RUNNING HEAD: The Map in Our Head

Is the Map in Our Head Oriented North?

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Abstract

We examined how a highly familiar environmental space – one's city of residence - is represented in memory. Facing a photorealistic virtual model of their hometown in various body orientations, 26 participants pointed to well-known targets. Each participant's pointing accuracy showed the pattern of best performance when facing north and increasing error with further deviation from north. Pointing error and latency were not related to target distance. These results are inconsistent with an orientation-free memory and with storing local views. Although participants self-localized by recognizing experienced local views, their strategy for pointing relied on a single, north-oriented reference frame, which was acquired from a map rather than formed from daily exploration. Despite participants spending a magnitude of time longer navigating the city, their pointing behavior seemed to rely on a north-up map-in-the-head.

Keywords: spatial memory; environmental space; reference frame; local and global reference frames; orientation-free; alignment; map; Virtual Tübingen

Introduction

Unlike navigating unfamiliar terrain, navigating around one's city of residence is usually an error-free and effortless endeavor. In this paper, we investigated how such highly familiar spaces are represented in memory. One property often proposed for memory of highly familiar spaces is orientation-independency (Byrne, Becker & Burgess, 2007; Evans & Pezdek, 1980; Gallistel, 1990; Sholl, 1987). Performance based on an orientation-free memory is thought not to depend on one's orientation within this environment. To the contrary, some theories propose that spatial memory is oriented; at least at one hierarchical level, locations of the city are represented within one oriented global reference frame (GRF) (McNamara, Sluzenski & Rump, 2008; O'Keefe, 1991; Poucet, 1993; Trullier, Wiener, Berthoz & Meyer, 1997). Therefore, survey estimates such as pointing, distance estimation, or shortcutting will rely on this oriented GRF.

Evidence for the use of an oriented GRF for solving survey tasks when located within the environment is obtained from a global *alignment effect*: performance of navigators is best when their body orientation (i.e., viewing direction) is parallel to the orientation of the oriented GRF representing this space (Iachini & Logie 2003; Levine, Marchon & Hanley, 1982; McNamara et al., 2008). Otherwise, costs for re-alignment (e.g., by mental rotation) may lead to poorer performance. While in general performance decreases with increasing misalignment (Iachini & Logie, 2003), orthogonal body orientations and contra-alignment often yield better performance compared to oblique misalignments (McNamara et al., 2008). The alignment effect should be identical for all locations represented within one GRF. The orientation of this GRF should also be determined by both environmental structure and navigators' individual experiences. Therefore, different navigators –due to their individual experiences- are likely to conceive differently oriented GRF. All target locations represented within one GRF can be accessed equally fast and precisely. Therefore performance should *not* vary due to target’s distance (*distance effect*). However, oriented GRFs constructed from exploration may contain errors and distortions accumulating with increasing navigation distance and thus size of the represented area (Loomis et al., 1993). In this case, larger target distances may yield larger pointing errors.

Other theoretical positions (Christou & Bülthoff, 1999; Gillner, Weiß & Mallot, 2008; Meilinger, 2008; Wang & Spelke, 2002) propose spatial knowledge to be stored using local reference frames (LRFs). These correspond to surroundings usually visible from one single vantage point such as streets or places. Their orientation is derived from local geometry (e.g., street orientation) and/or the experienced perspective. To complete survey tasks, individuals integrate LRFs into a single reference frame. Meilinger (2008) proposed that this integration is made while performing the survey task, and is based on the LRF of the navigator’s current (real or imagined) position. Participants should perform best when aligned with a local street, as they encode LRFs parallel to streets while walking. Pointing to more distant locations also requires more LRFs to be integrated, resulting in longer latencies and larger errors (distance effect).

Spatial relations can be learned from maps as well (Thorndyke & Hayes-Roth, 1982; Richardson, Montello & Hegarty, 1999; Sun, Chan & Campos, 2004). Maps typically display locations within a north-oriented GRF. If spatial relations are learned from maps, western participants should perform best when facing north, and performance should decrease with the angle of misalignment. No distance effect is expected as map memory for close-by and distant locations should not differ in access time or precision.

