incidental | 0 | 90 | 180 | 180 | 180 | 90 | 180 | 0 |
| 13 | Incidental | -93 | -18 | -38 | | | | | |
| 14 | Incidental | -43 | 138 | 43 | -142 | 44 | 0 | 90 | 0 |
| 15 | Incidental | -18 | 32 | | | | | | |
| 16 | Incidental | -90 | -41 | | | | | | |
| 17 | Incidental | -43 | 90 | | | | | | |
| 18 | Incidental | -43 | 90 | -39 | 43 | | | | |
| 19 | Incidental | -63 | 18 | 127 | 151 | -34 | -42 | 165 | 0 |
| 20 | Incidental | | -45 | 45 | | | | | |

## Signed errors (degrees)

| *Subject* | *Learning condition* | *1a* | *1b* | *1c* | *1d* | *2a* | *2b* | *2c* | *2d* |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Intentional | 35 | -37 | -36.5 | -22.00 | -122 | -72 | 45 | 0 |
| 2 | Intentional | 8 | 19 | 0 | 18.00 | 152.5 | -72 | -90 | 0 |
| 3 | Intentional | -55 | -127 | -36.5 | 25.50 | -88 | 163 | 55 | 0 |
| 4 | Intentional | | -37 | -36.5 | 68.00 | -122 | -119.5 | -42 | 0 |
| 5 | Intentional | 48 | 38 | -4 | -42.00 | -47 | -72 | 90 | 0 |
| 6 | Intentional | -55 | -37 | -80 | -67.00 | | | | |
| 7 | Intentional | -11 | | | | 179.5 | -42 | 0 | 0 |
| 8 | Intentional | 80 | -7 | -24.5 | 14.50 | -85.5 | -146.5 | 0 | 0 |
| 9 | Intentional | -145 | -127 | -80 | | -32 | 108 | 0 | 0 |
| 10 | Intentional | -2 | -178.5 | -113.5 | -112.00 | | | | |
| 11 | Incidental | -99 | -144.5 | -111.5 | -112.00 | -122 | -72 | 120 | 0 |
| 12 | Incidental | 35 | 53 | 100 | 68.00 | -122 | 108 | 0 | 0 |
| 13 | Incidental | -58 | -54.5 | -117.5 | | | | | |
| 14 | Incidental | -8 | 100.5 | -37 | -73.50 | 101.5 | 18 | -90 | 0 |
| 15 | Incidental | 18 | -5.5 | | | | | | |
| 16 | Incidental | -55 | -78 | | | | | | |
| 17 | Incidental | -8 | 53 | | | | | | |
| 18 | Incidental | -8 | 53 | -119 | -69.50 | | | | |
| 19 | Incidental | -28 | -19.5 | 46.5 | 39.00 | 24 | -24 | -15 | 0 |
| 20 | Incidental | | -82 | -35 | | | | | |

Signed errors excluding errors greater than 90° (degrees)

| *Subjects* | *Learning condition* | *1a* | *1b* | *1c* | *1d* | *2a* | *2b* | *2c* | *2d* |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Intentional | 35 | -37 | -38 | -22 | | -72 | 45 | 0 |
| 2 | Intentional | -10 | 17 | 0 | 18 | | -72 | | 0 |
| 3 | Intentional | -55 | | -38 | 28 | -86 | | 50 | 0 |
| 4 | Intentional | | -37 | -38 | 68 | | | -61 | 0 |
| 5 | Intentional | 50 | 33 | 8 | -62 | -42 | | | 0 |
| 6 | Intentional | -55 | -37 | -80 | -77 | | | | |
| 7 | Intentional | -18 | | | | | -32 | 0 | 0 |
| 8 | Intentional | | -15 | -29 | 9 | -79 | | 0 | 0 |
| 9 | Intentional | | | 80 | | -32 | | 0 | 0 |
| 10 | Intentional | 5 | | | | | | | |
| 11 | Incidental | | | | | | -41 | | 0 |
| 12 | Incidental | 35 | 53 | | 68 | | | 0 | 0 |
| 13 | Incidental | -6 | -53 | | | | | | |
| 14 | Incidental | -6 | | -39 | | | 18 | | 0 |
| 15 | Incidental | 25 | -19 | | | | | | |
| 16 | Incidental | -55 | -74 | | | | | | |
| 17 | Incidental | -10 | 53 | | | | | | |
| 18 | Incidental | -5 | 53 | | -80 | | | | |
| 19 | Incidental | -30 | -17 | 38 | 40 | -30 | -31 | -15 | 0 |
| 20 | Incidental | | -62 | -35 | | | | | |

## 8.2 Experiment II

### Left-oriented environment - judgements (degrees)

| | *S9* | *S10* | *S11* | *S12* | *S13* | *S14* | *S15* | *S16* |
|---|---|---|---|---|---|---|---|---|
| J1 | 60 | -10 | 20 | 45 | 45 | 30 | 90 | 20 |
| J2 | 25 | 30 | 15 | -30 | 180 | -30 | 180 | 95 |
| J3 | 50 | 45 | 45 | -60 | 45 | -60 | 45 | 100 |
| J4 | 110 | 80 | 15 | -90 | 40 | -85 | 45 | 90 |
| J5 | 30 | -10 | 30 | 30 | 90 | 45 | 45 | 60 |
| J6 | 65 | -10 | 60 | 30 | 140 | 40 | 90 | 20 |
| J7 | 170 | 250 | 170 | 150 | 45 | 170 | 90 | 30 |
| J8 | 160 | 25 | 120 | 110 | 120 | 135 | 180 | 45 |
| J9 | 70 | 60 | 45 | -60 | 140 | -75 | 90 | 120 |
| J10 | 30 | 45 | 45 | -60 | 45 | -60 | 180 | 70 |
| J11 | 55 | 45 | 60 | -60 | 140 | -60 | 45 | 60 |
| J12 | 60 | 60 | 60 | -60 | 90 | -60 | 45 | 95 |

### Left-oriented environment - signed errors excluding error greater than 90°

| | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| J1 | -3 | | 2 | 2 | -13 | -63 | 12 | -48 |
| J2 | -15 | -5 | -5 | -25 | 10 | 45 | -15 | -15 |
| J3 | 4 | 9 | -6 | 14 | -11 | | 4 | 74 |
| J4 | 57 | -18 | 2 | -8 | -18 | -48 | -18 | |
| J5 | | | -15 | -5 | 35 | -15 | 75 | |
| J6 | | -82 | -22 | -57 | 8 | | | 3 |
| J7 | -5 | | -5 | 75 | 15 | | -45 | 35 |
| J8 | -5 | 80 | -5 | 75 | -5 | | 15 | 5 |
| J9 | 15 | 15 | 0 | 15 | -25 | 35 | 0 | 30 |
| J10 | | -34 | -19 | 76 | 11 | 26 | -4 | -4 |
| J11 | | -8 | -8 | 17 | -8 | 7 | -83 | |
| J12 | | -15 | -30 | 0 | -55 | 5 | -30 | -15 |

Right-oriented environment - judgements (degrees)

| | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| J1 | -15 | 90 | -20 | -20 | -5 | 45 | -30 | 30 |
| J2 | 30 | 20 | 20 | 40 | 5 | -30 | 30 | 30 |
| J3 | 30 | 25 | 40 | 20 | 45 | 180 | 30 | -40 |
| J4 | 15 | 90 | 70 | 80 | 90 | 120 | 90 | 220 |
| J5 | 45 | 150 | -30 | -40 | -80 | -30 | -120 | 60 |
| J6 | 45 | 45 | -15 | 20 | -45 | -180 | 120 | -40 |
| J7 | -160 | 20 | -160 | 120 | -180 | 15 | -120 | -200 |
| J8 | -130 | 145 | -130 | 150 | -130 | 90 | -150 | -140 |
| J9 | 45 | 45 | 60 | 45 | 85 | 25 | 60 | 30 |
| J10 | -60 | 90 | 75 | -20 | 45 | 30 | 60 | 60 |
| J11 | -60 | 45 | 45 | 20 | 45 | 30 | 120 | 160 |
| J12 | -60 | 45 | 60 | 30 | 85 | 25 | 60 | 45 |

Right-oriented environment - signed errors excluding error greater than 90°

| | *S1* | *S2* | *S3* | *S4* | *S5* | *S6* | *S7* | *S8* |
|---|---|---|---|---|---|---|---|---|
| J1 | -41.6 | 28.4 | -1.6 | -26.6 | -26.6 | -11.6 | -71.6 | -1.6 |
| J2 | -40.3 | -45.3 | -30.3 | 14.7 | | 14.7 | | |
| J3 | -83.7 | -78.7 | -78.7 | 26.3 | -78.7 | 26.3 | -78.7 | |
| J4 | | | -86.6 | 18.4 | | 13.4 | | |
| J5 | 15.0 | 55.0 | 15.0 | 15.0 | -45.0 | 0.0 | 0.0 | -15.0 |
| J6 | -28.1 | 46.9 | -23.1 | 6.9 | | -3.1 | -53.1 | 16.9 |
| J7 | -5.3 | -85.3 | -5.3 | 14.7 | | -5.3 | 74.7 | |
| J8 | -25.0 | | 15.0 | 25.0 | 15.0 | 0.0 | -45.0 | |
| J9 | | | | -0.3 | | 14.7 | | |
| J10 | -86.3 | | | 3.7 | | 3.7 | | |
| J11 | | -81.9 | | 23.1 | | 23.1 | -81.9 | |
| J12 | | | | 30.3 | | 30.3 | -74.7 | |

