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Exosomatic Route Choice in Navigation

Evidence from video game player data

SAM McELHINNEY[1], FIONA ZISCH[2], MICHAEL HORNBERGER[3], ANTOINE COUTROT[4], HUGO SPIERS[5], SEAN HANNA[6]

ABSTRACT

We investigate the extent to which navigation may be performed using exosomatic cues directly viewed in the environment, as opposed to relying on memory of a map or mental representation. Using trajectory data from a virtual navigation game app, Sea Hero Quest, we analyse the moment to moment route choices of 200 participants, and compare these against the expected routes based on several spatial variables measured from current isovists. Observations suggest that there is substantial evidence that for most participants navigation in a novel environment is indeed largely based on direct exosomatic information, and is based specifically on the space actually viewed, as opposed to that inferred by the shape of occluding edges. We also find evidence that strategies differ between individuals, in that the better navigators will deviate more from the exosomatic method, and rely more on their own memory and internal knowledge of the environment.

KEYWORDS

Spatial Cognition, Wayfinding, Isovists

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1 INTRODUCTION

The information on which we rely to navigate may come either from the environment we observe in the present moment, or internal representations constructed from guides, simple choices and inferences. Space Syntax models sometimes take the former, simpler view, such as the exosomatic hypothesis (Turner and Penn 2002) of memoryless agents, and sometimes suggest the latter, such as the angular route optimization implied by segment choice (Hillier and Iida 2005), but the actual cognitive strategies of an individual remain unclear. Our paper addresses two related questions: To what extent do we take our navigational information directly from our environment (i.e. exosomatic navigation)? And to the extent we do, what are the local spatial variables that inform our choice: seen information, such as visible area (as used by the visual agents of Turner and Penn 2002), unseen information, such as that implied by occlusive edges, or some other factor?

The difficulty in addressing these questions is partly methodological and partly due to availability of data; Space Syntax models have typically represented aggregate movement rather than individual decisions and paths. The correlations that such models find between predicted and observed aggregate movement cannot distinguish between a case of many individuals acting entirely upon external cues and one in which they plan routes based on internal models, given that individual choices are not preserved in the data.

We employ an alternative approach, in which we draw on data collected from the single player navigation game app, Sea Hero Quest. In Sea Hero Quest players start a level with a view of a map indicating the environment and checkpoints to reach, which is then closed by the player, and they steer a first-person presented virtual boat through different environments (e.g. tropical bays) to reach the checkpoints (Coutrot et al., 2018, Spiers, Coutrot and Hornberger, 2021). Movement data is recorded at a high spatial and temporal resolution, providing consecutive and regular samples of orientation and direction choice over the course of a continuous game path (referred to as a 'trajectory'). We recreate the unique series of isovists perceived along each trajectory, and through analysis of the direction selected for onward movement at each point, we examine the apparent navigational strategies of individuals over their route.

We then examine this general result in the light of varying cognitive capacity. Reviewing the difference in results for different population segments that may reflect memory or cognitive impairment, we discuss whether reliance on external information differs, and so the extent to which navigation strategies may differ within the population.

THEORY

Widespread evidence supports the underlying premise that movement is affected by spatial configuration, but several distinct hypotheses can be stated as to how. For our purpose, we distinguish these into two classes: the exosomatic, and the internal representational.

The exosomatic hypothesis, exemplified by the exosomatic visual agent system (EVAS) of Turner and Penn (2002) used widely in Space Syntax, is that navigation decisions are based only on localised spatial information immediately available to an agent from their current position. Such information includes the view at the present time, and so any isovist measures (Benedikt, 1979) that might be extracted from it, but precludes any memory of the previous path or larger map of the environment beyond. In the case of the EVAS agents, a choice of direction is made at time t, within a 170-degree forward-facing field of view, by a random selection of directions weighted by the area visible in each. As such, directions in which the agent sees farthest are most likely to be chosen. The agent is realigned to the new direction, moved three steps forward and then the process repeats at time t+1 with a new partial isovist [Fig. 1]. No information is carried over between steps, and the agent has no wider knowledge of the network. Despite the simplicity of the EVAS model, it has been shown to correlate well with observed aggregate movement (Turner and Penn 2002).

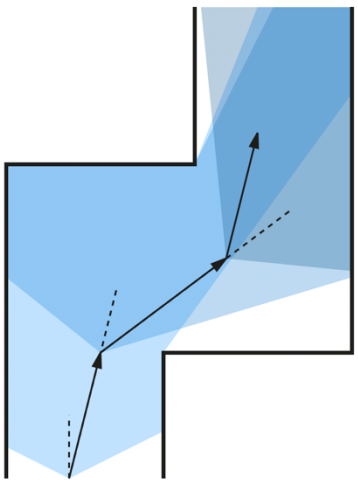
The exosomatic hypothesis is attractive for its simplicity, in requiring no memory or the explanation of non-local spatial knowledge. It has been implied in a range of empirically successful movement models based on a memoryless random walk either in direct simulation (Jiang and Jia 2011), or used as a mathematical abstraction (Blanchard and Volchenkov 2009; Fidler and Hanna 2015; Hanna 2021).

The contrasting hypothesis, of internal representation, is that wider knowledge of the space is required, and represented in some fashion (the memory of a path, a map, or planned route) on which the agent operates to make decisions. In Space Syntax such a representation is rarely explicit, but usually implied, as in the case of centrality measures: Integration (Hillier 1996; Penn 2003) and Choice (Hillier and Iida 2005) both measure multiple minimum paths across the entire network, or at least a set radius. The theory of movement implied by such models is one of path optimisation, to achieve either a minimum metric distance or overall turn angle (Turner 2009) in the overall route selected compared with all other possible routes.

