Distance Estimation in Minimal Virtual Environments

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This paper reports on an experimental study into distance estimation in a simple virtual environment. The results have been then compared with an experimental study of spatial cognition in the real world. It is concluded that the minimal virtual environment resembles a *restricted* Euclidean environment (or Euclidean environments viewed in a restricted or blinkered manner).

Keywords: cognitive maps, distance estimation, virtual environments

1. Spatial cognition and virtual environments

This paper begins by addressing the question of how we navigate the virtual environments presented to us in non-immersive desktop virtual reality games. As very little research has addressed this specific question to date, it seems reasonable to assume that psychological research into real-world spatial cognition may offer a starting point for investigating virtual navigation.

1.1 Spatial cognition

Much research in spatial cognition has focused on the concept of *cognitive mapping*, which can be 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 vary greatly in nature. The notion of the cognitive map can be traced in the psychological literature as far back as Gulliver in 1908, but it is Tolman

(1948) who is widely credited with the development of the concept. The appeal of the term *cognitive map* is that it is immediately, although superficially, clear what is meant. An initial view of a cognitive map might be ...*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 still does not exist. One reason for this may be that research in this area has been informed by a number of different sources and disciplines which have included geography (e.g. Gould and White, 1974), developmental psychology (e.g. Kosslyn, Pick and Fariello, 1974), environmental psychology (e.g. Evans, 1980), cognitive psychology (e.g. Baum and Jonides, 1979; Thorndyke and Hayes-Roth, 1982; Tversky, 1993). The following selection of definitions of cognitive maps illustrate this diversity:

- Tolman (1948) discussing experimental data from rats: '...*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*.'
- Kuipers (1978) identifies 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 are both less and more 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) suggest that cognitive maps are networks of stimulus-response-stimulus connections, 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...
- Menzel (1987) writes from the perspective of a comparative psychologist: '*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... 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 and as such do not offer a firm basis for research into spatial cognition in virtual environments. However there are a small number of empirically-based models of aspects of spatial cognition which could be used as a theoretical basis for virtual reality research. One such model is Thorndyke and Hayes-Roth's (1982) account of distance estimation.

1.2 Thorndyke and Hayes-Roth

Thorndyke and Hayes-Roth began with the following premises: spatial knowledge acquired from the free exploration of the environment is qualitatively different from spatial knowledge acquired from maps. 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 go on to model how Euclidean (*as the crow flies*) and route distance estimates are made. The table below summarises their position.

Euclidean judgements	***Route judgements***
Mentally simulate route	Mentally simulate route
Estimate leg lengths	Estimate leg lengths
Estimate turning angles	Sum lengths
Perform informal algebra	Generate response
Generate response	

As can be seen from this Thorndyke and Hayes-Roth have 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.

1.2.1 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. Thorndyke and Hayes-Roth selected as their environment the first floor of the Rand Corporation in Santa Monica, USA. 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, their subjects were required to learn a map of the building so that they could reproduce it without error. 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.

1.3 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. In contrast the groups which had studied the map of the building produced relatively inaccurate route estimates which did not improve with additional study.
- 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. Again the groups which had studied the map of the building produced a different pattern of results. Their Euclidean judgements proved to be accurate (much more so than the route judgements) but did not improve with extended study.

1.4 In summary

Thorndyke and Hayes-Roth have produced a model of large scale 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 Euclidean estimates this difference diminishes with increased exploration. No such improvement is observed in the map learning.
Armed with these findings a basis for comparison between distance estimation in the real world and a virtual environment can be made.

2. Thorndyke and Hayes-Roth in the virtual world

In contrast to Thorndyke and Hayes-Roth, the investigation we report here used a very simple virtual environment was in place of a real building. This virtual 'building' 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 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'). For practical reasons, only the Euclidean and route distance estimates were investigated.
While the differences between this investigation and Thorndyke and Hayes-Roth's are pronounced, there are no *a priori* reasons to suppose that they affect the validity of the comparison.