## 8.3 Experiment III

Out of the line of sight - Judgements (degrees)

| | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| J1 | 110 | 45 | 45 | 45 | 60 | 45 | 45 | 50 |
| J2 | -65 | -125 | 20 | 30 | 15 | 15 | 15 | 30 |
| J3 | -50 | 135 | -40 | -45 | -45 | -45 | -45 | -80 |
| J4 | -45 | 55 | -30 | -45 | -60 | -45 | -45 | -50 |
| J5 | 125 | 45 | 50 | 45 | 45 | 45 | 45 | 50 |
| J6 | -10 | 145 | -20 | -30 | 0 | -15 | -15 | -35 |
| J7 | 30 | 135 | 20 | 30 | 30 | 15 | 15 | 35 |
| J8 | -45 | -60 | -40 | -45 | -45 | -45 | -45 | -80 |
| J9 | 75 | 75 | 45 | 45 | -75 | 45 | 45 | 45 |
| J10 | 45 | 30 | 50 | 45 | 45 | 45 | 45 | 80 |
| J11 | -10 | 0 | -20 | -30 | -15 | -60 | 0 | -30 |
| J12 | -45 | 145 | -45 | -45 | -30 | -45 | -45 | -50 |

Out of the line of sight - signed errors (degrees)

| | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| J1 | 62 | -3 | -3 | -3 | 12 | -3 | -3 | 2 |
| J2 | -20 | | -25 | -15 | -30 | -30 | -30 | -15 |
| J3 | -20 | | -10 | -15 | -15 | -15 | -15 | -50 |
| J4 | -3 | | 12 | -3 | -18 | -3 | -3 | -8 |
| J5 | 80 | 0 | 5 | 0 | 0 | 0 | 0 | 5 |
| J6 | 1 | | -9 | -19 | 11 | -4 | -4 | -24 |
| J7 | -38 | 67 | -48 | -38 | -38 | -53 | -53 | -33 |
| J8 | 0 | -15 | 5 | 0 | 0 | 0 | 0 | -35 |
| J9 | 24 | 24 | -6 | -6 | | -6 | -6 | -6 |
| J10 | -15 | -30 | -10 | -15 | -15 | -15 | -15 | 20 |
| J11 | 69 | 79 | 59 | 49 | 64 | 19 | 79 | 49 |
| J12 | -6 | 4 | -6 | -6 | 9 | -6 | -6 | -11 |

## In the line of sight - Judgements (degrees)

| | *S1* | *S2* | *S3* | *S4* | *S5* | *S6* | *S7* | *S8* |
|---|---|---|---|---|---|---|---|---|
| J1 | 0 | 0 | -8 | -5 | -10 | 0 | -20 | -7 |
| J2 | 75 | 65 | 85 | 35 | 60 | 45 | 30 | 65 |
| J3 | -45 | -15 | -25.5 | -80 | -30 | -45 | -15 | -40 |
| J4 | 0 | 0 | -15 | 0 | -10 | -10 | -20 | -15 |
| J5 | -40 | -30 | -50 | -70 | -40 | -30 | -30 | -60 |
| J6 | 85 | 80 | 80 | 15 | 70 | 45 | 60 | 20 |
| J7 | -10 | -45 | -25 | -45 | -30 | -45 | -20 | -30 |
| J8 | 30 | 35 | 50 | 65 | 45 | 45 | 60 | 60 |
| J9 | 20 | 15 | 32.5 | 30 | 40 | 5 | 45 | 27 |
| J10 | 45 | 60 | 65 | 45 | 60 | 50 | 40 | 55 |
| J11 | -20 | -45 | 17.5 | -45 | -60 | -40 | -30 | -20 |
| J12 | 20 | 15 | 32.5 | 35 | 40 | 5 | 30 | 30 |

## In the line of sight - signed errors (degrees)

| | *S1* | *S2* | *S3* | *S4* | *S5* | *S6* | *S7* | *S8* |
|---|---|---|---|---|---|---|---|---|
| J1 | -6 | -6 | 2 | -1 | 4 | -6 | 14 | 1 |
| J2 | -16 | -6 | -26 | 24 | -1 | 14 | 29 | -6 |
| J3 | 13 | -17 | -7 | 48 | -2 | 13 | -17 | 8 |
| J4 | -6 | -6 | 9 | -6 | 4 | 4 | 14 | 9 |
| J5 | -1 | -11 | 9 | 29 | -1 | -11 | -11 | 19 |
| J6 | -22 | -17 | -17 | 48 | -7 | 18 | 3 | 43 |
| J7 | -21 | 14 | -6 | 14 | -1 | 14 | -11 | -1 |
| J8 | 19 | 14 | -1 | -16 | 4 | 4 | -11 | -11 |
| J9 | 7 | 12 | -6 | -3 | -13 | 22 | -18 | 0 |
| J10 | 13 | -2 | -7 | 13 | -2 | 8 | 18 | 3 |
| J11 | -7 | 18 | -44 | 18 | 33 | 13 | 3 | -7 |
| J12 | 7 | 12 | -6 | -8 | -13 | 22 | -3 | -3 |

## 8.4 Experiment IV

### Condition 1a

| ***Signed errors*** | | | | | | |
|---|---|---|---|---|---|---|
| Aligned | -7 | -2.59 | 22.41 | -20.24 | -10.24 | -0.24 |
| Counter-aligned | -2.59 | -67.59 | -2.59 | 17.47 | -82.53 | 32.47 |
| Non-aligned-right | 78 | | 18 | 13 | -26 | 4 |
| Non-aligned-left | 49 | 14 | | 2.47 | 5 | -10 |
| ***Unsigned errors*** | | | | | | |
| Aligned | 7 | 3 | 22 | 20 | 10 | 0 |
| Counter-aligned | 3 | 68 | 3 | 17 | 83 | 32 |
| Non-aligned-right | 78 | | 18 | 13 | 26 | 4 |
| Non-aligned-left | 49 | 14 | | 2 | 5 | 10 |

| ***Signed errors*** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Aligned | -7 | -2.59 | 22.41 | -20.24 | -10.24 | -0.24 | | | | |
| Counter-aligned | -2.59 | -67.59 | -2.59 | 17.47 | -82.53 | 32.47 | | | | |
| Non-aligned | 78 | 18 | 13 | -26 | 4 | 49 | 14 | 2.47 | 5 | -10 |
| ***Unsigned errors*** | | | | | | | | | | |
| Aligned | 7 | 2.59 | 22.41 | 20.24 | 10.24 | 0.24 | | | | |
| Counter-aligned | 2.59 | 67.59 | 2.59 | 17.47 | 82.53 | 32.47 | | | | |
| Non-aligned | 78 | 18 | 13 | 26 | 4 | 49 | 14 | 2.47 | 5 | 10 |

### Condition 1b

| ***Signed errors*** | | | | | | |
|---|---|---|---|---|---|---|
| Aligned | 18.4 | -11.6 | -51.6 | -4.7 | 5.3 | -7.0 |
| Non-aligned-right | 5.0 | -30.0 | 30.0 | -45.0 | 38.2 | 28.2 |
| Non-aligned-left | 0.0 | -5.0 | -2.0 | 9.4 | 0.0 | -15.0 |
| ***Unsigned errors*** | | | | | | |
| Aligned | 18.4 | 11.6 | 51.6 | 4.7 | 5.3 | 7.0 |
| Non-aligned-right | 5.0 | 30.0 | 30.0 | 45.0 | 38.2 | 28.2 |
| Non-aligned-left | 0.0 | 5.0 | 2.0 | 9.4 | 0.0 | 15.0 |

| ***Signed errors*** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aligned | 18.4 | -11.6 | -51.6 | -4.7 | 5.3 | -7.0 | | | | | | |
| Non-aligned | 5.0 | -30.0 | 30.0 | -45.0 | 38.2 | 28.2 | 0.0 | -5.0 | -2.0 | 9.4 | 0.0 | -15.0 |
| ***Unsigned errors*** | | | | | | | | | | | | |
| Aligned | 18.4 | 11.6 | 51.6 | 4.7 | 5.3 | 7.0 | | | | | | |
| Non-aligned | 5.0 | 30.0 | 30.0 | 45.0 | 38.20 | 28.20 | 0.0 | 5.0 | 2.0 | 9.44 | 0.0 | 15.0 |

# Condition 1c

| *Signed errors* | | | | | |
|---|---|---|---|---|---|
| Aligned | -9.0 | 21.0 | -37.0 | 13.0 | 28.0 |
| Counter-aligned | | -11.6 | -26.6 | | -15.3 |
| Non-aligned-right | | -21.0 | -21.0 | -21.0 | -12.5 |
| Non-aligned-left | 8.7 | -1.3 | | -12.5 | -22.5 |
| ***Unsigned errors*** | | | | | |
| Aligned | 9.0 | 21.0 | 37.0 | 13.0 | 28.0 |
| Counter-aligned | | 11.6 | 26.6 | | 15.3 |
| Non-aligned-right | | 21.0 | 21.0 | 21.0 | 12.5 |
| Non-aligned-left | 8.7 | 1.3 | | 12.5 | 22.5 |

| *Signed errors* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Aligned | -9.0 | 21.0 | -37.0 | 13.0 | 28.0 | | | |
| Counter-aligned | -11.6 | -26.6 | -15.3 | | | | | |
| Non-aligned | -21.0 | -21.0 | -21.0 | -12.5 | 8.7 | -1.3 | -12.5 | -22.5 |
| ***Unsigned errors*** | | | | | | | | |
| Aligned | 9.0 | 21.0 | 37.0 | 13.0 | 28.0 | | | |
| Counter-aligned | 11.6 | 26.6 | 15.3 | | | | | |
| Non-aligned | 21.0 | 21.0 | 21.0 | 12.5 | 8.7 | 1.3 | 12.5 | 22.5 |

# Condition 1d

| *Signed errors* | | | | | | |
|---|---|---|---|---|---|---|
| Aligned | 15.0 | -8.8 | -8.8 | 0.0 | 45.0 | 0.0 |
| Counter-aligned | | 80.0 | -81.0 | -11.0 | | 45.0 |
| Non-aligned-right | 75.0 | 45.0 | 45.0 | 45.0 | -7.0 | 58.0 |
| ***Unsigned errors*** | | | | | | |
| Aligned | 15.0 | 8.8 | 8.8 | 0.0 | 45.0 | 0.0 |
| Counter-aligned | | 80.0 | 81.0 | 11.0 | | 45.0 |
| Non-aligned-right | 75.0 | 45.0 | 45.0 | 45.0 | 7.0 | 58.0 |