To summarize, by observing alignment effects relative to LRFs (parallel to a street) or orientated GRFs (north-up or individual), we can determine the spatial encoding strategy of individuals. If individuals use orientation-free representations no alignment effect should occur. If individuals use LRFs we should observe distance effects for pointing errors and latency. However, if individuals use navigation-based oriented GRFs we predict distance effects for pointing error, but not latency. If individuals rely on map-based oriented GRFs, we expect no distance effects.

To test these predictions, we conducted a novel pointing experiment. Participants wearing a head-mounted display (HMD) faced five familiar locations (initial locations) in a virtual model of their hometown (see Figure 1). They were asked to point to different target locations not visible to them. We examined performance depending on varying body orientation and target distance.

Methods

Participants

Thirteen female and fourteen male naïve participants, aged 18 to 50 years (*M* = 28.5; *SD* = 7.7) recruited from a subject database participated in exchange for monetary compensation. They lived for at least two years in Tübingen (*M* = 6.7; *SD* = 5.4). One additional participant did not complete the experiment.

Apparatus and Materials

We used a highly realistic virtual model of Tübingen, Germany (see Figure 1; http://virtual.tuebingen.mpg.de; Meilinger, Knauff & Bülthoff, 2008). Participants saw the model in ground perspective through a HMD while sitting on a high chair. Simulated fog ensured similar viewing depths in all directions. The experiment was programmed in Virtools® 4.0 (© Dassault Systemes).

Participants' head coordinates were tracked by four high-speed motion capture cameras with 120 Hz (Vicon® MX 13) to render an egocentric view of the virtual environment in the HMD in realtime. We used a NVIDIA GO 6800 Ultra graphics card with 256 MB RAM and a Kaiser SR80 HMD with a field of view of 63° (horizontal) x 53° (vertical), and a resolution of 1280×1024 pixels for each eye. The interpupillar distance was fixed at 8 cm. We adjusted HMD fit and screen placement individually for every participant. The overall setup provided important depth cues such as stereo vision and motion parallax. We measured participants' pointing performance with a custom-made joystick providing a resolution of approximately two degrees.

Procedure

In every trial, participants faced an initial location in a specific orientation. After self-localizing (i.e., confirming recognition of location and orientation by pressing a button) they pointed into the virtual direction of three different specific target locations (castle courtyard, three taverns, train station, fire hall, mall, museum, cinema, three intersections, university building) whose written names appeared separately on the HMD-screen. For self-localization, participants were free to rotate. During pointing we enforced a fixed head orientation by blanking the HMD screen for changes in original heading larger than 10 degrees.
Participants faced twelve orientations (differing in multiples of 30°) in each of five initial locations once (see Figure 1). These 60 trials resulted in 180 pointings per participant. Trials were fully randomized, with the constraint that all targets were pointed to equally often, and no target was pointed to twice in one trial. Inter-trial intervals were controlled by participants. We recorded self-localization time, pointing latency and the absolute pointing error. Afterwards, participants were asked to draw a map including all locations occurring in the experiment.

Data was collected only from participants able to identify all locations beforehand from photographs (target locations) or 360° snapshots (initial locations). Participants received written and oral instructions including the exact spot where to point to for each target. They were familiarized with the procedure during training trials in a location not used in the experiment.

(Figure 1)

We plotted pointing performance against local or global orientation. Local orientation was expressed as the minimal angle between street and head orientation ranging from -90° to 90° and categorized in steps of 30°. Global orientation was expressed as head orientation relative to North (for map based oriented GRFs) or the drawn map orientation (for individual oriented GRFs). To test whether performance dropped with increased misalignment, we used contrasts centered on a local or global orientation (see Keppel & Wickens, 2004 for detail; contrast weights for GFRs: 3/2/1/0/-1/-2/-3/-2/-1/0/1/2 with -3 corresponding to north or individual map orientation respectively; contrast weights for LRFs: 9/2/-5/-12/-5/2/9 with -12 corresponding to street alignment). To estimate distance effects, we correlated pointing performance with the Euclidian distance to the targets. Every participants' pointing performance was better than the chance level of 90° obtained by random pointing (27 $t(179)$'s < -3.86; p's < .001). For statistical analysis, values deviating more than two standard deviations from the overall mean were eliminated (less than 4%).