The notion that we operate on some internal spatial representation fits better with our subjective experience, our memory of space, use of maps, etc., and is often what we assume by default. Empirical evidence of actual navigators, such as individual vehicular paths (Turner 2009) suggest that individuals indeed approximate an optimisation of their routes. Neuroscience research has provided compelling evidence for a set of sophisticated neural systems to support internally guided navigation (Ekstrom, Spiers, Bohbot and Rosenbaum, 2018). In particular, it has been

proposed that in mammals the hippocampus and connected brain regions form a 'cognitive map' of the environment (O'Keefe and Nadel 1978, Epstein et al 2017). This brain network encodes an internal representation of the geometry (and context) of the external environment as an internal map which underlies memory-based allocentric navigation. Extensive evidence suggests that the hippocampal navigational network relies on a system of interconnected neurons (Grieves and Jeffrey 2017). These cells include place cells in the hippocampus proper (O'Keefe and Dostrovsky 1971), which fire when an animal is in a certain location of a space; grid cells in the medial entorhinal cortex (Hafting et al 2005), which fire as a regular, hexagonal grid pattern across an environment; head direction cells in cortical and subcortical structures (Taube et al 1990, Taube 2007), which fire in accordance with an animal's head orientation and heading direction; and boundary/boundary vector cells (O'Keefe and Burgess 1996, Lever et al 2009), which fire offset from an environment's boundaries. Further cells in the navigational network have been identified that map direction and distance to goals (Sarel 2017; Nyberg et al., 2022). Recent human brain imaging evidence has indicated that the hippocampus tracks the changes in segment integration and segment connectivity during memory guided navigation (Javadi et al., 2017).

Both hypotheses are extreme, simplified versions of what may in fact be the case, and some models of movement are compromises. Even among memoryless random walk models there is some disagreement in the literature over the spatial extent of the minimal necessary view; Ma et al (2018) suggest that units consisting of "natural streets" or axial lines are required, which can encode more remote topological information than the immediate isovist. It is also very likely that there is considerable overlap between the exosomatic and representational, as in many urban graphs the route chosen by a weighted random walk closely resembles that chosen by route optimization (Hanna 2021). For our purposes the exosomatic hypothesis is limited strictly both to the immediate time and viewed space, and any other information required is assumed to require internal representation. Our aim is to test the plausibility of the latter, stricter definition.



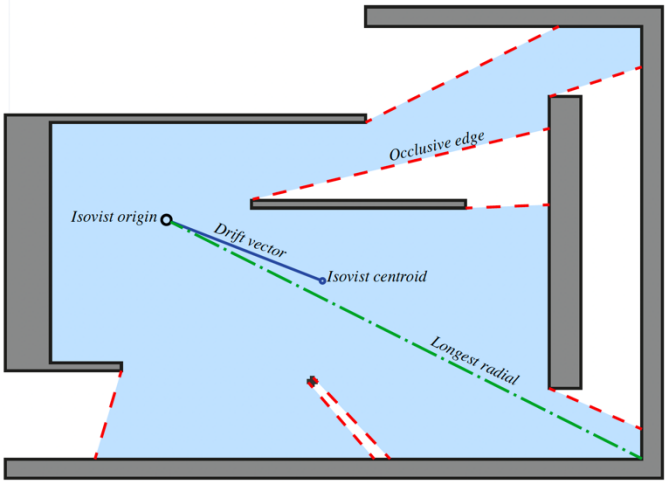


Figure 1 [left]: An agent making its way through space by progressive area choices (from Turner, 2002).

Figure 2 [right]: An isovist in space, with key spatial variables (beyond area) annotated.

1.1 Spatial variables

To the extent that navigation is exosomatic, several cues that might drive it can be derived as measures from the spatial unit of the isovist (Benedikt, 1979) [Fig. 2]. The assumption on which EVAS agents are based can be described as isovist 'area'. As usually implemented, the partial (170 degree) isovist in front of an agent is divided into bins or segments of equal angle, and each is weighted in proportion to its visible area; a bin with larger area is just that much more likely to be selected than one with smaller. The intuitive notion of such an agent is that it tends to select directions in which it sees the farthest, and the line of greatest depth ('vista depth') has been suggested as a legitimate variable in empirical studies of VR wayfinding (Emo 2014). In practice, a greatest area bin will typically also be the one in which the distance seen is greater, although this is not necessarily the case, e.g. for irregular isovists or wide bins. In theory these are highly related: as the resolution of area bins approaches that of the isovist itself, they reduce to lines of distance and the ranking of the two measures becomes identical, with area $\propto$ distance^2. In practice, in a real world or virtual environment, a long but narrow vista may occasionally open to the agent, distorting the value of vista whilst area remains comparatively low.

A related isovist metric, 'drift' (Dalton and Dalton 2001), is calculated by finding the centroid of the shape of the isovist, and recording the vector from the agent's location to that point. When considered for a partial isovist of less than 180 degrees, drift has some ability to resolve divergencies between directional weightings of area and vista that arise from outlier irregularities of the isovist perimeter. As such it may negotiate between some of the complexities described above. Drift is expressed as a directional vector, and so contains both a magnitude (as a length unit) and an angular heading. For the current study, we examine aspects of each, separately. We introduce a related metric of 'segmented centroid depth' (see section 3.2 below) to allow us to compare qualities of drift magnitude against those of area and vista; and we also examine the relation of the overall drift heading with actual subsequent movement (section 4.4).

A secondary distinct argument can be made that we are driven by assumptions about the space we cannot yet see, but which is still localised, as inferred directly by the shape, rather than the size, of the immediate visible field. In such an argument we are drawn toward occluding edges; those edges of the isovist which are 'open', or unbounded by physical edges in the environment, and so which will, upon movement, reveal more space to us. Related agent models designed to select paths from occluding edges rather than overall area have been shown to yield individual paths that much more closely resemble single pedestrians (Turner 2006); detailed observations of visual fixation points in individual human navigators (Emo 2014) also tend to fall on occluding edges. As a metric, occlusivity is usually measured by comparing the length of the occlusive edges of an isovist against the total length of its perimeter, but can also be considered as an absolute length.

These separate measures suggest two distinct takes on the exosomatic hypothesis. Area, vista distance and centroid measures quantify *space actually seen*, with the assumption that we move in the direction of more space. Occlusivity differs from these in that it quantifies an estimate of space not yet seen, but *inferred*. These two versions of the hypothesis will be compared throughout.

2 DATASETS AND METHODS

The data were provided from the large-scale data set of over 4 million participants who played the citizen science video game Sea Hero Quest (SHQ, Coutrot et al., 2018; Spiers et al., 2021). The game was created by a science team led by Profs Hornberger and Spiers and the game design company Glitchers Ltd. SHQ was provided by the App Store and Google Play for download on mobile and tablet devices. The game provides a set of different tasks and levels, but the main level format is a wayfinding task (see Spiers et al. 2021 for details of the development of the task). The main purpose of the project was develop a potential disease monitoring tool for Alzheimer's dementia where a key early symptom is spatial disorientation.