## Condition 2a

| *Signed errors* | | | | | | | |
|---|---|---|---|---|---|---|---|
| Aligned | 8.0 | | -7.0 | 68.0 | | -10.6 | 37.4 |
| Counter-aligned | -43.4 | -0.4 | -7.5 | -7.5 | | 72.4 | -3.6 |
| Non-aligned-right | 83.0 | -17.0 | 18.0 | | 79.0 | -81.9 | -16.9 |
| Non-aligned-left | 74.0 | -1.0 | 10.0 | | 20.0 | 27.5 | 32.5 |
| ***Unsigned errors*** | | | | | | | |
| Aligned | 8.0 | | 7.0 | 68.0 | | 10.6 | 37.4 |
| Counter-aligned | 43.4 | 0.4 | 7.5 | 7.5 | | 72.4 | 3.6 |
| Non-aligned-right | 83.0 | 17.0 | 18.0 | | 79.0 | 81.9 | 16.9 |
| Non-aligned-left | 74.0 | 1.0 | 10.0 | | 20.0 | 27.5 | 32.5 |

| *Signed errors* | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aligned | 8.0 | -7.0 | 68.0 | -10.6 | 37.4 | | | | | | | |
| Counter-aligned | -43.4 | -0.4 | -7.5 | -7.5 | 72.4 | -3.6 | | | | | | |
| Non-aligned | 83.0 | -17.0 | 18.0 | 79.0 | -81.9 | -16.9 | 74.0 | -1.0 | 10.0 | 20.0 | 27.5 | 32.5 |
| ***Unsigned errors*** | | | | | | | | | | | | |
| Aligned | 8.0 | 7.0 | 68.0 | 10.6 | 37.4 | | | | | | | |
| Counter-aligned | 43.4 | 0.4 | 7.5 | 7.5 | 72.4 | 3.6 | | | | | | |
| Non-aligned | 83.0 | 17.0 | 18.0 | 79.0 | 81.9 | 16.9 | 74.0 | 1.0 | 10.0 | 20.0 | 27.5 | 32.5 |

## Condition 2b

| *Signed errors* | | | | | | | |
|---|---|---|---|---|---|---|---|
| Aligned | 10.3 | 83.0 | -52.0 | 8.0 | 8.4 | 18.4 | |
| Non-aligned-right | 15.0 | 30.0 | 78.0 | 45.0 | -45.0 | 8.2 | 38.2 |
| Non-aligned-left | -45.0 | 0.0 | -10.6 | 25.0 | 0.0 | 80.0 | |
| ***Unsigned errors*** | | | | | | | |
| Aligned | 10.3 | 83.0 | 52.0 | 8.0 | 8.4 | 18.4 | |
| Non-aligned-right | 15.0 | 30.0 | 78.0 | 45.0 | 45.0 | 8.2 | 38.2 |
| Non-aligned-left | 45.0 | 0.0 | 10.6 | 25.0 | 0.0 | 80.0 | |

| *Signed errors* | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aligned | 10.3 | 83.0 | -52.0 | 8.0 | 8.4 | 18.4 | | | | | | | |
| Non-aligned | 15.0 | 30.0 | 78.0 | 45.0 | -45.0 | 8.2 | 38.2 | -45.0 | 0.0 | -10.6 | 25.0 | 0.0 | 80.0 |
| ***Unsigned errors*** | | | | | | | | | | | | | |
| Aligned | 10.3 | 83.0 | 52.0 | 8.0 | 8.4 | 18.4 | | | | | | | |
| Non-aligned | 15.0 | 30.0 | 78.0 | 45.0 | 45.0 | 8.2 | 38.2 | 45.0 | 0.0 | 10.6 | 25.0 | 0.0 | 80.0 |

## Condition 2c

| *Signed errors* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Aligned | | -39.0 | -19.0 | -24.0 | -9.0 | -4.0 | -47.0 | 23.0 |
| Counter-aligned | | -24.0 | -4.0 | 29.7 | | 18.4 | -11.6 | 63.4 |
| Non-aligned-right | 21.0 | 14.0 | -31.0 | 14.0 | 69.0 | | -12.5 | 2.5 |
| Non-aligned-left | 12.7 | | -2.3 | -12.5 | -12.5 | | 32.5 | -47.3 |
| ***Unsigned errors*** | | | | | | | | |
| Aligned | | 39.0 | 19.0 | 24.0 | 9.0 | 4.0 | 47.0 | 23.0 |
| Counter-aligned | | 24.0 | 4.0 | 29.7 | | 18.4 | 11.6 | 63.4 |
| Non-aligned-right | 21.0 | 14.0 | 31.0 | 14.0 | 69.0 | | 12.5 | 2.5 |
| Non-aligned-left | 12.7 | | 2.3 | 12.5 | 12.5 | | 32.5 | 47.3 |

| *Signed errors* | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aligned | -39.0 | -19.0 | -24.0 | -9.0 | -4.0 | -47.0 | 23.0 | | | | | | |
| Counter-aligned | -24.0 | -4.0 | 29.7 | 18.4 | -11.6 | 63.4 | | | | | | | |
| Non-aligned | 21.0 | 14.0 | -31.0 | 14.0 | 69.0 | -12.5 | 2.5 | 12.7 | -2.3 | -12.5 | -12.5 | 32.5 | -47.3 |
| ***Unsigned errors*** | | | | | | | | | | | | | |
| Aligned | 39.0 | 19.0 | 24.0 | 9.0 | 4.0 | 47.0 | 23.0 | | | | | | |
| Counter-aligned | 24.0 | 4.0 | 29.7 | 18.4 | 11.6 | 63.4 | | | | | | | |
| Non-aligned | 21.0 | 14.0 | 31.0 | 14.0 | 69.0 | 12.5 | 2.5 | 12.7 | 2.3 | 12.5 | 12.5 | 32.5 | 47.3 |

## Condition 2d

| *Signed errors* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Aligned | 45.0 | 0.0 | -45.0 | 0.0 | -32.0 | | 8.0 | -45.0 | 0.0 | 0.0 |
| Counter-aligned | 85.0 | 0.0 | | -81.0 | 9.0 | -81.0 | -36.0 | -36.0 | -36.0 | -81.0 |
| Non-aligned-right | | -45.0 | | | 0.0 | -45.0 | -45.0 | 13.0 | | -45.0 |
| ***Unsigned errors*** | | | | | | | | | | |
| Aligned | 45.0 | 0.0 | 45.0 | 0.0 | 32.0 | | 8.0 | 45.0 | 0.0 | 0.0 |
| Counter-aligned | 85.0 | 0.0 | | 81.0 | 9.0 | 81.0 | 36.0 | 36.0 | 36.0 | 81.0 |
| Non-aligned-right | | 45.0 | | | 0.0 | 45.0 | 45.0 | 13.0 | | 45.0 |

## 8.5 Experiment V

### One period of exploration (route judgements)

| *Route* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Red - green | 8.0 | 10.0 | 12.0 | 6.0 | 14.0 | 12.0 | 12.0 | 8.0 |
| Clock - green | 11.0 | 10.0 | 14.0 | 14.0 | 14.0 | 15.0 | 10.0 | 11.0 |
| Window-green | 22.0 | 24.0 | 22.0 | 42.0 | 25.0 | 10.0 | 25.0 | 25.0 |
| Purple - green | 14.0 | 12.0 | 14.0 | 15.0 | 20.0 | 12.0 | 12.0 | 17.0 |
| Clock - red | 9.0 | 10.0 | 12.0 | 13.0 | 18.0 | 10.0 | 10.0 | 12.0 |
| Window - red | 20.0 | 24.0 | 23.0 | 41.0 | 25.0 | 15.0 | 25.0 | 25.0 |
| Purple - red | 12.0 | 12.0 | 15.0 | 14.0 | 18.0 | 15.0 | 12.0 | 18.0 |
| Window - clock | 10.0 | 18.0 | 16.0 | 32.0 | 20.0 | 12.0 | 18.0 | 18.0 |
| Purple - clock | 8.0 | 8.0 | 11.0 | 11.0 | 10.0 | 10.0 | 7.0 | 11.0 |
| Purple - window | 10.0 | 18.0 | 15.0 | 25.0 | 25.0 | 8.0 | 16.0 | 23.0 |
| Green - red | 8.0 | 12.0 | 12.0 | 6.0 | 6.0 | 10.0 | 10.0 | 12.0 |
| Green - clock | 16.0 | 18.0 | 8.0 | 13.0 | 13.0 | 12.0 | 15.0 | 16.0 |
| Green - window | 20.0 | 32.0 | 18.0 | 41.0 | 41.0 | 15.0 | 25.0 | 35.0 |
| Green - purple | 12.0 | 18.0 | 14.0 | 17.0 | 17.0 | 12.0 | 15.0 | 24.0 |
| Red - clock | 12.0 | 12.0 | 11.0 | 14.0 | 18.0 | 10.0 | 15.0 | 14.0 |
| Red - window | 20.0 | 32.0 | 18.0 | 40.0 | 26.0 | 10.0 | 20.0 | 26.0 |
| Red - purple | 8.0 | 12.0 | 15.0 | 17.0 | 18.0 | 15.0 | 15.0 | 15.0 |
| Clock - window | 10.0 | 26.0 | 16.0 | 30.0 | 20.0 | 10.0 | 25.0 | 24.0 |
| Clock - purple | 7.0 | 11.0 | 11.0 | 14.0 | 12.0 | 20.0 | 15.0 | 11.0 |
| Window - purple | 15.0 | 18.0 | 20.0 | 28.0 | 18.0 | 8.0 | 18.0 | 18.0 |