2.1 The virtual environment

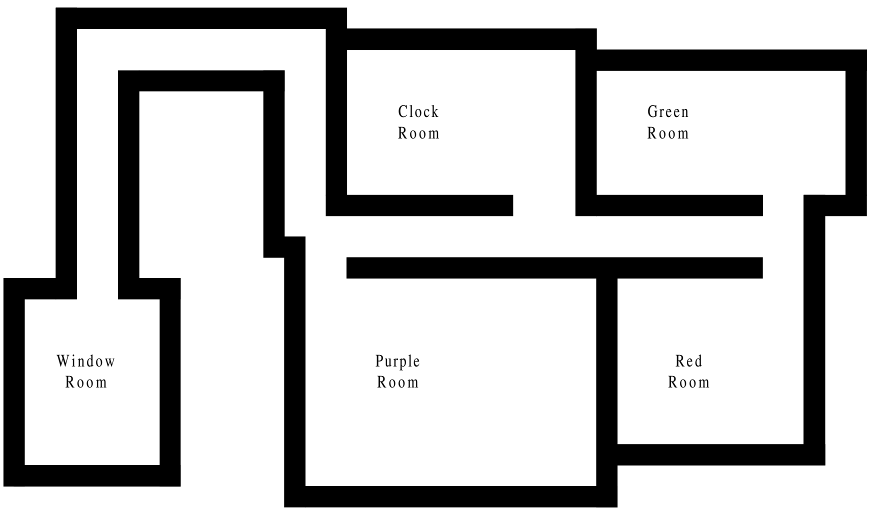

Figure 1

Figure 1 is a representation of the virtual building which was created using the PC application ACK3D (see appendix for a description of this application).

This study only *parallels* 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.

2.2 Distance estimation

The vexed quesiton of how distances can be estimated in a virtual environment must now be addressed. In this particular study the virtual environment was constructed from regular graphic blocks which necessarily provide a considerable amount of metric information. Figure 2 illustrates one such virtual environment constructed from these blocks. The participants in this study were thus asked to estimate distances in terms of numbers of these blocks. It must be stressed that while the temptation to count distances may have existed, participants were asked to estimate (from memory) distances and indeed the results indicate that explicit counting did not take place.

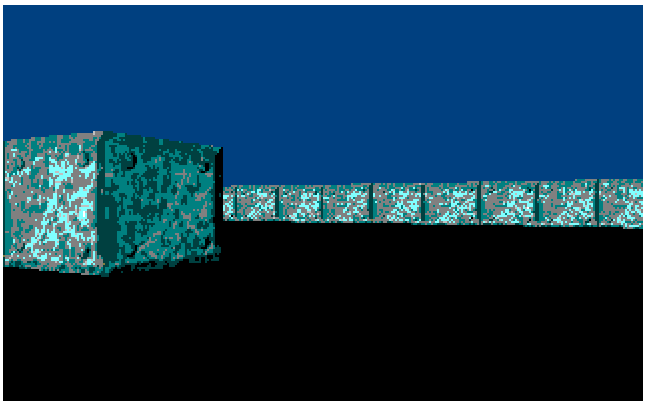

Figure 2

2.3 Inter-feature estimation

Following Thorndyke and Hayes-Roth, the participants in this study were asked to estimate the route and Euclidean distances between the centres of each of the five rooms. Each estimate was made twice (that is, A to B, B to A).

3. Results

Free exploration of this 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.

The apparent independence of the Euclidean estimates from route estimates is the most striking feature of the results from this study. As discussed above Thorndyke and Hayes-Roth had suggested that route judgements plus 'mental algebra' is used to produce estimates of Euclidean distances based route estimates. Yet results from this study have demonstrated that route judgements are systematically inaccurate (increasingly so as the distance to estimate increase) and vary as a function of the distance to judge while the Euclidean judgements are relatively accurate independent of the distance to judge. As accurate Euclidean judgements cannot be consistently made from inaccurate route judgements they must have been arrived at independently.

3.1 Distance estimation: No improvement in accuracy with practice

This study 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 slightly decreased. Although these results are counter-intuitive, support for the findings of this study comes from an experiment reported by Kozlowski and Bryant (1977) who failed to find improvements in accuracy in judgements of distance as a function of trials after subjects explored a windowless maze.