In wayfinding levels the participants are shown a map indicating current position, terrain and checkpoints to be navigated to in a particular order (see Fig. 3). After closing the map participants steer a boat in first-person view, tapping left or right of the boat to select direction and swiping up and down to go faster or to stop. Reaching the targets in a short time rewards the players with stars which allowed them to upgrade their boat between levels. Between levels participants were asked a range of demographic questions (such as age and gender). Ethical consent to transferring data was incorporated into the game and the data was sent anonymously to T-systems at T-mobile for storage. To date, the data has been used to reveal differences in navigation performance across the life-span, between genders, different countries (Coutrot et al., 2018) and home environment (Coutrot et al., 2020). The game has been shown to show good real-world validity (Coutrot et al. 2019) and predict those at greater genetic risk of Alzheimer's disease (Coughlan et al., 2019). See Spiers et al. (2021) for a summary.

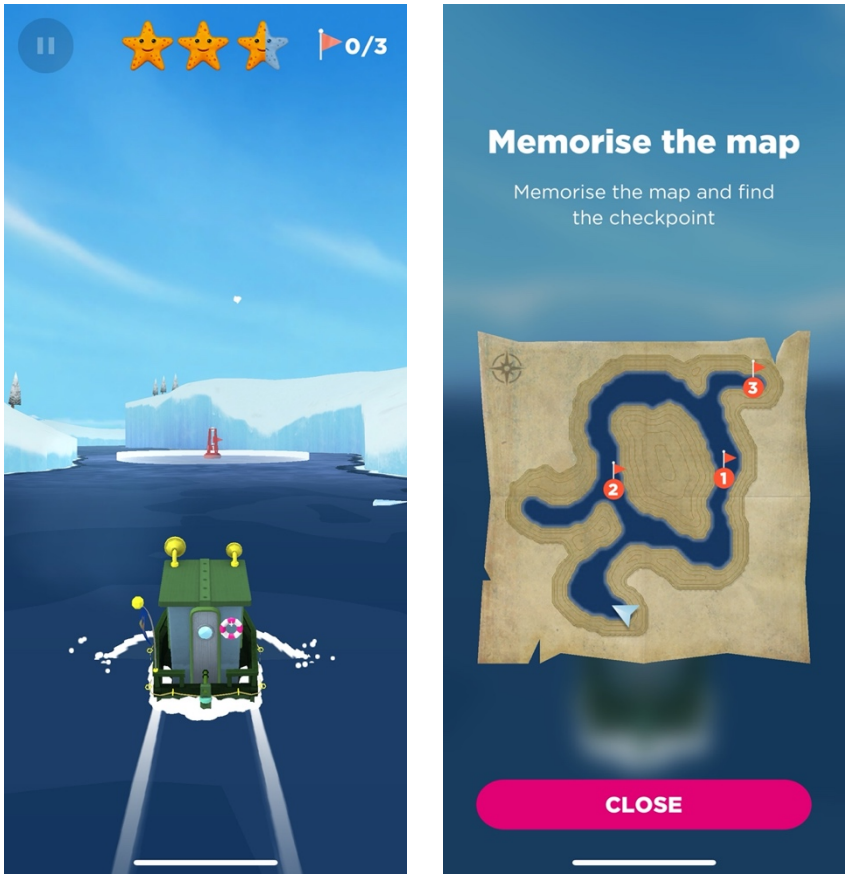


Figure 3: Sea Hero Quest. Left) screenshot during one of the levels. Right) Example map displayed before navigation. Top right arrow indicates currently location and the numbers indicate checkpointst to navigated to in a particular order. The map is viewed at the start of the level and then closed by the player. Then the participant navigates by tapping left or right of the boat to steer to the location. The map is no available for re-inspection during navigation.

2.1 Data selection and preparation

We chose to examine data for 200 individuals' trajectories from one single level of SHQ (Level 13), in which more complex environmental factors such as fog, heavy seas, navigational blockages, and so forth were not experienced. Trajectory data of individuals navigating the level were provided in .csv form as a sequence of time stamped integer coordinates, with locations recorded on a grid with a resolution of 64x64 cells. Individuals were recorded every 0.5 seconds, whilst their view heading (i.e. direction looked) was recorded to a 15 degree resolution (Coutrot et al. 2018).

Information of the environmental bounds of the game was reconstructed by retracing the outlines of the 'land' and 'sea' in plan form; a relatively simple exercise given the fact that the latter had originally also been based on an underlying 64x64 grid. A realignment and rescaling exercise allowed the trajectory data to subsequently be transposed to match the scale and origins of the recreated plan information. At first assessment the resulting trajectory paths often overran the plan boundaries created, believed to be a result of bitmap-gradient related artefacts of the generation of terrain in the game. The latter issue was satisfactorily resolved by uniformly

offsetting the basic land outline by half a grid-cell dimension, bringing all trajectory paths within the adjusted environmental bounds.

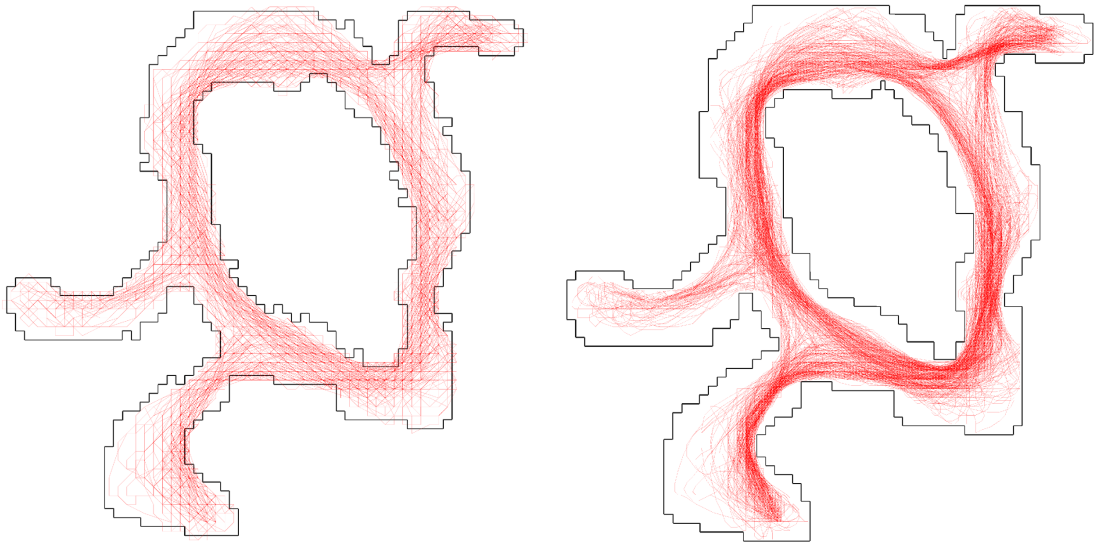


Figure 4: Reconstructed Sea Hero Quest environment bounds, with orthogonally constrained movement trajectory imports; [4i, left] and expanded bounds with smoothed trajectory data [4ii, right].