### One period of exploration (Euclidean judgements)

| *Euclidean* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Red - green | 8.0 | 9.0 | 8.0 | 6.0 | 14.0 | 12.0 | 7.0 | 6.0 |
| Clock - green | 10.0 | 7.0 | 8.0 | 12.0 | 8.0 | 12.0 | 7.0 | 7.0 |
| Window-green | 14.0 | 15.0 | 15.0 | 42.0 | 20.0 | 12.0 | 12.0 | 15.0 |
| Purple - green | 10.0 | 8.0 | 10.0 | 8.0 | 8.0 | 25.0 | 10.0 | 12.0 |
| Clock - red | 9.0 | 12.0 | 11.0 | 11.0 | 15.0 | 10.0 | 10.0 | 8.0 |
| Window - red | 6.0 | 8.0 | 17.0 | 41.0 | 14.0 | 15.0 | 15.0 | 13.0 |
| Purple - red | 8.0 | 6.0 | 6.0 | 11.0 | 10.0 | 20.0 | 6.0 | 7.0 |
| Window - clock | 6.0 | 12.0 | 11.0 | 32.0 | 16.0 | 15.0 | 12.0 | 9.0 |
| Purple - clock | 6.0 | 7.0 | 8.0 | 8.0 | 12.0 | 20.0 | 8.0 | 9.0 |
| Purple - window | 8.0 | 6.0 | 14.0 | 8.0 | 20.0 | 15.0 | 6.0 | 7.0 |
| Green - red | 8.0 | 12.0 | 8.0 | 6.0 | 14.0 | 14.0 | 7.0 | 6.0 |
| Green - clock | 12.0 | 18.0 | 6.0 | 14.0 | 15.0 | 15.0 | 7.0 | 7.0 |
| Green - window | 12.0 | 11.0 | 12.0 | 40.0 | 18.0 | 18.0 | 10.0 | 13.0 |
| Green - purple | 10.0 | 32.0 | 12.0 | 17.0 | 14.0 | 14.0 | 16.0 | 8.0 |
| Red - clock | 6.0 | 5.0 | 10.0 | 14.0 | 18.0 | 10.0 | 7.0 | 8.0 |
| Red - window | 4.0 | 18.0 | 15.0 | 42.0 | 26.0 | 20.0 | 18.0 | 6.0 |
| Red - purple | 4.0 | 18.0 | 8.0 | 18.0 | 18.0 | 12.0 | 10.0 | 10.0 |
| Clock - window | 10.0 | 5.0 | 8.0 | 32.0 | 12.0 | 15.0 | 25.0 | 12.0 |
| Clock - purple | 7.0 | 9.0 | 9.0 | 14.0 | 8.0 | 12.0 | 15.0 | 9.0 |
| Window - purple | 13.0 | 6.0 | 14.0 | 28.0 | 20.0 | 12.0 | 8.0 | 7.0 |

## One period of exploration (signed route errors)

| *Route* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Red - green | -3.0 | -1.0 | 1.0 | -5.0 | 3.0 | 1.0 | 1.0 | -3.0 |
| Clock - green | -7.0 | -8.0 | -4.0 | -4.0 | -4.0 | -3.0 | -8.0 | -7.0 |
| Window-green | -21.0 | -19.0 | -21.0 | -1.0 | -18.0 | -33.0 | -18.0 | -18.0 |
| Purple - green | -10.0 | -12.0 | -10.0 | -9.0 | -4.0 | -12.0 | -12.0 | -7.0 |
| Clock - red | -11.0 | -10.0 | -8.0 | -7.0 | -2.0 | -10.0 | -10.0 | -8.0 |
| Window - red | -25.0 | -21.0 | -22.0 | -4.0 | -20.0 | -30.0 | -20.0 | -20.0 |
| Purple - red | -13.0 | -13.0 | -10.0 | -11.0 | -7.0 | -10.0 | -13.0 | -7.0 |
| Window - clock | -28.0 | -20.0 | -22.0 | -6.0 | -18.0 | -26.0 | -20.0 | -20.0 |
| Purple - clock | -12.0 | -12.0 | -9.0 | -9.0 | -10.0 | -10.0 | -13.0 | -9.0 |
| Purple - window | -27.0 | -19.0 | -22.0 | -12.0 | -12.0 | -29.0 | -21.0 | -14.0 |
| Green - red | -3.0 | 1.0 | 1.0 | -5.0 | -5.0 | -1.0 | -1.0 | 1.0 |
| Green - clock | -2.0 | 0.0 | -10.0 | -5.0 | -5.0 | -6.0 | -3.0 | -2.0 |
| Green - window | -23.0 | -11.0 | -25.0 | -2.0 | -2.0 | -28.0 | -18.0 | -8.0 |
| Green - purple | -12.0 | -6.0 | -10.0 | -7.0 | -7.0 | -12.0 | -9.0 | 0.0 |
| Red - clock | -8.0 | -8.0 | -9.0 | -6.0 | -2.0 | -10.0 | -5.0 | -6.0 |
| Red - window | -25.0 | -13.0 | -27.0 | -5.0 | -19.0 | -35.0 | -25.0 | -19.0 |
| Red - purple | -17.0 | -13.0 | -10.0 | -8.0 | -7.0 | -10.0 | -10.0 | -10.0 |
| Clock - window | -28.0 | -12.0 | -22.0 | -8.0 | -18.0 | -28.0 | -13.0 | -14.0 |
| Clock - purple | -13.0 | -9.0 | -9.0 | -6.0 | -8.0 | 0.0 | -5.0 | -9.0 |
| Window - purple | -22.0 | -19.0 | -17.0 | -9.0 | -19.0 | -29.0 | -19.0 | -19.0 |

## One period of exploration (signed Euclidean errors)

| Euclidean | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Red - green | -0.1 | 0.9 | -0.1 | -2.1 | 5.9 | 3.9 | -1.1 | -2.1 |
| Clock - green | -1.7 | -4.7 | -3.7 | 0.3 | -3.7 | 0.3 | -4.7 | -4.7 |
| Window-green | -6.6 | -5.6 | -5.6 | 21.4 | -0.6 | -8.6 | -8.6 | -5.6 |
| Purple - green | -2.7 | -4.7 | -2.7 | -4.7 | -4.7 | 12.3 | -2.7 | -0.7 |
| Clock - red | 0.9 | 3.9 | 2.9 | 2.9 | 6.9 | 1.9 | 1.9 | -0.1 |
| Window - red | -12.1 | -10.1 | -1.1 | 22.9 | -4.1 | -3.1 | -3.1 | -5.1 |
| Purple - red | 0.9 | -1.1 | -1.1 | 3.9 | 2.9 | 12.9 | -1.1 | -0.1 |
| Window - clock | -7.0 | -1.0 | -2.0 | 19.0 | 3.0 | 2.0 | -1.0 | -4.0 |
| Purple - clock | -5.1 | -4.1 | -3.1 | -3.1 | 0.9 | 9.0 | -3.1 | -2.1 |
| Purple - window | -2.4 | -4.4 | 3.6 | -2.4 | 9.6 | 4.6 | -4.4 | -3.4 |
| Green - red | -0.1 | 3.9 | -0.1 | -2.1 | 5.9 | 5.9 | -1.1 | -2.1 |
| Green - clock | 0.3 | 6.3 | -5.7 | 2.3 | 3.3 | 3.3 | -4.7 | -4.7 |
| Green - window | -8.6 | -9.6 | -8.6 | 19.4 | -2.6 | -2.6 | -10.6 | -7.6 |
| Green - purple | -2.7 | 19.3 | -0.7 | 4.3 | 1.3 | 1.3 | 3.3 | -4.7 |
| Red - clock | -2.1 | -3.1 | 1.9 | 5.9 | 9.9 | 1.9 | -1.1 | -0.1 |
| Red - window | -14.1 | -0.1 | -3.1 | 23.9 | 7.9 | 1.9 | -0.1 | -12.1 |
| Red - purple | -3.1 | 10.9 | 0.9 | 10.9 | 10.9 | 4.9 | 2.9 | 2.9 |
| Clock - window | -3.0 | -8.0 | -5.0 | 19.0 | -1.0 | 2.0 | 12.0 | -1.0 |
| Clock - purple | -4.1 | -2.1 | -2.1 | 3.0 | -3.1 | 0.9 | 4.0 | -2.1 |
| Window - purple | 2.6 | -4.4 | 3.6 | 17.6 | 9.6 | 1.6 | -2.4 | -3.4 |

## One period of exploration (unsigned route errors)

| Route | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Red - green | 3.0 | 1.0 | 1.0 | 5.0 | 4.0 | 1.0 | 1.0 | 2.0 |
| Clock - green | 4.5 | 4.0 | 7.0 | 4.5 | 4.5 | 4.5 | 5.5 | 4.5 |
| Window-green | 22.0 | 15.0 | 23.0 | 1.5 | 10.0 | 30.5 | 18.0 | 13.0 |
| Purple - green | 11.0 | 9.0 | 10.0 | 8.0 | 5.5 | 12.0 | 10.5 | 3.5 |
| Clock - red | 9.5 | 9.0 | 8.5 | 6.5 | 2.0 | 10.0 | 7.5 | 7.0 |
| Window - red | 25.0 | 17.0 | 24.5 | 4.5 | 19.5 | 32.5 | 22.5 | 19.5 |
| Purple - red | 15.0 | 13.0 | 10.0 | 9.5 | 7.0 | 10.0 | 11.5 | 8.5 |
| Window - clock | 28.0 | 16.0 | 22.0 | 7.0 | 18.0 | 27.0 | 16.5 | 17.0 |
| Purple - clock | 12.5 | 10.5 | 9.0 | 7.5 | 9.0 | 5.0 | 9.0 | 9.0 |
| Purple - window | 24.5 | 19.0 | 19.5 | 10.5 | 15.5 | 29.0 | 20.0 | 16.5 |

## One period of exploration (unsigned Euclidean errors)

| Euclidean | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Red - green | 0.1 | 2.4 | 0.1 | 2.1 | 5.9 | 4.9 | 1.1 | 2.1 |
| Clock - green | 1.0 | 5.5 | 4.7 | 1.3 | 3.5 | 1.8 | 4.7 | 4.7 |
| Window-green | 7.6 | 7.6 | 7.1 | 20.4 | 1.6 | 5.6 | 9.6 | 6.6 |
| Purple - green | 2.7 | 12.0 | 1.7 | 4.5 | 3.0 | 6.8 | 3.0 | 2.7 |
| Clock - red | 1.5 | 3.5 | 2.4 | 4.4 | 8.4 | 1.9 | 1.5 | 0.1 |
| Window - red | 13.1 | 5.1 | 2.1 | 23.4 | 6.0 | 2.5 | 1.6 | 8.6 |
| Purple - red | 2.0 | 6.0 | 1.0 | 7.4 | 6.9 | 8.9 | 2.0 | 1.5 |
| Window - clock | 5.0 | 4.5 | 3.5 | 19.0 | 2.0 | 2.0 | 6.5 | 2.5 |
| Purple - clock | 4.6 | 3.1 | 2.6 | 3.0 | 2.0 | 5.0 | 3.5 | 2.1 |
| Purple - window | 2.5 | 4.4 | 3.6 | 10.0 | 9.6 | 3.1 | 3.4 | 3.4 |