3.2 Distance estimation: correlations

Comparing errors in judgements with the actual distances further confirms the independence of the process by which route and Euclidean judgements are made. Figure 3 is a graph of the line of best fit plotting the errors made in judging route distances against the actual route distance for the one period of exploration condition (as the graph for the three periods of exploration is almost identical it has been omitted). However, this also poses 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 (e.g. Kosslyn, 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.

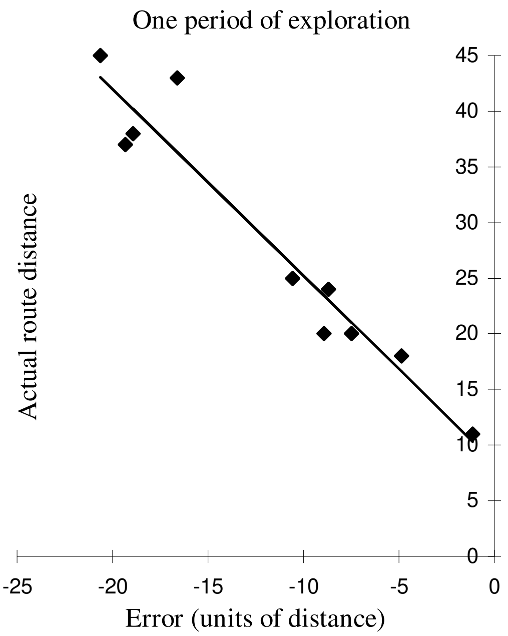

Figure 3

4. Some words of conclusion

On the balance of evidence it would appear that the exploration of virtual environments give rise to primary spatial knowledge, that is spatial knowledge which has similar characteristics to that which is acquired from exploring the real world rather than secondary spatial knowledge (derived from maps and figures). But it might be more accurately described as being most like spatial knowledge acquired from a *restricted Euclidean environment* or acquired from a Euclidean environment *presented* in a restricted manner. Examples of what is meant by restricted Euclidean environment are such things tunnels or caves, where the field of view is restricted in some way. In contrast, a restricted presentation of a Euclidean environment might include exploring the world while wearing a helmet or blinkers or watching a television or a motion picture. Indeed the highly trained astronauts of Apollo XIV failed to find Hadley Rille despite being within 10 metres of it (Chaikin, 1994), here raising the question of whether their helmets interfered. Inevitably further work is required to distinguish between whether these two possibilities.

5. Acknowledgements

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7. Appendix

The minimal virtual reality system used in this experiment is a *public-ware* pair of applications consisting of Mapedit and ACK3D.

Mapedit presents the user with a 64x64 grid which may be populated with either graphical blocks or free standing objects. Figure 4, left, illustrates the grid, a green graphics block and a free standing ceiling light.

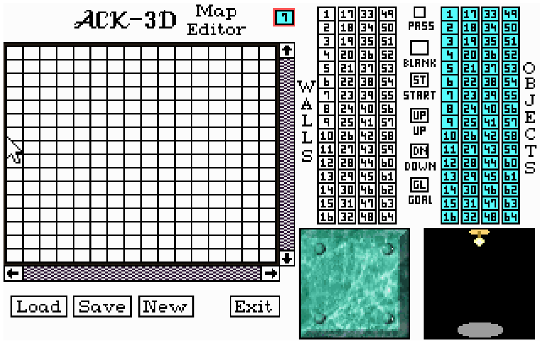

Figure 4

Figure 5 illustrates what the end result when this configuration is executed using ACK3D.

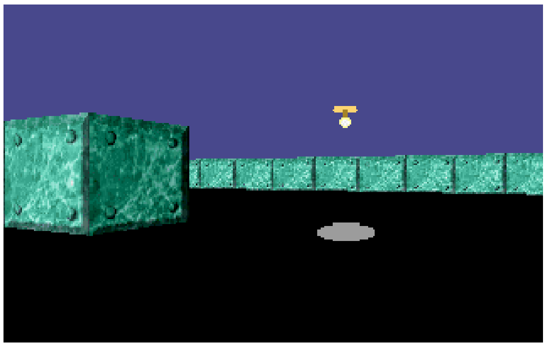

Figure 5