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Short Communication

Contracted time and expanded space: The impact of circumnavigation on judgements of space and time

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ABSTRACT

The ability to estimate distance and time to spatial goals is fundamental for survival. In cases where a region of space must be navigated around to reach a location (circumnavigation), the distance along the path is greater than the straight-line Euclidean distance. To explore how such circumnavigation impacts on estimates of distance and time, we tested participants on their ability to estimate travel time and Euclidean distance to learned destinations in a virtual town. Estimates for approximately linear routes were compared with estimates for routes requiring circumnavigation. For all routes, travel times were significantly underestimated, and Euclidean distances overestimated. For routes requiring circumnavigation, travel time was further underestimated and the Euclidean distance further overestimated. Thus, circumnavigation appears to enhance existing biases in representations of travel time and distance.

1. Introduction

Knowing how far away a destination is or how quickly one can travel there can be important for survival and shapes our daily lives. Ideally, our estimates of distance and time would be accurate, but often they are systematically distorted by many factors, such as the number of turns required, density of structures in the environment, and familiarity with the environment (Arnold, Iaria, & Ekstrom, 2016; Bonasia, Blommesteyn, & Moscovitch, 2015; Briggs, 1973; Jafarpour & Spiers, 2016; Sadalla & Magel, 1980; Saisa, Svensson-Garling, Garling, & Lindberg, 1986; Thorndyke, 1981).

In some situations, it can be necessary to circumnavigate an obstacle in the environment to reach a location. Navigating to a goal in the world and returning home requires knowledge of the environmental geometry and, frequently, the ability to circumnavigate obstacles while keeping track of the goal's location (McNaughton, Battaglia, Jensen, Moser, & Moser, 2006; Mittelstaedt & Mittelstaedt, 1980). Such circumnavigation, however, introduces disparities between path distance and straight-line (Euclidean) distance to the goal. Recent neuroimaging research has shown that medial temporal lobe (MTL) regions track the distance to the goal during navigation (Balaguer, Spiers, Hassabis, & Summerfield, 2016; Chrastil, Sherrill, Hasselmo, & Stern, 2015; Morgan, Macevoy, Aguirre, & Epstein, 2011; Sherrill et al., 2013; Spiers & Maguire, 2007; Viard, Doeller, Hartley, Bird, & Burgess, 2011), where activity in the entorhinal region correlated with Euclidean distance and activity in the posterior hippocampus correlated with the path distance (Howard et al., 2014). At decision points, hippocampal activity was related to both how close the goal was and the egocentric direction to it (Howard et al., 2014). Activity was maximal when the goal was close and directly ahead and low when the goal was along a path curved away from the current heading and far away (Howard et al., 2014). Thus, it seems possible that the geometry of the path to the goal may systematically impact on how the brain represents space. However, there has been little investigation of how the geometry of a path impacts on the internal representation of the route or the spatial relationship to the goal, despite the suggestion that environmental geometry provides a crucial orientation cue to both animals and humans (Cheng, 1986; Cheng & Newcombe, 2005; Gallistel, 1990). However, it remains unknown if the environmental geometry of a path (curvature) has a significant impact on estimates of the distance or the time estimated to travel to goals.

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Here, we used verbal judgments to measure biases in the estimates of travel time and Euclidean distance on routes to goals that either matched in path distance but differed in Euclidean distance, or matched in Euclidean distance but differed in path distance. We created a virtual reality (VR) environment to control for prior experience, curvature, direction, and angle to goal during navigation (Fig. 1). In two experiments, participants travelled to different numbers of locations in the environment.

We predicted that on U-shaped routes, the goal might be perceived as farther away because the travel time would lead to an impression of it being conceptually farther away. We considered that time estimation might plausibly decrease or lengthen with the curvature.

2. Experiment 1

2.1. Methods

Twenty-three participants took part in Experiment 1 (15 females). Their age range was 18–30 years (mean 22.2 years), all were right-handed, and none reported any history of psychiatric or neurological disorders. All participants gave their informed consent. This research was approved by the ethics committee at University College London.

Participants were instructed that their task would be to deliver pizzas to various locations in the virtual town. A one-way system of routes was constructed to create pairs of routes with equal Euclidean distance but different path distance (Fig. 1). The virtual town was built to a consistent scale so the size of buildings and blocks was representative of real-world objects/buildings and could be used to infer distances when making estimates. There were 21 locations. The driving speed was set to approximately 35 km/h. Participants were first led through the town by pressing arrow keys corresponding to green arrows displayed on the screen. The order of the routes was randomized, but in every three trials, one route was sampled from each part of the environment (A-E, I-M, I′-M′). In this drive-through, they were forced to turn toward each goal location before they could continue, ensuring exposure to all goal locations prior to delivering to them. After the drive-through, the participants were instructed to find the shortest possible route for each goal location contingent on the one-way road layout from the pizzeria as their starting point. Their goal was displayed in the upper right hand corner throughout the search. After each delivery, they were teleported to the starting point and given a new goal.