Results

Global Reference Frames acquired from Maps

Acquiring an oriented GRF from a map leads to best performance for north-aligned head orientations, no distance effect is expected. Exactly this pattern was observed. Participants' average pointing accuracy varied as a function of their global head orientation (Figure 2A; $F(5.9, 153.9) = 66.29$, $p < .001$, $n_p^2 = .72$ – Greenhouse-Geisser correction; self-localization time: $F(11, 286) = 1.59$, $p = .103$, $n_p^2 = .06$; pointing time: $F < 1$). Every single participant's pointing accuracy was predicted by the applied contrast and increased linearly with the amount of misalignment (t's > 5.44, p's < .001). This suggests that mental rotation was used to compensate for misalignments. Neither the correlations between target distance and pointing error (Figure 2 B; $t(26) = -.42$, $p = .679$; range r [-.32; .24]; $M = -.01$, $SD = .14$) nor between target distance and pointing time (Figure 2 C; $t(26) = -1.55$, $p = .132$; range r [-.35; .24]; $M = -.05$, $SD = .16$) significantly differed from 0. Contrary, individual data revealed a small negative correlation between target distance and pointing error for two participants (strongest correlation: $r = -.32$, $p < .014$), and a small negative correlation between target distance and pointing time in five participants (strongest correlation: $r = -.35$, $p < .006$). The data meets all predictions from a map based GRF: best performance when oriented north and no positive distance correlation.

Global Reference Frames acquired from Navigation

The orientation of GRFs acquired from navigation is likely to differ between participants. We used the orientation of map drawings to estimate this direction. Two independent experimenters rated map orientations in terms of North, East, South and West with equal judgments on 26 of the 27 maps entering further analysis (inter-rater reliability of kappa = 0.93). Most participants drew their maps south-up (17 south-up, 5 north-up, 4 west-up). Pointing accuracy differed as a function of head orientation relative to the orientation of drawn maps ($F(2.7, 67.7) = 5.62$, $p = .002$, $n_p^2 = .18$; self-localization and pointing time $F < 1$). All individual contrast analyses for participants with south-up maps became significant, but revealed inverse values expressing best performance when oriented north. No significance was found in any participant with west-up maps (p's > .136, t's < 1.51). Even participants with maps oriented in other directions pointed best when facing north. Furthermore, oriented GRFs acquired from navigation predict a positive correlation between distance and pointing error. An assumed small distance effect of $\rho = .20$ in the population is inconsistent with the observed data (error: $t(26) = -7.64$, $p < .001$; time: $t(26) = -7.93$, $p < .001$). Predictions from navigation-based oriented GRFs were therefore not supported.

Local Reference Frames

LRFs predicted better performance for being aligned with a local street. Indeed, pointing accuracy varied as a function of street alignment ($F(4.08, 106.09) = 12.25$, $p < .001$, $n_p^2 = .32$; self-localization time: $F(3.80, 98.91) = 2.29$, $p = .068$, $n_p^2 = .08$; pointing time: $F < 1$). But the effect found contradicted the hypothesis: six participants performed *worse* (t's < -2.13, p's < .034) when being aligned with a street as indicated in the contrast; only one participant performed better ($t = 2.62$, $p = .010$). Distance effects for pointing time and error were predicted, but not observed. Our data does not match predictions from LRFs.

(Figure 2)

Discussion

The benefit of north-alignment and the lack of distance effects suggest that participants used representations based on city maps, which are north-oriented, single frame representations. Errors increased with misalignment from north suggesting that mental rotation was used for compensation (Iachini & Logie 2003). For contra-aligned (i.e., south) body orientations, participants performed better than they would by mental rotation. Such a pattern is probably due to applying a different strategy in this case which has been described for map memory (Hintzman, Dell & Arndt, 1981).

This pattern was observed in every participant, not indicating variation in strategy. Alternative explanations for north alignment seem implausible as Tübingen has no prevalent north-south grid pattern or widely visible characteristic landmarks indicating north, and during data collection participants were not physically oriented north. These alternatives would also not explain the lack of a distance effect.