## Three period of exploration (signed route judgements)

| Judgements | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Red - green | 15.0 | 8.0 | 11.0 | 8.0 | 10.0 | 10.0 | 6.0 | 9.0 |
| Clock - green | 10.0 | 8.0 | 10.0 | 14.0 | 11.0 | 20.0 | 20.0 | 13.0 |
| Window-green | 25.0 | 40.0 | 32.0 | 30.0 | 19.0 | 28.0 | 16.0 | 31.0 |
| Purple - green | 12.0 | 8.0 | 14.0 | 18.0 | 14.0 | 16.0 | 11.0 | 16.0 |
| Clock - red | 10.0 | 8.0 | 11.0 | 12.0 | 15.0 | 16.0 | 16.0 | 12.0 |
| Window - red | 20.0 | 40.0 | 33.0 | 33.0 | 22.0 | 28.0 | 16.0 | 30.0 |
| Purple - red | 10.0 | 8.0 | 15.0 | 17.0 | 16.0 | 20.0 | 11.0 | 16.0 |
| Window - clock | 25.0 | 45.0 | 35.0 | 29.0 | 14.0 | 20.0 | 16.0 | 28.0 |
| Purple - clock | 12.0 | 6.0 | 17.0 | 13.0 | 11.0 | 16.0 | 7.0 | 14.0 |
| Purple - window | 10.0 | 30.0 | 23.0 | 24.0 | 14.0 | 20.0 | 14.0 | 24.0 |
| Green - red | 8.0 | 8.0 | 11.0 | 9.0 | 7.0 | 12.0 | 7.0 | 7.0 |
| Green - clock | 10.0 | 8.0 | 9.0 | 4.5 | 13.0 | 16.0 | 10.0 | 14.0 |
| Green - window | 30.0 | 40.0 | 34.0 | 26.0 | 18.0 | 28.0 | 24.0 | 30.0 |
| Green - purple | 15.0 | 12.0 | 17.0 | 14.0 | 13.0 | 16.0 | 15.0 | 17.0 |
| Red - clock | 15.0 | 16.0 | 18.0 | 12.0 | 14.0 | 14.0 | 11.0 | 14.0 |
| Red - window | 20.0 | 60.0 | 32.0 | 32.0 | 20.0 | 28.0 | 16.0 | 31.0 |
| Red - purple | 10.0 | 10.0 | 16.0 | 12.0 | 26.0 | 20.0 | 11.0 | 19.0 |
| Clock - window | 15.0 | 30.0 | 32.0 | 32.0 | 23.0 | 24.0 | 24.0 | 28.0 |
| Clock - purple | 12.0 | 4.0 | 17.0 | 17.0 | 7.0 | 12.0 | 12.0 | 15.0 |
| Window - purple | 20.0 | 30.0 | 25.0 | 23.0 | 20.0 | 20.0 | 16.0 | 24.0 |

## Three period of exploration (signed Euclidean judgements)

| Judgements | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Red - green | 10.0 | 8.0 | 10.0 | 6.0 | 6.0 | 6.0 | 10.0 | 5.0 |
| Clock - green | 10.0 | 12.0 | 7.0 | 8.0 | 8.0 | 6.0 | 12.0 | 12.0 |
| Window-green | 45.0 | 60.0 | 26.0 | 16.0 | 18.0 | 15.0 | 28.0 | 14.0 |
| Purple - green | 20.0 | 12.0 | 13.0 | 8.0 | 10.0 | 5.0 | 8.0 | 8.0 |
| Clock - red | 22.0 | 10.0 | 9.0 | 7.0 | 12.0 | 6.0 | 8.0 | 7.0 |
| Window - red | 55.0 | 60.0 | 22.0 | 15.0 | 20.0 | 17.0 | 24.0 | 16.0 |
| Purple - red | 20.0 | 12.0 | 8.0 | 10.0 | 14.0 | 12.0 | 12.0 | 12.0 |
| Window - clock | 35.0 | 55.0 | 16.0 | 12.0 | 12.0 | 8.0 | 20.0 | 14.0 |
| Purple - clock | 15.0 | 8.0 | 14.0 | 8.0 | 8.0 | 6.0 | 16.0 | 16.0 |
| Purple - window | 32.0 | 50.0 | 9.0 | 6.0 | 12.0 | 10.0 | 10.0 | 9.0 |
| Green - red | 10.0 | 8.0 | 10.0 | 7.0 | 6.0 | 6.0 | 10.0 | 8.0 |
| Green - clock | 20.0 | 12.0 | 7.0 | 4.0 | 12.0 | 6.0 | 8.0 | 7.0 |
| Green - window | 40.0 | 60.0 | 24.0 | 14.0 | 15.0 | 15.0 | 20.0 | 16.0 |
| Green - purple | 25.0 | 16.0 | 15.0 | 9.0 | 11.0 | 8.0 | 16.0 | 13.0 |
| Red - clock | 15.0 | 14.0 | 8.0 | 7.0 | 12.0 | 6.0 | 10.0 | 12.0 |
| Red - window | 55.0 | 40.0 | 18.0 | 12.0 | 18.0 | 12.0 | 26.0 | 14.0 |
| Red - purple | 30.0 | 8.0 | 8.0 | 6.0 | 22.0 | 9.0 | 8.0 | 5.0 |
| Clock - window | 35.0 | 50.0 | 13.0 | 14.0 | 18.0 | 10.0 | 8.0 | 15.0 |
| Clock - purple | 20.0 | 6.0 | 10.0 | 10.0 | 6.0 | 6.0 | 12.0 | 12.0 |
| Window - purple | 40.0 | 50.0 | 13.0 | 6.0 | 18.0 | 6.0 | 24.0 | 7.0 |

## Three period of exploration (unsigned route errors)

| Judgements | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| Red - green | 4.0 | -3.0 | 0.0 | -3.0 | -1.0 | -1.0 | -5.0 | -2.0 |
| Clock - green | -8.0 | -10.0 | -8.0 | -4.0 | -7.0 | 2.0 | 2.0 | -5.0 |
| Window-green | -18.0 | -3.0 | -11.0 | -13.0 | -24.0 | -15.0 | -27.0 | -12.0 |
| Purple - green | -12.0 | -16.0 | -10.0 | -6.0 | -10.0 | -8.0 | -13.0 | -8.0 |
| Clock - red | -10.0 | -12.0 | -9.0 | -8.0 | -5.0 | -4.0 | -4.0 | -8.0 |
| Window - red | -25.0 | -5.0 | -12.0 | -12.0 | -23.0 | -17.0 | -29.0 | -15.0 |
| Purple - red | -15.0 | -17.0 | -10.0 | -8.0 | -9.0 | -5.0 | -14.0 | -9.0 |
| Window - clock | -13.0 | 7.0 | -3.0 | -9.0 | -24.0 | -18.0 | -22.0 | -10.0 |
| Purple - clock | -8.0 | -14.0 | -3.0 | -7.0 | -9.0 | -4.0 | -13.0 | -6.0 |
| Purple - window | -27.0 | -7.0 | -14.0 | -13.0 | -23.0 | -17.0 | -23.0 | -13.0 |
| Green - red | -3.0 | -3.0 | 0.0 | -2.0 | -4.0 | 1.0 | -4.0 | -4.0 |
| Green - clock | -8.0 | -10.0 | -9.0 | -13.5 | -5.0 | -2.0 | -8.0 | -4.0 |
| Green - window | -13.0 | -3.0 | -9.0 | -17.0 | -25.0 | -15.0 | -19.0 | -13.0 |
| Green - purple | -9.0 | -12.0 | -7.0 | -10.0 | -11.0 | -8.0 | -9.0 | -7.0 |
| Red - clock | -5.0 | -4.0 | -2.0 | -8.0 | -6.0 | -6.0 | -9.0 | -6.0 |
| Red - window | -25.0 | 15.0 | -13.0 | -13.0 | -25.0 | -17.0 | -29.0 | -14.0 |
| Red - purple | -15.0 | -15.0 | -9.0 | -13.0 | 1.0 | -5.0 | -14.0 | -6.0 |
| Clock - window | -23.0 | -8.0 | -6.0 | -6.0 | -15.0 | -14.0 | -14.0 | -10.0 |
| Clock - purple | -8.0 | -16.0 | -3.0 | -3.0 | -13.0 | -8.0 | -8.0 | -5.0 |
| Window - purple | -17.0 | -7.0 | -12.0 | -14.0 | -17.0 | -17.0 | -21.0 | -13.0 |

