Remember the North -

Reference Frames and Spatial Cognition at Different Scale

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Abstract—**The North-up reference frame on cartographic maps is a cultural convention that originates in the astronomical-geometrical worldview of ancient Greek cosmology. Although a relatively young tradition, it had substantial influence on human spatial thinking from the Renaissance. Recent geo-visualization applications may display maps with dynamic, head-up orientation to support turn-by-turn navigation. Increased GPS use seems not to support survey knowledge related to spatial memory. In the current study we tested the sense of North in a sample of young adults. We created an ecologically valid experimental setting and carefully selected a special location at ELTE university campus in Budapest. Standing near river Danube and heading an easterly direction our 36 participants first indicated North in a vista space; then they pointed toward salient urban landmarks in the city. In the second part they marked graphically the directions of important cities in Europe and, finally, they once again indicated the direction of the North in a geographic reference frame. Our results demonstrate that the participants had a clear sense of geographical North, which was not biased by the setting, buildings and available landmark cues. Furthermore, test subjects living longer in Budapest had a better sense of North, supporting a learned component in this directional knowledge. Our experiment in the physical world resulted in supporting evidence that North is still maintained in human cognitive maps as the cardinal direction for orientation.**

Keywords— Spatial Cognition; Reference frame; Orientation; Navigation; Cartography

I. Introduction

The problem of map-assisted orientation is the translation of the user's *egocentric* reference frame to the *allocentric* reference frame of the map. Along with positioning (finding the starting point), it includes the task to find the geographical parallel of the user's actual head-direction in the field (finding directions). Because of the strong tradition to construct maps with North at the top margin, navigation in large geographical environment, learned by map reading, is greatly influenced by cartographic representations [1].

Is there a similar directional bias to North when orienting in a smaller scale, environmental spaces? Is there a representation of the North in the human mind? Are the hierarchically organized mental representations we call 'cognitive maps' oriented to the North?

The concept 'cognitive map', as a mental representation of the environment, was proposed by the psychologist Edward C. Tolman in 1948 [2]. His famous experiments that studied the spatial behavior of rats in a maze pointed to relations of navigation and a hypothetical structure in the brains of both animals and humans. Today this much-discussed and controversial concept, an internal representation of the environment is still called '*cognitive map*'. After seventy years of research, especially using modern medical imaging technology, it is better understood as a complex function of different human brain areas. The cognitive map as a spatial memory structure is most directly related to the hippocampus, as well as parahippocampal and retrosplenial areas in the human brain [3] [4]. Even if the exciting discoveries of the neural foundations of the spatial brain in the identification of the place cells, grid cells, border cells and head direction cells and their proposed interaction models in recent publications [5], the better understanding of human spatial cognition is still a multidisciplinary research challenge.

Orientation is considered here as a goal-directed interaction with the environment [6], in our case either as physical or as mental procedures. As orientation is a fundamental activity for spatial behavior and wayfinding and navigation are also based on right orientation, in our experiments we studied spatial orientation in connection with the sense of North. Although this may seem a rather simple task, it is surprisingly rarely studied and, consequently, we have little knowledge about this aspect of the cultural history of our spatial cognition with maps. Specifically, the evidence on how much this knowledge is learned and/or innate is incomplete. Traditional maps helped us building cognitive maps by depicting the spatial relations in an environmental or geographical context, and they still provide us a useful reference to integrate further navigational experience.

In their 2012 experiment, Frankenstein and her colleagues studied the spatial behavior of 26 residents of Tübingen, who navigated in a virtual, three-dimensional urban model while wearing head-mounted displays [7]. They were asked to point to well-known locations in the town, all invisible from their virtual position. All participants performed best when facing North, and the pointing error increased with increasing deviation from this direction. Using knowledge gained from navigation to link their perceived position to the corresponding position on a city map,

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participants could easily retrieve the locations from their memory of city maps, typically north-oriented.

Today people solve highly diverse spatial problems at a different scale, from manipulating objects in their personal space to using cognitive info-communications technology [8] to collaborate in global and, virtual spaces e.g. *MaxWhere* educational workspace [9]. With global navigational satellite systems (GNSS), practical navigation seems no longer the problem it used to be. Billions of people have access to the now ubiquitous network map services like GoogleMaps and we habitually use our mobile phones to find our ways in the increasingly complex modern cities. Although these popular and free services were available only in the past decade – e.g. Google map service became available in 2005 – they substantially transformed navigation. The printed map is no longer the primary tool of wayfinding and dashboard navigation displays are now common in all kind of vehicles. While these systems effectively solve spatial problems (essentially route-finding and optimization) their use has negative effect on their users. Users of GPS instruments usually did not construct a holistic, map-like mental representation of the environment – although they may remember the routes taken [10]. The limited size of the display is certainly a key factor responsible for the lack of overview. Although in most cases system assisted navigation provides a visual display, in actual navigational task the human attention is focused on the environment, especially at higher speed movements (e.g. car driving). To compensate the narrow visual channel, onboard systems make use of the auditory channel and support navigation by verbal navigational instructions. Voice navigation is really convenient as the human user could listen to and follow the turn-by-turn instructions.

However, once a user relies on the automatic system no cognitive map is constructed in the human brain. Users degrade their navigational skills when not training them [11]. Navigating, route finding and building up a mental map by experience are demanding and complex processes for the human brain, and they are closely connected to human memory. For this reason, the cognitive heritage of traditional cartography should be better understood and maps should be used to preserve human spatial intelligence [12].