Our data does not support theories proposing individual global or local reference frames acquired by navigation (McNamara et al., 2008; Meilinger 2008; O'Keefe, 1991; Poucet, 1993; Trullier et al., 1997; Wang & Spelke, 2002) or orientation-free memory postulated especially for highly familiar environments experienced from multiple perspectives (Byrne et al., 2007; Evans & Pezdek, 1980; Gallistel, 1990; Sholl, 1987). Still, long-time experience of a city from navigation only, without any access to a common map, might yield orientation-free representations as well as individual global or local reference frames. Additionally, most previous studies used smaller scale spaces, shorter learning periods with reduced perceptual input (e.g. visual only), or different tasks (e.g., route navigation). Indeed, alterations to these factors within our experimental paradigm might yield different representations as might testing populations without (e.g., children) or different map experiences (e.g., Japanese).

It is a surprising result that memory for a highly familiar western city seems to rely strongly on maps although participants spent orders of magnitude more time navigating the city day-by-day, than looking at maps of their hometown (either physical or digital). Some participants reported not having looked at a map of Tübingen for decades. Maps are mainly perceived visually (while navigation provides rich multimodal experiences), and the visual information provided by maps is limited. Only very few visual features of a location (if at all) are displayed within a map (e.g., the geometry), and only few locations within a city are explicitly highlighted in maps - most locations used in this experiment were not. Therefore, participants had to identify their location and orientation by navigational knowledge, and relate this navigational knowledge to map knowledge, thereby switching from ground perspective to birds-eye-view. Why did participants nevertheless make this effort and weighted map-based representational structures more heavily than representations derived from multisensory navigational experience? Maps represent an environment within a single reference frame, and accurately reflect multiple spatial relations without the need to be verified and adapted due to further navigational experience. They present a reliable structure to organize complex navigational experiences, and contain survey relations required for pointing. Remembering and mentally rotating a city map might be computationally easier than deriving survey relations by integrating multiple navigational experiences within a single reference frame. Our results indicate that the popular intuition that we have access to something like a map in our head is true, and – at least for the present participants and environment - this map is oriented north.

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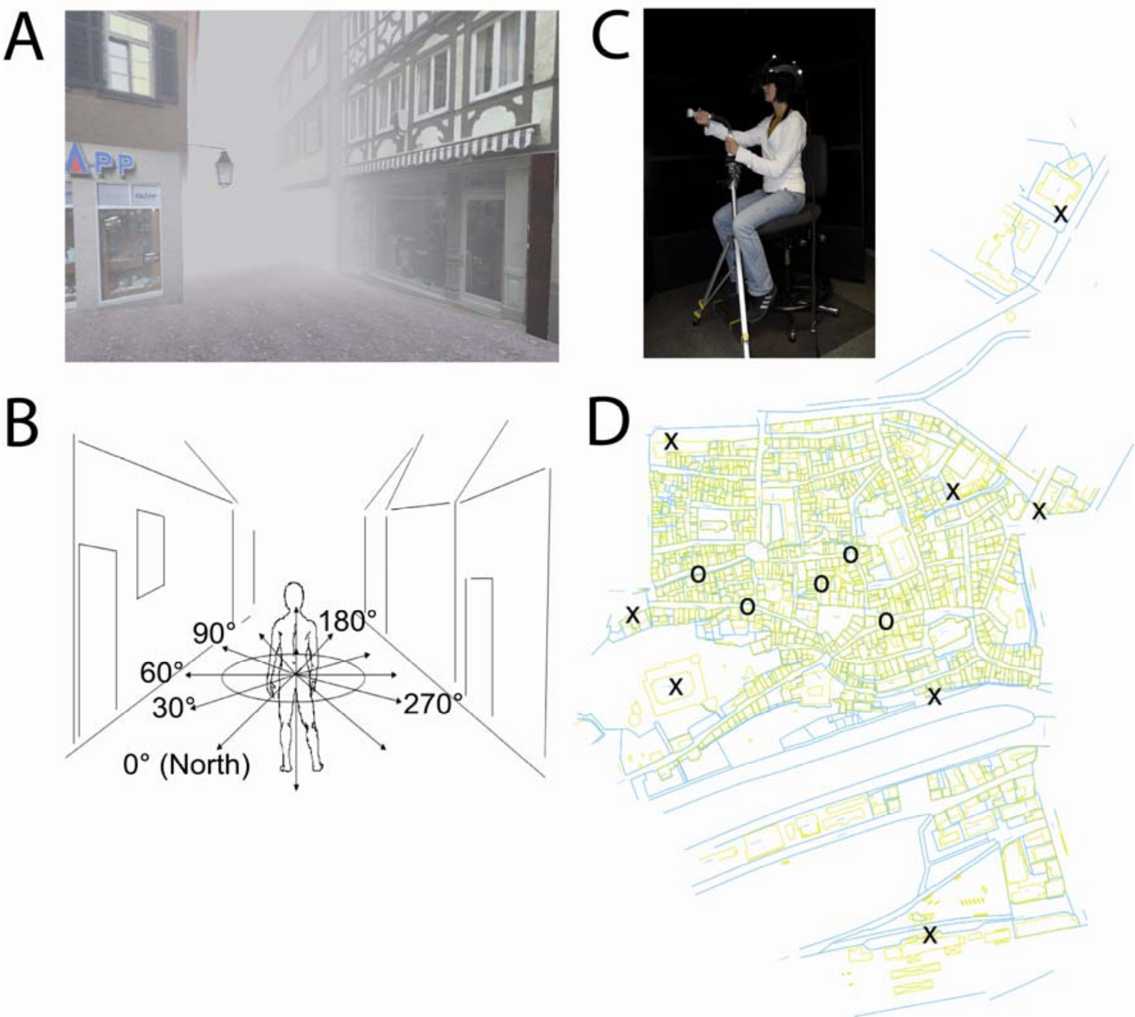