## Three period of exploration (unsigned Euclidean errors)

| Judgements | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| Red - green | 1.9 | -0.1 | 1.9 | -2.1 | -2.1 | -2.1 | 1.9 | -3.1 |
| Clock - green | -1.7 | 0.3 | -4.7 | -3.7 | -3.7 | -5.7 | 0.3 | 0.3 |
| Window-green | 24.4 | 39.4 | 5.4 | -4.6 | -2.6 | -5.6 | 7.4 | -6.6 |
| Purple - green | 7.3 | -0.7 | 0.3 | -4.7 | -2.7 | -7.7 | -4.7 | -4.7 |
| Clock - red | 13.9 | 1.9 | 0.9 | -1.1 | 3.9 | -2.1 | -0.1 | -1.1 |
| Window - red | 36.9 | 41.9 | 3.9 | -3.1 | 1.9 | -1.1 | 5.9 | -2.1 |
| Purple - red | 12.9 | 4.9 | 0.9 | 2.9 | 6.9 | 4.9 | 4.9 | 4.9 |
| Window - clock | 22.0 | 42.0 | 3.0 | -1.0 | -1.0 | -5.0 | 7.0 | 1.0 |
| Purple - clock | 4.0 | -3.1 | 3.0 | -3.1 | -3.1 | -5.1 | 5.0 | 5.0 |
| Purple - window | 21.6 | 39.6 | -1.4 | -4.4 | 1.6 | -0.4 | -0.4 | -1.4 |
| Green - red | 1.9 | -0.1 | 1.9 | -1.1 | -2.1 | -2.1 | 1.9 | -0.1 |
| Green - clock | 8.3 | 0.3 | -4.7 | -7.7 | 0.3 | -5.7 | -3.7 | -4.7 |
| Green - window | 19.4 | 39.4 | 3.4 | -6.6 | -5.6 | -5.6 | -0.6 | -4.6 |
| Green - purple | 12.3 | 3.3 | 2.3 | -3.7 | -1.7 | -4.7 | 3.3 | 0.3 |
| Red - clock | 6.9 | 5.9 | -0.1 | -1.1 | 3.9 | -2.1 | 1.9 | 3.9 |
| Red - window | 36.9 | 21.9 | -0.1 | -6.1 | -0.1 | -6.1 | 7.9 | -4.1 |
| Red - purple | 22.9 | 0.9 | 0.9 | -1.1 | 14.9 | 1.9 | 0.9 | -2.1 |
| Clock - window | 22.0 | 37.0 | 0.0 | 1.0 | 5.0 | -3.0 | -5.0 | 2.0 |
| Clock - purple | 9.0 | -5.1 | -1.1 | -1.1 | -5.1 | -5.1 | 0.9 | 0.9 |
| Window - purple | 29.6 | 39.6 | 2.6 | -4.4 | 7.6 | -4.4 | 13.6 | -3.4 |

## Three period of exploration (unsigned route errors)

| Route | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| Red - green | 0.5 | 3.0 | 0.0 | 2.5 | 2.5 | 0.0 | 4.5 | 3.0 |
| Clock - green | 8.0 | 10.0 | 8.5 | 8.8 | 6.0 | 0.0 | 3.0 | 4.5 |
| Window-green | 15.5 | 3.0 | 10.0 | 15.0 | 24.5 | 15.0 | 23.0 | 12.5 |
| Purple - green | 10.5 | 14.0 | 8.5 | 8.0 | 10.5 | 8.0 | 11.0 | 7.5 |
| Clock - red | 7.5 | 8.0 | 5.5 | 8.0 | 5.5 | 5.0 | 6.5 | 7.0 |
| Window - red | 25.0 | 5.0 | 12.5 | 12.5 | 24.0 | 17.0 | 29.0 | 14.5 |
| Purple - red | 15.0 | 16.0 | 9.5 | 10.5 | 4.0 | 5.0 | 14.0 | 7.5 |
| Window - clock | 18.0 | 0.5 | 4.5 | 7.5 | 19.5 | 16.0 | 18.0 | 10.0 |
| Purple - clock | 8.0 | 15.0 | 3.0 | 5.0 | 11.0 | 6.0 | 10.5 | 5.5 |
| Purple - window | 22.0 | 7.0 | 13.0 | 13.5 | 20.0 | 17.0 | 22.0 | 13.0 |

## Three period of exploration (unsigned Euclidean errors)

| Euclidean | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| Red - green | 1.9 | 0.1 | 1.9 | 1.6 | 2.1 | 2.1 | 1.9 | 1.6 |
| Clock - green | 3.3 | 0.3 | 4.7 | 5.7 | 1.7 | 5.7 | 1.7 | 2.2 |
| Window-green | 21.9 | 39.4 | 4.4 | 5.6 | 4.1 | 5.6 | 3.4 | 5.6 |
| Purple - green | 9.8 | 1.3 | 1.3 | 4.2 | 2.2 | 6.2 | 0.7 | 2.2 |
| Clock - red | 10.4 | 3.9 | 0.4 | 1.1 | 3.9 | 2.1 | 0.9 | 1.4 |
| Window - red | 36.9 | 31.9 | 1.9 | 4.6 | 0.9 | 3.6 | 6.9 | 3.1 |
| Purple - red | 17.9 | 2.9 | 0.9 | 0.9 | 10.9 | 3.4 | 2.9 | 1.4 |
| Window - clock | 22.0 | 39.5 | 1.5 | 0.0 | 2.0 | 4.0 | 1.0 | 1.5 |
| Purple - clock | 6.5 | 4.1 | 0.9 | 2.1 | 4.1 | 5.1 | 3.0 | 3.0 |
| Purple - window | 25.6 | 39.6 | 0.6 | 4.4 | 4.6 | 2.4 | 6.6 | 2.4 |

## Map learning (judgements)

| Judgement | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| Red-green | 15.0 | 12.0 | 10.0 | 10.0 | 10.0 | 20.0 | 20.0 | 4.0 |
| Clock-green | 10.0 | 12.0 | 10.0 | 12.0 | 10.0 | 16.0 | 40.0 | 6.0 |
| Window-green | 30.0 | 26.0 | 20.0 | 17.0 | 22.0 | 40.0 | 54.0 | 12.0 |
| Purple-green | 34.0 | 16.0 | 14.0 | 18.0 | 12.0 | 28.0 | 14.0 | 9.0 |
| Clock-red | 12.0 | 16.0 | 16.0 | 14.0 | 15.0 | 24.0 | 30.0 | 4.0 |
| Window-red | 20.0 | 22.0 | 20.0 | 14.0 | 20.0 | 32.0 | 60.0 | 9.0 |
| Purple-red | 20.0 | 12.0 | 10.0 | 10.0 | 8.0 | 16.0 | 24.0 | 10.0 |
| Window-clock | 25.0 | 14.0 | 16.0 | 12.0 | 18.0 | 24.0 | 45.0 | 10.0 |
| Purple-clock | 40.0 | 14.0 | 16.0 | 12.0 | 10.0 | 16.0 | 20.0 | 7.0 |
| Purple-window | 25.0 | 14.0 | 20.0 | 11.0 | 10.0 | 20.0 | 32.0 | 14.0 |
| Green - red | 15.0 | 6.0 | 12.0 | 11.0 | 9.0 | 24.0 | 30.0 | 4.0 |
| Green - clock | 20.0 | 8.0 | 10.0 | 15.0 | 5.0 | 20.0 | 36.0 | 8.0 |
| Green- window | 25.0 | 22.0 | 20.0 | 20.0 | 30.0 | 40.0 | 48.0 | 16.0 |
| Green - purple | 30.0 | 16.0 | 16.0 | 15.0 | 12.0 | 32.0 | 28.0 | 8.0 |
| Red - clock | 25.0 | 20.0 | 16.0 | 14.0 | 13.0 | 24.0 | 16.0 | 5.0 |
| Red - window | 30.0 | 14.0 | 22.0 | 16.0 | 15.0 | 24.0 | 38.0 | 9.0 |
| Red - purple | 40.0 | 16.0 | 8.0 | 8.0 | 8.0 | 16.0 | 24.0 | 4.0 |
| Clock - window | 30.0 | 20.0 | 20.0 | 12.0 | 20.0 | 28.0 | 45.0 | 7.0 |
| Clock - purple | 40.0 | 16.0 | 10.0 | 10.0 | 10.0 | 20.0 | 38.0 | 5.0 |
| Window-purple | 30.0 | 12.0 | 14.0 | 8.0 | 18.0 | 20.0 | 36.0 | 8.0 |

## Map learning (signed Euclidean errors)

| Euclidean errors | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| Red-green | 6.9 | 3.9 | 1.9 | 1.9 | 1.9 | 11.9 | 11.9 | -4.1 |
| Clock-green | -1.1 | 0.9 | -1.1 | 0.9 | -1.1 | 4.9 | 28.9 | -5.1 |
| Window-green | 9.4 | 5.4 | -0.6 | -3.6 | 1.4 | 19.4 | 33.4 | -8.6 |
| Purple-green | 21.3 | 3.3 | 1.3 | 5.3 | -0.7 | 15.3 | 1.3 | -3.7 |
| Clock-red | 3.9 | 7.9 | 7.9 | 5.9 | 6.9 | 15.9 | 21.9 | -4.1 |
| Window-red | 1.9 | 3.9 | 1.9 | -4.1 | 1.9 | 13.9 | 41.9 | -9.1 |
| Purple-red | 12.9 | 4.9 | 2.9 | 2.9 | 0.9 | 8.9 | 16.9 | 2.9 |
| Window-clock | 12.0 | 1.0 | 3.0 | -1.0 | 5.0 | 11.0 | 32.0 | -3.0 |
| Purple-clock | 29.0 | 3.0 | 5.0 | 0.9 | -1.1 | 5.0 | 9.0 | -4.1 |
| Purple-window | 14.6 | 3.6 | 9.6 | 0.6 | -0.4 | 9.6 | 21.6 | 3.6 |
| Green - red | 6.9 | -2.1 | 3.9 | 2.9 | 0.9 | 15.9 | 21.9 | -4.1 |
| Green - clock | 8.9 | -3.1 | -1.1 | 3.9 | -6.1 | 8.9 | 24.9 | -3.1 |
| Green- window | 4.4 | 1.4 | -0.6 | -0.6 | 9.4 | 19.4 | 27.4 | -4.6 |
| Green - purple | 17.3 | 3.3 | 3.3 | 2.3 | -0.7 | 19.3 | 15.3 | -4.7 |
| Red - clock | 16.9 | 11.9 | 7.9 | 5.9 | 4.9 | 15.9 | 7.9 | -3.1 |
| Red - window | 11.9 | -4.1 | 3.9 | -2.1 | -3.1 | 5.9 | 19.9 | -9.1 |
| Red - purple | 32.9 | 8.9 | 0.9 | 0.9 | 0.9 | 8.9 | 16.9 | -3.1 |
| Clock - window | 17.0 | 7.0 | 7.0 | -1.0 | 7.0 | 15.0 | 32.0 | -6.0 |
| Clock - purple | 29.0 | 5.0 | -1.1 | -1.1 | -1.1 | 9.0 | 27.0 | -6.1 |
| Window-purple | 19.6 | 1.6 | 3.6 | -2.4 | 7.6 | 9.6 | 25.6 | -2.4 |