The participants were then instructed that their task and the environment would remain the same but they would additionally have to estimate the duration of each delivery prior to each journey (*time estimation*) and then to reach each goal using the shortest, most direct route possible. A probe window appeared at the start of each journey asking participants to type in the number of seconds they thought the journey would take. They again navigated to each location 3 times. After completing all navigation trials, participants were asked to estimate straight-line distances (*Euclidean distance estimation*) to each of the goals shown to them one at a time without any background or surrounding buildings in a randomized order.

2.2. Results

The travelled time was subtracted from estimates to yield a *bias score* for the degree of under- or overestimation observed on each trial. These were averaged across the three visits to each location. Similarly, bias scores for distance estimates were calculated by subtracting actual from estimated Euclidean distance (ED). All suboptimal journeys (any path other than the shortest possible) were excluded from the analysis, excluding 3.73% of trials on U-shaped and 20.6% on L-shaped routes. This discrepancy is due to more frequent exposure to locations along the U-shaped routes. For example, participants had to travel past G' every time they delivered to any location along U-shaped routes, while this was not the case for L-shaped routes (see Fig. 1). This issue was resolved in Experiment 2. The distribution of errors can be found in Supplementary Materials (Fig. S1).

Participants' mean travel time on L-shaped routes was 28.7 s (SD = 1.65) and the mean estimated time was 22.2 s (SD = 8.58). The mean travel time on U-shaped routes was 36.9 s (SD = 1.92) and estimated time was 26.9 s (SD = 8.19). In this experiment, travel times were significantly longer on U-shaped routes than L-shaped routes with matched PD ($t_{(22)} = 9.84$, $p < 0.001$; this is addressed and resolved in Experiment 2). This is due to a larger number of keypresses required each time participants travelled to locations on U-shaped routes, which was not the case on the L-shaped routes, where participants remained on the main road until they decided to make a turn (see Fig. 1). Participants' estimates were then expressed as a proportion of actual travel times. The average proportion on L-shaped routes was 0.78 (SD = 0.25), and on U-shaped routes, it was 0.73 (SD = 0.21).

We then fitted two individual 2-level linear mixed-effects models to predict (1) bias and (2) proportion in time and ED estimates, averaged across the three repetitions. Participants were entered as a random factor. We compared only routes with matched PD for time estimates (G-M & G′-M′) and routes with matched ED for distance estimates (A-G & M′-G′). Prior to analysis, continuous independent variables (travelled time, Euclidean distance) were centred by subtracting the mean from each parameter, as per standard procedure in multi-level modelling. The strength of such linear generalised multi-level modelling is increased statistical power (Mathieu & Chen, 2011), as the inclusion of individual trials for each participant accounts for the maximal amount of variance in the dataset as the linear predictor contains random effects (in our case, participants) in addition to the fixed effects. The statistics are reported in Table 1.

We found that estimated travel time was significantly underestimated as the travel time increased and that this underestimation was significantly greater on U-shaped routes (Table 1, Fig. 2A). When analysis focused on the proportion of the estimate relative to the correct travel time, there was a significant main effect of route type, but no significant main effect of PD, suggesting that while underestimation was greater on U-shaped routes overall, these proportions did not significantly change as a function of the actual distance travelled (reflected by the grey bars in Fig. 2A).

The same analyses were applied to ED estimates. In contrast to time estimates, distances were consistently and increasingly overestimated (Fig. 2B). The mean estimated ED on U-shaped routes (158.4 m; SD = 196.2) was significantly greater than the mean estimated ED on L-shaped routes (130.0 m; SD = 165.7): $t_{(22)} = 2.59$, $P = 0.017$. Bias in ED estimates was modelled as a function of route type and PD for locations with matched ED. There was a significant main effect of route type ($P = 0.023$) and a significant interaction between route type and PD, suggesting that bias increased as a function of path distance and that this bias was increased for locations on U-shaped routes (Fig. 2A).

Participants' estimates were again calculated as proportions of actual Euclidean distance. On L-shaped routes, participants overestimated distances by a factor of 1.63 (SD = 2.05) and on U-shaped routes by 2.04 (SD = 2.45), indicating that locations on U-shaped routes were perceived to be on average twice as far away as they were in reality. The main effect of route type was again significant, but the route type x PD interaction was not (Fig. 2B).