Having originally been recorded to whole integer locations, the imported trajectory paths were constrained to movement upon an orthogonal grid; i.e. all movement conformed to either a north-south or east-west stepping pattern [Fig. 4i]. In order to reconstruct more natural movement from such patterns, a simple spline smoothing algorithm was used, re-sampling each point on each trajectory by comparison with the two points immediately before and after it. The relative time-spacings of all recording points along each trajectory were preserved, allowing heading data to be re-located to match its corresponding adjusted location data. The smoothing results maintained the effect of relatively sharp turns in each path, but evened out minor shifts across the underlying grid, thus compensating for the lack of float data in the original locational recordings [Fig. 4ii].

2.2 Isovist analysis

Isovists were generated by using the sequential sets of location and respective heading data for all locations along all trajectories. A generating angle of 67.5 degrees was used to match the player view, centre aligned to the view heading recorded at that location. Each isovist was subsequently subdivided into sub-isovists or 'bins', each being a segment of equal angle of 22.5 degrees [Fig. 5]. Metric magnitude values for area, vista depth, and occlusivity were then extracted from both the parent-isovist and bins at each location. To provide a comparable metric that is drift related, we also calculated the centroid of each bin, and measured the distance from the player viewpoint to that location. The resulting magnitude is the metric we call 'segmented centroid depth'.

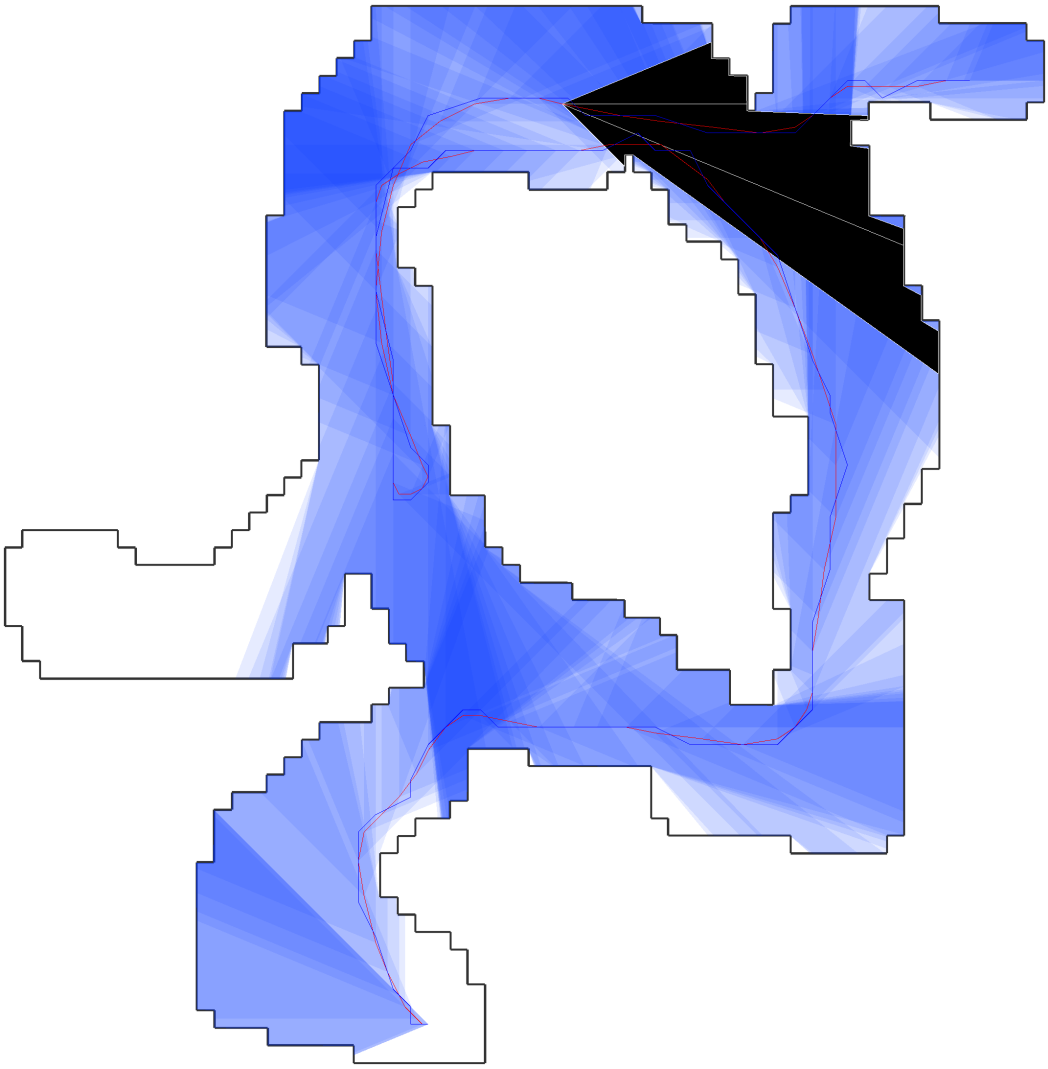


Figure 5: All isovist geometries from all trajectories recreated and overlaid to the environmental bounds (blue); a single isovist in a trajectory is highlighted in black, with defined sub-bins outlined in white.

By comparison between the appropriate maximum or parent-isovist metric, and each of the bins' metrics, the relative values for each bin were found (expressed as a percentage for each location). The latter provides a data representation of 'where' in each isovist, at each step, of each trajectory, the relative 'weightings' of each spatial metric is to be found.

Each bin that contained subsequent onward movement was identified by comparing the angle of movement from each trajectory location to the next against the individual heading-angle of each isovist bin. Doing so provided a proxy for which of the three bins 'was chosen' at every location on every trajectory. Recording the latter allowed us to build representations of the patterns of bin choice, for every location, on all trajectories, for ready comparison against the data of isovist metrics observed. The results of such comparisons are presented in the following section.