# Map learning (unsigned route errors)

| Route errors | s1 | s2 | s3 | s4 | s5 | s6 | s7 | s8 |
|---|---|---|---|---|---|---|---|---|
| Red-green | 1.5 | 8.0 | 2.0 | 1.5 | 1.5 | 9.0 | 22.0 | 7.0 |
| Clock-green | 24.5 | 4.0 | 2.0 | 2.0 | 5.0 | 14.0 | 24.0 | 8.5 |
| Window-green | 13.0 | 11.0 | 9.0 | 20.0 | 8.0 | 13.0 | 30.5 | 27.0 |
| Purple-green | 11.0 | 7.0 | 8.0 | 6.0 | 8.0 | 10.0 | 20.0 | 13.5 |
| Clock-red | 5.0 | 2.0 | 3.0 | 2.0 | 7.5 | 10.0 | 23.0 | 11.5 |
| Window-red | 7.5 | 10.0 | 9.5 | 20.5 | 9.5 | 3.0 | 33.0 | 32.0 |
| Purple-red | 15.0 | 6.0 | 5.0 | 9.0 | 9.0 | 1.0 | 16.0 | 15.5 |
| Window-clock | 8.0 | 11.0 | 14.0 | 20.0 | 8.0 | 10.0 | 22.0 | 27.0 |
| Purple-clock | 2.5 | 9.0 | 8.0 | 7.0 | 10.5 | 8.0 | 18.0 | 13.5 |
| Purple-window | 13.0 | 4.0 | 11.0 | 19.0 | 4.5 | 11.0 | 13.0 | 26.0 |

# Map learning (unsigned Euclidean errors)

| Euclidean errors | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| Red-green | 6.9 | 0.9 | 2.9 | 2.4 | 1.4 | 13.9 | 16.9 | 4.1 |
| Clock-green | 3.9 | 1.1 | 1.1 | 2.4 | 3.6 | 6.9 | 26.9 | 4.1 |
| Window-green | 6.9 | 3.4 | 0.6 | 2.1 | 5.4 | 19.4 | 30.4 | 6.6 |
| Purple-green | 19.3 | 3.3 | 2.3 | 3.8 | 0.7 | 17.3 | 8.3 | 4.2 |
| Clock-red | 10.4 | 9.9 | 7.9 | 5.9 | 5.9 | 15.9 | 14.9 | 3.6 |
| Window-red | 6.9 | 0.1 | 2.9 | 3.1 | 0.6 | 9.9 | 30.9 | 9.1 |
| Purple-red | 22.9 | 6.9 | 1.9 | 1.9 | 0.9 | 8.9 | 16.9 | 0.1 |
| Window-clock | 14.5 | 4.0 | 5.0 | 1.0 | 6.0 | 13.0 | 32.0 | 4.5 |
| Purple-clock | 29.0 | 4.0 | 2.0 | 0.1 | 1.1 | 7.0 | 18.0 | 5.1 |
| Purple-window | 17.1 | 2.6 | 6.6 | 0.9 | 3.6 | 9.6 | 23.6 | 0.6 |

# 8.6 Experiment VI

All judgements and errors for experiment V are in units of distance unless otherwise stated.

## Euclidean judgements (units of distance)

| *Subject* | Control | 1a | 1b | 2a | 2b |
|---|---|---|---|---|---|
| 1 | 60 | 30 | 10 | 25 | 30 |
| 2 | 100 | 50 | 20 | 40 | 70 |
| 3 | 25 | 15 | 20 | 15 | 25 |
| 4 | | 26 | 4 | 30 | |
| 5 | 58 | 5 | 10 | 20 | 20 |
| 6 | 100 | 25 | 15 | 20 | 30 |
| 7 | 60 | 10 | 18 | 40 | 20 |
| 8 | 33 | 30 | 30 | 10 | 20 |
| 9 | 100 | 25 | 10 | 60 | 50 |
| 10 | 100 | 35 | 8 | 20 | 20 |
| 11 | 45 | 30 | 30 | 30 | 40 |
| 12 | 100 | 40 | 30 | 45 | 45 |
| 13 | 42 | 35 | 38 | 27 | 45 |
| 14 | 50 | 20 | 15 | 0 | 30 |
| 15 | 50 | 28 | 35 | 25 | 34 |
| 16 | 50 | 40 | 40 | 40 | 40 |

## Euclidean errors (units of distance)

| *Errors* | Control | 1a | 1b | 2a | 2b |
|---|---|---|---|---|---|
| 1 | 0.0 | 24.3 | 4.3 | -5.1 | -0.1 |
| 2 | 40.0 | 44.3 | 14.3 | 9.9 | 39.9 |
| 3 | -35.0 | 9.3 | 14.3 | -15.1 | -5.1 |
| 4 | | 20.3 | -1.7 | -0.1 | |
| 5 | -2.0 | -0.7 | 4.3 | -10.1 | -10.1 |
| 6 | 40.0 | 19.3 | 9.3 | -10.1 | -0.1 |
| 7 | 0.0 | 4.3 | 12.3 | 9.9 | -10.1 |
| 8 | -27.0 | 24.3 | 24.3 | -20.1 | -10.1 |
| 9 | 40.0 | 19.3 | 4.3 | 29.9 | 19.9 |
| 10 | 40.0 | 29.3 | 2.3 | -10.1 | -10.1 |
| 11 | -15.0 | 24.3 | 24.3 | -0.1 | 9.9 |
| 12 | 40.0 | 34.3 | 24.3 | 14.9 | 14.9 |
| 13 | -18.0 | 29.3 | 32.3 | -3.1 | 14.9 |
| 14 | -10.0 | 14.3 | 9.3 | -30.1 | -0.1 |
| 15 | -10.0 | 22.3 | 29.3 | -5.1 | 3.9 |
| 16 | -10.0 | 34.3 | 34.3 | 9.9 | 9.9 |

## Route judgements (units of distance)

| Subject | Control | 1a | 1b | 2a | 2b |
|---|---|---|---|---|---|
| 1 | 60 | 50 | 60 | 50 | 50 |
| 2 | 100 | 80 | 35 | 70 | 100 |
| 3 | 24 | 20 | 30 | 30 | 40 |
| 4 | | 50 | 49 | 46 | 45 |
| 5 | 58 | 35 | 50 | 30 | 40 |
| 6 | 100 | 55 | 70 | 80 | 70 |
| 7 | 60 | 50 | 50 | 50 | 40 |
| 8 | 33 | 48 | 42 | 42 | 33 |
| 9 | 100 | 100 | 60 | 75 | 80 |
| 10 | 100 | 45 | 47 | 45 | 45 |
| 11 | 45 | 60 | 60 | 55 | 60 |
| 12 | 100 | 64 | 53 | 70 | 70 |
| 13 | 42 | 42 | 42 | 35 | 53 |
| 14 | 50 | 50 | 55 | 50 | 44 |
| 15 | 56 | 34 | 49 | 32 | 45 |
| 16 | 60 | 60 | 80 | 90 | 80 |

## Route errors (units of distance)

| *Subject* | *Control* | *1a* | *1b* | *2a* | *2b* |
|---|---|---|---|---|---|
| 1 | 0 | -10 | 0 | -10 | -10 |
| 2 | 40 | 20 | -25 | 10 | 40 |
| 3 | -36 | -40 | -30 | -30 | -20 |
| 4 | -60 | -10 | -11 | -14 | -15 |
| 5 | -2 | -25 | -10 | -30 | -20 |
| 6 | 40 | -5 | 10 | 20 | 10 |
| 7 | 0 | -10 | -10 | -10 | -20 |
| 8 | -27 | -12 | -18 | -18 | -27 |
| 9 | 40 | 40 | 0 | 15 | 20 |
| 10 | 40 | -15 | -13 | -15 | -15 |
| 11 | -15 | 0 | 0 | -5 | 0 |
| 12 | 40 | 4 | -7 | 10 | 10 |
| 13 | -18 | -18 | -18 | -25 | -7 |
| 14 | -10 | -10 | -5 | -10 | -16 |
| 15 | -4 | -26 | -11 | -28 | -15 |
| 16 | 0 | 0 | 20 | 30 | 20 |

## Judgements of angles (degrees)

| *Subject* | *Control* | *1a* | *1b* | *2a* | *2b* |
|---|---|---|---|---|---|
| 1 | 5 | 60 | 45 | 0 | 10 |
| 2 | 0 | 90 | 90 | 45 | 0 |
| 3 | 0 | 45 | 65 | 25 | 50 |
| 4 | 0 | 70 | 145 | 10 | |
| 5 | 0 | -90 | 110 | 10 | 0 |
| 6 | 0 | 95 | -10 | 60 | 5 |
| 7 | 0 | 180 | 90 | 25 | 45 |
| 8 | 0 | 10 | 10 | 90 | -70 |
| 9 | 0 | 90 | 180 | 0 | 0 |
| 10 | 0 | -45 | 90 | | 0 |
| 11 | 0 | 80 | -70 | 25 | 35 |
| 12 | 0 | 135 | 315 | 0 | -45 |
| 13 | 0 | 90 | 45 | 45 | 0 |
| 14 | 0 | 4 | 160 | 0 | 45 |
| 15 | -15 | 45 | 30 | 45 | 45 |
| 16 | -45 | 30 | 315 | 20 | 0 |