Figure 1: A: Snapshot of the city model used. B: At each initial location participants faced twelve orientations, some of which were aligned with a street (here 150° and 330°). C: The setup with a head tracked HMD and a pointing stick. D: A map of Tübingen with the initial (o) and target-only (x) locations.

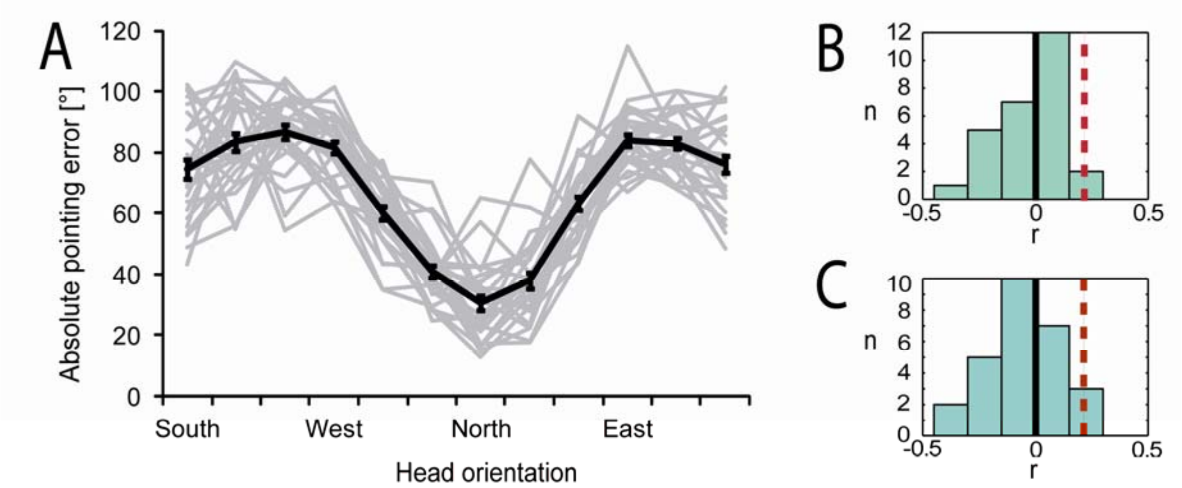

Figure 2: Global map based RFs. A: Individual (grey lines) and averaged pointing error (black lines with standard errors) as a function of global head orientation. Distance effect: Histogram of individual correlations between pointing error (B) and pointing latency (C) with the Euclidean distance to a target. The black line corresponds to no distance effect ($\rho = 0$), the dotted red line to the right side corresponds to a small distance effect ($\rho = .20$) in the population.