3 RESULTS

3.1 General spatial characteristics

By reviewing the general distributions of all isovist metrics for each and all bins across the trajectories, we can observe the general spatial characteristics experienced by players in the game level [Fig. 6]. Here we see an approximately normal distribution of area in the central bin (bin 2), but an increase in frequency of small areas in bins 1 and 3; reflecting the fact that the view captured in these bins is often limited by the potential view cone being intersected by the bounds of the navigable environment.

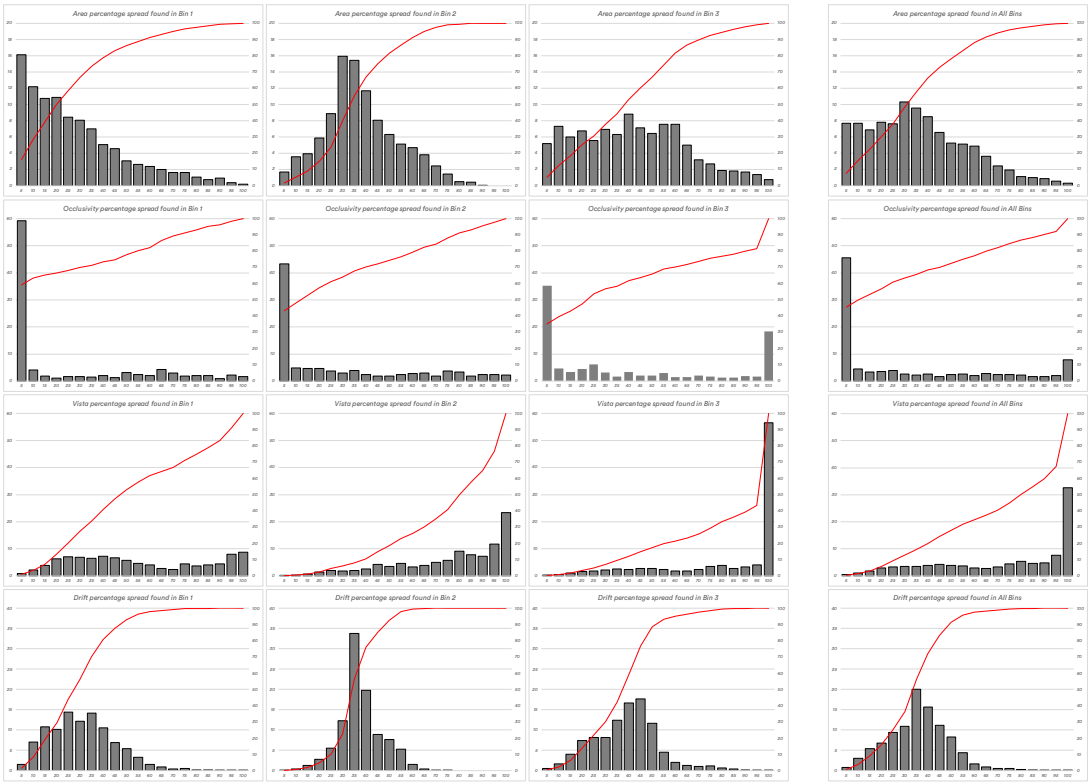


Figure 6: Plots showing the distribution of isovist metrics between bins and for all bins; x-axis in each case denotes relative magnitude of bin metric value, whilst y-axis denotes absolute frequency of bin occurrence. Accumulative percentage of occurrence is shown as a red line for each. From top; Area, Occlusivity, Vista and Drift; from left to right, bin nos. 1, 2, 3 and all bins combined.

Occlusivity frequencies across all bins are notably low; with high scores for 'zero' occlusivity in all bins, and a high frequency of the maximum occlusivity value in bin three. Interestingly, vista depth echoes the pattern, with maximum values commonly occurring in bin three, suggesting a distinct irregularity of the environment is being captured here. In practice the orbital nature of the layout of Level 13 means that, at each step, a bin is likely to contain either none, or all, of the occlusive edges and longest views available. The skewing of high values of occlusivity and vista towards bin three therefore suggests that the latter often interacts with the central 'island' feature of the layout, around which players tend to perambulate and so gain longer, more glancing views.

We note it is possible that the environment of Level 13 does not afford a great deal of meaningful occlusive edge potential with respect to navigational decisions.

Finally, the drift (segmented centroid depth) metrics exhibit the most 'normal' distribution across all bins, albeit with greater values in the central bin, capturing the fact that the latter generally contains wider, less restricted views through the environment. The relatively standard distribution of metric occupancies for segmented centroid depth may indicate that the metric successfully balances out irregularities of isovist perimeter and provides a more balanced 'sense of space', as previously suggested.

3.2 Movement comparison with magnitude of local spatial metric

The basic exosomatic navigation hypothesis suggests that navigators will choose a direction with a probability weighted by some relevant variable. A simulated visual agent system implementing an exosomatic movement model (Turner and Penn 2002) would be expected to converge on a perfect correlation between the expected frequency of direction chosen as given by the variable in question (horizontal axis) and the actual frequency of direction chosen (vertical axis). The strength of such correlations with actual observations similarly indicates the degree to which each variable represents a plausible exosomatic explanation of real movement. To test the hypothesis, we plot each of our test variables against the frequency of bins chosen, for gradations of each 5% of the relative metric extracted for the magnitude values of area, vista depth, segmented centroid depth, and occlusivity. Doing so allows the review of how often (or how likely) relative weightings of metric are to be chosen, and thereby how they may be acting as a navigational motivator.

In all cases the players' assessment of isovist depth is taken from images of the screen view of the SHQ game, which is limited by resolution, a lack of monocular vision, and a rendered distance haze effect. As such, the successful judgement of depth (or corresponding area, etc) variables becomes increasingly challenging for the greater distance views (by our estimate, markedly so for those above approximately 15-20 grid cells). Given that such longer views usually occur in the bins with higher relative metrics, in our analysis of these variables, we have considered both correlations of the entire metric range, and also of the first 50% of that range, where assessment of the relevant variable is likely more accurate.