## Unsigned Errors (degrees)

| | *Control* | *1a* | *1b* | *2a* | *2b* |
|---|---|---|---|---|---|
| 1 | 5 | 9 | -94 | -10 | 1.5 |
| 2 | 0 | 39 | -49 | 35 | -8.5 |
| 3 | 0 | -6 | -74 | 15 | 41.5 |
| 4 | 0 | 19 | 6 | 0 | -8.5 |
| 5 | 0 | -141 | -29 | 0 | -8.5 |
| 6 | 0 | 44 | -149 | 50 | -3.5 |
| 7 | 0 | 129 | -49 | 15 | 36.5 |
| 8 | 0 | -41 | -129 | 80 | -78.5 |
| 9 | 0 | 39 | 41 | -10 | -8.5 |
| 10 | 0 | -96 | -49 | -10 | -8.5 |
| 11 | 0 | 29 | -29 | 15 | 26.5 |
| 12 | 0 | 84 | 176 | -10 | -53.5 |
| 13 | 0 | 39 | -94 | 35 | -8.5 |
| 14 | 0 | -47 | 21 | -10 | 36.5 |
| 15 | -15 | -6 | -109 | 35 | 36.5 |
| 16 | -45 | -21 | 176 | 10 | -8.5 |

Signed Errors (degrees)

| *Unsigned* | *Control* | *1a* | *1b* | *2a* | *2b* |
|---|---|---|---|---|---|
| 1 | 5 | 9 | 94 | 10 | 1.5 |
| 2 | 0 | 39 | 49 | 35 | 8.5 |
| 3 | 0 | 6 | 74 | 15 | 41.5 |
| 4 | 0 | 19 | 6 | 0 | 8.5 |
| 5 | 0 | 141 | 29 | 0 | 8.5 |
| 6 | 0 | 44 | 149 | 50 | 3.5 |
| 7 | 0 | 129 | 49 | 15 | 36.5 |
| 8 | 0 | 41 | 129 | 80 | 78.5 |
| 9 | 0 | 39 | 41 | 10 | 8.5 |
| 10 | 0 | 96 | 49 | 10 | 8.5 |
| 11 | 0 | 29 | 29 | 15 | 26.5 |
| 12 | 0 | 84 | 176 | 10 | 53.5 |
| 13 | 0 | 39 | 94 | 35 | 8.5 |
| 14 | 0 | 47 | 21 | 10 | 36.5 |
| 15 | 15 | 6 | 109 | 35 | 36.5 |
| 16 | 45 | 21 | 176 | 10 | 8.5 |

## 8.7 Experiment VII

### Signed errors (units of distance)

| Condition | Exploration | Judgement | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|---|---|
| no clutter | Direct exploration | J1 | 1.4 | -1.6 | -2.6 | -0.6 | -0.6 | 1.4 | -1.6 | 5.4 |
| | | J2 | -1.2 | -3.2 | -3.2 | -1.2 | -2.2 | 8.8 | -4.2 | -3.2 |
| | | J3 | -3.2 | -2.2 | -2.2 | -0.2 | -1.2 | 3.8 | -6.2 | -2.2 |
| | | | S9 | S10 | S11 | S12 | S13 | S14 | S15 | S16 |
| | Indirect exploration | J1 | -2.6 | -1.6 | -2.6 | -0.6 | -6.6 | -1.9 | -2.1 | -2.6 |
| | | J2 | -1.7 | -1.7 | -2.2 | -2.2 | -2.2 | 1.4 | -3.2 | -2.2 |
| | | J3 | -2.2 | -1.2 | -4.2 | -1.2 | -2.2 | -4.3 | -2.2 | -2.2 |
| | | | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
| clutter | Direct exploration | J4 | -4.4 | -4.4 | -6.4 | 1.6 | -2.4 | -2.4 | -4.4 | 11.6 |
| | | J5 | 4.6 | -1.4 | 0.6 | 0.6 | 0.6 | 3.6 | -2.4 | -0.4 |
| | | J6 | -1.8 | -2.8 | -3.8 | 1.2 | 0.2 | 2.2 | -8.8 | -0.8 |
| | | | S9 | S10 | S11 | S12 | S13 | S14 | S15 | S16 |
| | Indirect exploration | J4 | -4.4 | -3.4 | -1.4 | -13.4 | -3.4 | -5.4 | -4.4 | -6.4 |
| | | J5 | -3.4 | 1.6 | 0.6 | -3.4 | -2.4 | -1.4 | 0.6 | 3.6 |
| | | J6 | -7.8 | -1.1 | -3.8 | -4.8 | -7.8 | -0.8 | -3.8 | -7.8 |

### Unsigned errors (units of distance)

| Condition | Exploration | Judgement | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|---|---|
| no clutter | Direct exploration | J1 | 1.4 | 1.6 | 2.6 | 0.6 | 0.6 | 1.4 | 1.6 | 5.4 |
| | | J2 | 1.2 | 3.2 | 3.2 | 1.2 | 2.2 | 8.8 | 4.2 | 3.2 |
| | | J3 | 3.2 | 2.2 | 2.2 | 0.2 | 1.2 | 3.8 | 6.2 | 2.2 |
| | | | S9 | S10 | S11 | S12 | S13 | S14 | S15 | S16 |
| | Indirect exploration | J1 | 2.6 | 1.6 | 2.6 | 0.6 | 6.6 | 1.9 | 2.1 | 2.6 |
| | | J2 | 1.7 | 1.7 | 2.2 | 2.2 | 2.2 | 1.4 | 3.2 | 2.2 |
| | | J3 | 2.2 | 1.2 | 4.2 | 1.2 | 2.2 | 4.3 | 2.2 | 2.2 |
| | | | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
| clutter | Direct exploration | J4 | 4.4 | 4.4 | 6.4 | 1.6 | 2.4 | 2.4 | 4.4 | 11.6 |
| | | J5 | 4.6 | 1.4 | 0.6 | 0.6 | 0.6 | 3.6 | 2.4 | 0.4 |
| | | J6 | 1.8 | 2.8 | 3.8 | 1.2 | 0.2 | 2.2 | 8.8 | 0.8 |
| | | | S9 | S10 | S11 | S12 | S13 | S14 | S15 | S16 |
| | Indirect exploration | J4 | 4.4 | 3.4 | 1.4 | 13.4 | 3.4 | 5.4 | 4.4 | 6.4 |
| | | J5 | 3.4 | 1.6 | 0.6 | 3.4 | 2.4 | 1.4 | 0.6 | 3.6 |
| | | J6 | 7.8 | 1.1 | 3.8 | 4.8 | 7.8 | 0.8 | 3.8 | 7.8 |

## 8.8 Experiment VIII

### Scanning time

| | *J1* | *J2* | *J3* | *J4* | *J5* | *J6* | *J7* | *J8* | *J9* | *J10* |
|---|---|---|---|---|---|---|---|---|---|---|
| set 1 | 2.90 | 2.47 | 3.51 | 2.81 | 3.24 | 2.74 | 4.34 | 3.05 | 4.35 | 3.34 |
| set 2 | 2.85 | 2.68 | 4.06 | 3.55 | 3.75 | 4.32 | 3.92 | 4.20 | 4.66 | 2.87 |
| mean scan time | 2.88 | 2.57 | 3.78 | 3.18 | 3.49 | 3.53 | 4.13 | 3.62 | 4.51 | 3.11 |
| distance | 2.83 | 2.83 | 5.66 | 6.32 | 6.71 | 9.22 | 10.00 | 10.77 | 11.70 | 13.15 |

### Time to locate

| | *J1* | *J2* | *J3* | *J4* | *J5* | *J6* | *J7* | *J8* | *J9* | *J10* |
|---|---|---|---|---|---|---|---|---|---|---|
| set 1 | 3.6 | 2.7 | 4.2 | 3.8 | 2.3 | 3.0 | 3.3 | 3.8 | 2.6 | 2.7 |
| set 2 | 3.1 | 2.8 | 3.7 | 2.2 | 2.0 | 2.7 | 2.4 | 3.6 | 3.1 | 2.5 |
| mean time | 3.4 | 2.8 | 4.0 | 3.0 | 2.1 | 2.8 | 2.9 | 3.7 | 2.8 | 2.6 |
| distance | 2.83 | 2.83 | 5.66 | 6.32 | 6.71 | 9.22 | 10.00 | 10.77 | 11.70 | 13.15 |

# 9. Appendix B

## Introduction

The virtual reality system used in experiments II-VIII inclusive is a *publicware* pair of applications consisting of Mapedit and ACK3D.

## Mapedit

This application presents the user with a 64x64 grid which may be populated with either graphical blocks or free standing objects. Figure 9-1, left, illustrates the grid, a green graphics block and a free standing ceiling light.

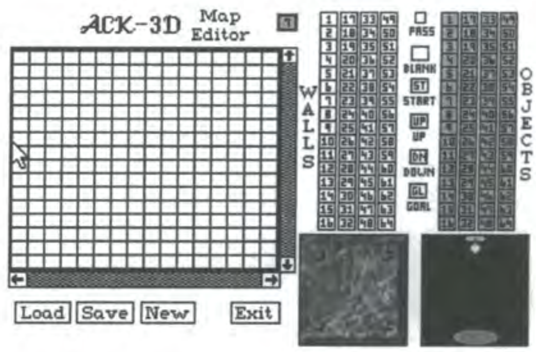


*Figure 9-1*

Figure 9-2 illustrates a partially populated grid. The numbers round the edge of the grid represent a continuous wall of blocks, while an intervening wall may be seen running from left to right. A ceiling light has been placed just beyond the wall.

This configuration may then be saved to a file.

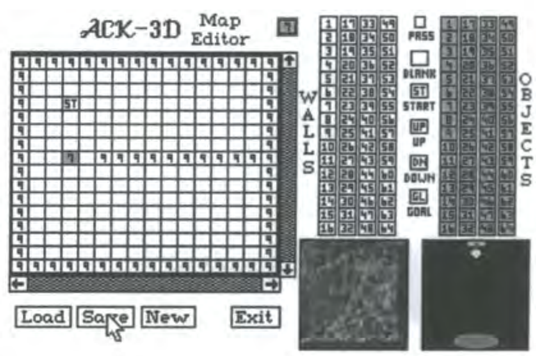


*Figure 9-2*

Figure 9-3 illustrates what the end result when this configuration is executed using ACK3D.

*Figure 9-3*

## ACK3D

ACK3D is the animation program which executes the configuration saved in the file generated from the mapedit utility. The virtual environment generated by ACK3D is navigated by means of the keyboard or a mouse.