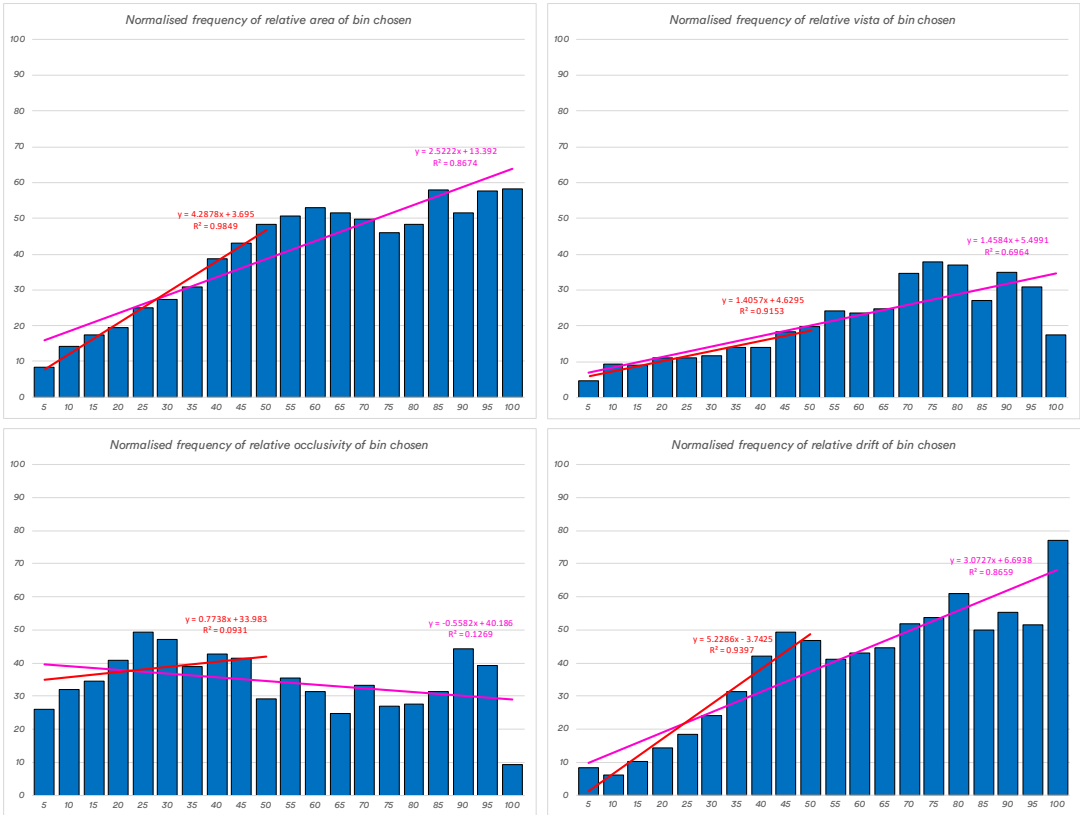


Figure 7: Isovist metric for the bins containing future movement, against normalised frequency of occurrence; x-axis in each plot denotes relative magnitude of bin value, whilst y-axis denotes relative occurrence of selection. Lines of fit are shown in red in each case.

Figure 7 indicates good correlations for the variables associated with *space seen*, particularly with area and centroid measures, and somewhat less with vista distance. Occlusivity, representing *space inferred*, shows no discernible correlation. If only the smaller 50% of isovist bins are considered, representing the zone of more accurate visual assessment of distance, positive correlations of the three *space seen* measures improve still further to very strong values of r^2=0.92 (vista distance), r^2=0.94 segmented centroid depth and r^2=0.98 (area).

3.3 Performance of individuals

Within the full cohort of players above, there may be a range of strategies not revealed in the aggregate data. Some individual players may rely more on information immediately available in the environment, whereas others may rely more on a mental map. We test the hypothesis that players with better cognitive ability to navigate are more able to draw on their memory, whereas, as this ability declines, players rely more on exosomatic cues in the environment. While the data used has no direct information on individual cognitive ability, we can use the relative length of trajectory (based on the total distance travelled in the level) as a proxy. We consider the latter a reasonable approximation of navigational 'success' of individuals in the game; longer distance journeys being expected to be related to less successful navigators.

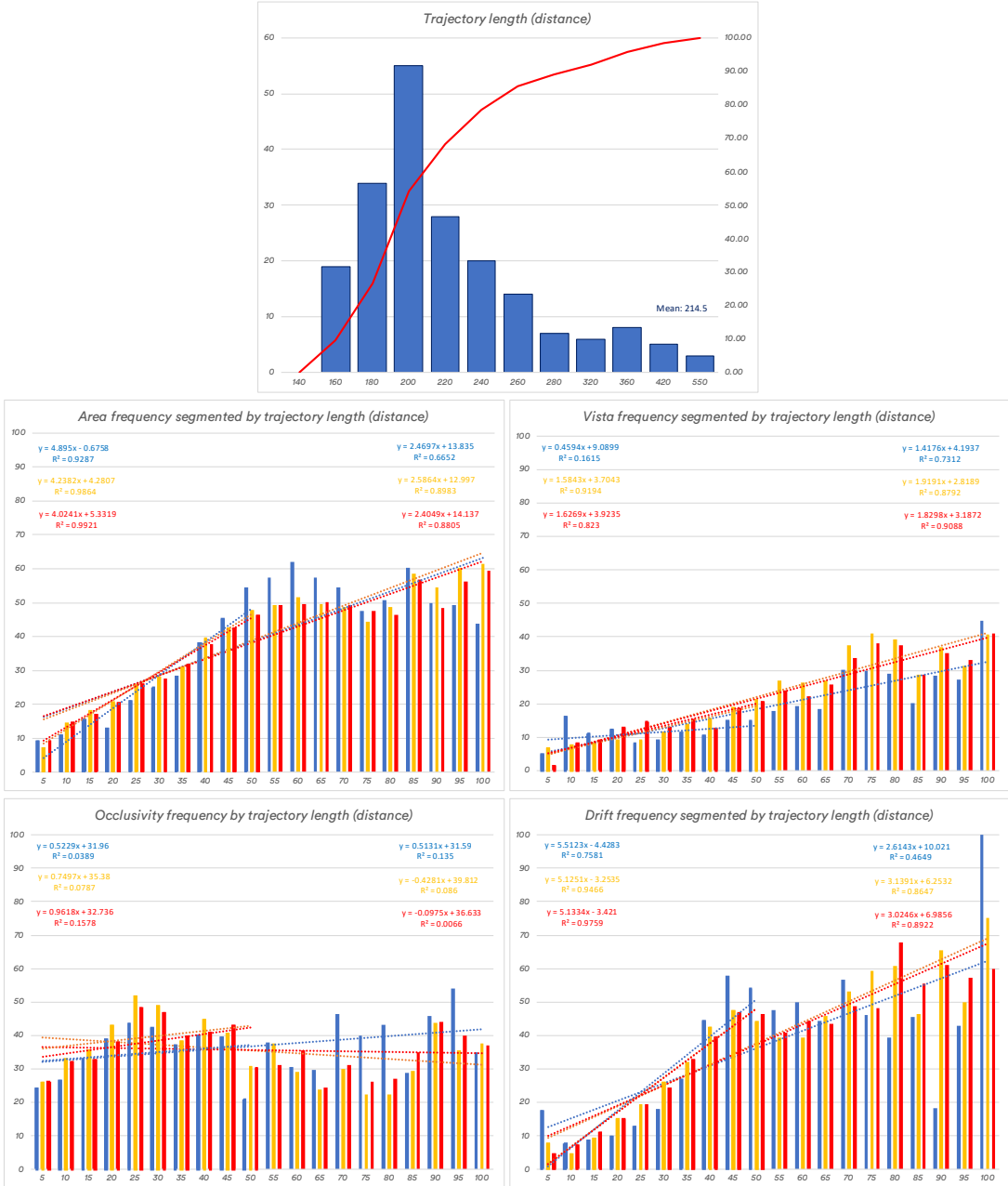


Figure 8: Top plot; distribution of trajectory lengths based on units of distance travelled. Lower four plots; Isovist metrics for bin containing future movement, against normalised frequency of occurrence, segmented by journey length. In all cases, Blue: 0-180 units of distance (approx. 25%); Yellow: 180-240 units of distance (approx. 50%); Red: 240 and higher units of distance (approx. 25%). In each case, left-hand correlations refer to the lower 50% of metric values, and the right hand correlations refer to the full set.

Overall path lengths in the data set range from approximately 150 to 550 grid cell units roughly approximating a bounded normal distribution with a mean of 214.5 units. We partition this into three sub-sets based on length: the first containing paths of 0-180 units (approx. 25%), the second 180-240 units (approx. 50%) and the third >240 units (approx. 25%). The same analysis of overall set correlations as in section 4.2 indicates distinct differences between groups [Fig. 8]. As journey length increases, correlations with vista distance increase monotonically from r^2=0.73 (first set) to r^2=0.88 (second set) to r^2=0.91 (third set) and correlations with centroid increase

from r^2=0.46 to r^2=0.86 to r^2=0.89. Correlations with area increase from r^2=0.67 to r^2=0.90 and then drop slightly to r^2=0.88. These results corroborate the hypothesis that poorer navigators in the set rely increasingly on exosomatic information, with the largest effect seen between the first set of roughly 25% of the best navigators and the remaining 75% of participants.

A similar pattern is also observed when the correlations of just the first 50% of metric range are considered. In these analyses, the shift of correlations for area is less pronounced, but still significant, ranging from r^2=0.92 to r^2=0.99. With area returning such high overall correlations (as mentioned in section 4.2 above), and a likely increased accuracy of assessment in the 'near field' metric range, some such convergence is perhaps to be expected.

In the other metrics, the range for vista depth becomes more pronounced, with very low correlation for strong navigators (r^2=0.16) but those correlations for the weaker navigators in both cases remaining above r^2=0.84. Segmented centroid depth shows the clearest change, with correlations for the weakest navigators improving to r^2=0.97, whilst that for the strongest navigators remains relatively low (r^2=0.75). It does appear that across both analyses of segmented centroid depth, the strong/weak navigator pattern is clearer, and more consistently so, than that exhibited for the other spatial metrics.

The varied correlative shifts observed between different metric types, but also between the full metric range and the restricted 50% range, suggest that cognitive or navigational abilities and deficiencies are exhibited differently within the navigation task and across population segments. Exactly how such an interplay occurs, the precise nature of relevant cognitive abilities and of actual navigation strategies used cannot be determined from the aggregate data alone, but may be worth exploring in a future extended investigation.

3.4 Consideration of drift vector heading

As described previously, drift is a unique isovist metric as it provides a distinct angular vector that can be considered. A single vector cannot not provide any estimation of the probability of other directions being chosen, so an analysis of correlations as in sections 4.2 and 4.3 is impossible. We present instead a comparison of that vector angle against the subsequent direction of movement, which gives a fine scale measure of angular variation for each step of each trajectory.

A significant, close approximation to drift is evident in the actual directions chosen by players [Fig. 9]. Over 20% percent of all movements in the layout environment fall within ± 1 degree of the drift angle at each step (a 99% alignment). Over 50% of all movements fall within ± 2 degrees of the drift angle at each step (a greater than 97.5% alignment). These are in line with the results of section 4.2, both in supporting the hypothesis of exosomatic navigation and more specifically based on space seen.

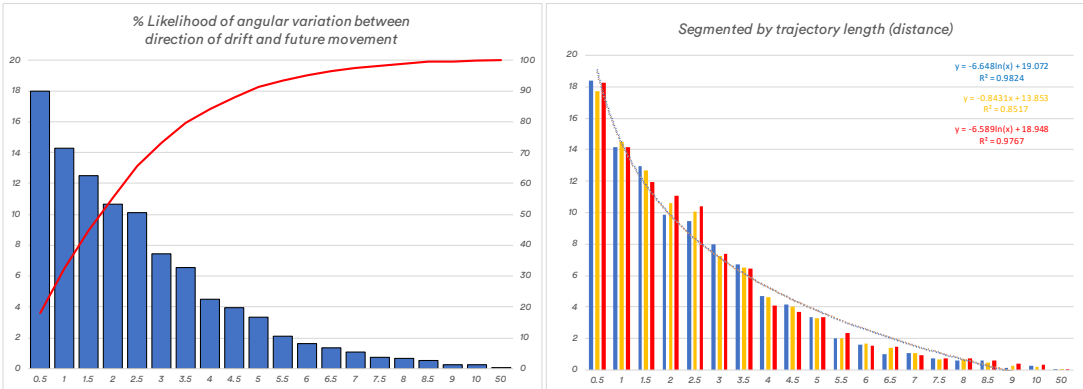


Figure 9: Comparison of the angle of drift vector against the angle of subsequent movement at each step. Left shows the frequency of each absolute angular difference; right shows the same data segmented based on trajectory length (distance travelled) for the same segments as outlined in 4.3

The segmentation by trajectory length shows no variation between 'strong' and 'weak' navigators as was found in section 4.3. All three groups have high correlations of r^2>0.85, and there is a high similarity between strong and weak navigators, with an r^2 variation of just 0.1. Such a similarity is surprising, given the discrepancy between these groups in the *space seen* measures (including segmented centroid depth) in section 4.3. Genuine differences between groups appear based on the probabilities of direction chosen, so why are these not evident in the actual angles indicated by overall drift?

One potential explanation is that these group differences are indeed real, but that both strong and weak players successively adhere to or deviate from the path predicted by drift for different reasons. A significant amount of the Sea Hero Quest gameplay depends upon players 'sailing' in a relatively steady manner towards their destination. or in a direction that they consider to be a 'correct next move'. During such a 'cruise phase', the ability to comprehend one's position and relation to a navigational goal, via a localised sense of spatial orientation, is clearly of value. In short, for all types of player, drift direction may provide a localised feedback mechanism for individuals to assess their own alignment with and progress towards a destination.
As in section 4.3 we might expect the 25% strongest players to deviate from such a 'cruise phase' due to their knowledge of the space suggesting a more optimal route. At the same time, but in contrast, the 25% weakest players might also deviate simply due to poor ability; from losing track of their relative progress, to an increased need to stop and look around, or due to spatial noise forming a distraction. As noted in section 4.3 the difference in navigation strategy was most pronounced in the strongest set of navigators, with the middle 50% appearing largely to rely on exosomatic cues. If the deviations taken by both the strongest and weakest navigators are different in their source but similar in magnitude, they would not be evident in figure 9.

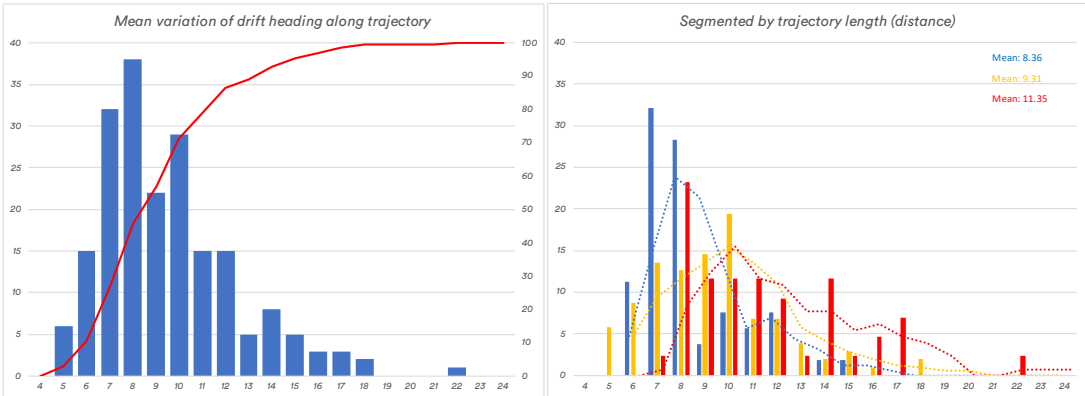


Figure 20: Distribution of the average 'step to step' variation of drift heading along each trajectory; right shows the same data segmented based on trajectory length (distance travelled) for the same segments as outlined in 4.3.

To investigate the above hypothesis we compared the average (mean) variation in drift heading (from each step to the next step) along the entirety of a player's trajectory. Doing so provides a measure of how much an individual's sense of a spatial direction 'wobbled' throughout the course of their travel. Again we segment the data by trajectory length [Fig. 10]. In the resulting chart we see a shift in distribution reappearing, with the relative degree of drift heading variation increasing from 'strong' to 'weak' navigators. Such a shift provides some evidence for the above explanations and perhaps itself merits further examination in future.

4 CONCLUSIONS

Data used in this study are substantial in volume and detail compared with many observations of movement in physical space, but we acknowledge some limitations. Only 200 participants' paths have been included from a total of 3.8 million players and 4.3 downloads of the game to date. Sea Hero Quest has 75 playable game levels (45 used to test wayfinding) that differ in spatial geometry, height of occluding terrain, fog and other factors relevant to view, and player behaviour in other levels may differ from the single one analysed here. Also, while trajectory length is used as a proxy for navigation ability, we did not use any additional knowledge of individuals' cognitive capacity directly. Each of these is worth further investigation with respect to the following conclusions.

At the broadest level, our results provide good evidence to support the exosomatic hypothesis that navigators operate to a significant degree based on information immediately available to them in the environment. The distribution of actual direction choice observed closely matches the expected probability (section 4.2) based on several measures, the strongest being isovist area, but closely followed by vista depth and segmented centroid depth. These outcomes suggest that navigators do rely directly on information from their environment visible at the present moment, and specifically that area is important, in line with assumptions behind previous Space Syntax models. Actual direction vectors also closely match those predicted by drift (section 4.4). Drift

has not previously been greatly explored, but might be a viable comparator to area for informing visual agent prototypes in the future.

In more detail, the nature of the information on which navigation relies appears to be that of space *actually seen* as opposed to *space inferred*. Measures of area, segmented centroid and vista depths, all of which quantify the actual isovist, correlate very well, but occlusivity does not (section 4.2). This observation comes with the caveat that it cannot yet reveal the exact mechanism or strategies of navigators' use of this information; it is certainly not a deterministic choice of largest visible area in which to move, and each variable suggests a different potential explanation. It may be that players in Sea Hero Quest actually gain meaningful advantage by disregarding regions of small area, with larger areas being a more equal choice, as evidenced by the plateau across larger metric values. It may also be that such behaviour is only a useful strategy for the particular game level and layout studied. An expanded study over multiple levels could provide greater insight here.

Finally, the reliance on exosomatic cues appears to vary between individuals in a manner that is consistent with their ability. The strongest navigators appear to rely less on immediate view information, and the weakest rely more (section 4.3). This suggests that of the two hypothesised strategies, the exosomatic and the internal mental representation, both are likely used in actual navigation, but they are used to varying degrees. In a novel, complex environment such as Sea Hero Quest, exosomatic navigation appears to be both adequate and the default for most people, most of the time, but the more able navigators will rely on their memory to a greater degree and more effectively to win.

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