A Learning and spatial knowledge

In 1975 Siegel and White proposed that human spatial knowledge acquisition followed a hierarchical structure [13]. In a novel environment, we acquire first *landmark knowledge* of distinctive elements of the environment or visual scenes stored in memory [14]. In literature landmarks sometimes are categorized as local or global ones [15]. Local landmarks are related to route navigation in smaller spaces. Global landmarks are point of reference from a broader viewpoint, therefore they can suggest a geocentric (geographic) framework for navigation [16]. R*oute knowledge* consists of landmarks, places and sequential turns or directions attached to them and route connections between them. [6]. An integrated spatial knowledge about the environment is *survey knowledge*. It is constructed by accumulated personal experience and/or by other external aids (e.g. maps) [17]. Survey knowledge helps more in effective navigation and route planning [11] [19], because it provides an external reference frame, making us able to work with mental imagery and - using a map-like memory representation - to take shortcuts or to navigate on unfamiliar routes.

The high importance of *reference frame* in human navigation is underlined by recent neuropsychological research, showing their dependence of viewpoint [5]. Furthermore, this integrated spatial representation provides metric information, such as the relationships between different locations and landmarks [20]. The type of spatial knowledge which can be acquired in a novel environment depends on the goals of learning, or on the effort taken into consideration or on the structure of the environment [21].

B Reference frames in spatial cognition

Cognitive neuroscience distinguishes two frames of reference: *egocentric*, where the position of objects is dynamically updated when the actor moves; and *allocentric*, where the objects and our own heading is defined by the position of other objects in the environment). Allocentric is sometimes also called *exocentric* [22][23] or *geocentric*[24]. However, the latter can also mean a third type of frame of reference, where the global orientation serves as reference [25]. While evidence from rodent studies supported the role of an allocentric frame of reference [26] research with humans suggested the crucial role of an egocentric frame of reference [27]. Wang and Spelke claim that the use of *geographic maps* led to the widely accepted notion that human navigation relies on *allocentric* frame of reference [28]. However, evidence from studies of navigation suggests the contrary: an essentially egocentric frame of reference. Their theory states that three systems underlie human spatial navigation: (1) path integration is used to dynamically update spatial representations during locomotion, (2) place recognition is based on snapshots from experienced viewpoints that are stored in memory, (3) reorientation is based on a geometric module which uses the layout of the surface. This latter system is encapsulated, and thus, can only interact with the other two systems through language. Furthermore, this geometric module represents space in a manner that does not meet all criteria of Euclidean geometry [29]. Interestingly, in their later theory Spelke and her colleagues identified two core geometric systems. One is active during navigation and represents length and direction but not the angle of edges, while the other is active during the analysis of visual forms, represents length and angle but not direction (i.e. this is the reason why objects and their mirrored versions are rather hard to distinguish).

However, not every type of navigational assistance contributes to the same aspects of spatial knowledge. We can make a distinction between *static* spatial representations and *dynamic* ones. The first category can refer to the classic paper-based, north-oriented maps with allocentric (or geographic) reference frame, while the second one includes novel navigational systems such as GPS-based and mobile apps. These latter systems can track and visualize the spatial location of the user and habitually offer a *forward-up* (egocentric) orientation, which means that they rotate themselves according to our headings [17].

D North and the orientation of maps

Despite the common belief maps were *not always* drawn with north at the top. Actually, it is a relatively new convention to organize the graphic space with the alignment of the structure to north as a prime direction. A short overview on cartographic history demonstrates that map orientation, and re-orientation, was not a natural, evolutionary but a culture-driven process. One important remark should be made before we would look at some historical examples: it seems that ancient maps did *not* serve practical navigational purposes in *physical* spaces. They were constructed as visualizations to support human mental imagery and spatial cognition in various, but not everyday situations. This makes the generally accepted influence of the long history of cartography on human spatial orientation even more remarkable [1].

The history of the orientation of geographic representation goes back to the first artefact identified as a map: the 'Nuzi clay tablet', found near Kirkuk, Iraq in 1930/31. From the cuneiform inscriptions on the map we know that this c. 4500 years old spatial representation was adjusted to the cardinal directions. These were named according to winds, for example, the top is marked as '*im-kur'* or 'mountain wind'. The *first map* with cartographic symbols is clearly a geographically oriented representation of a region [30]. Oriented, that is aligned to a geographical reference frame, the first map, however, was *no*t oriented to North.

Figure 1. South-oriented Islamic world map after Al-Idrisi (c. 1150).

East was the top of most of the medieval, circular world maps made in Christian Europe. These diagrammatic, OT-representations followed the general scheme of the letter 'T' in a letter 'O'. From few centimetre diameter initial letters in manuscripts occasionally they would extend to large-size, wall maps. Around 1450, to the order of the Portuguese crown, the Venetian monk *Fra Mauro* constructed a 2-meter diameter world map showing the expanding horizon of European explorers. For centuries in the middle ages European world maps were oriented to East, a sacred direction according to Christian faith.

In Islamic Cartography the primary direction was *South*, probably because in this way the central point in the Muslim religious space, Mecca were represented above the region from where the world was seen by believers. Islamic map makers like *Al-Idrisi* in the 12th century made upside-down maps for the modern reader. For this reason, the images of Islamic world maps are usually available on the web 'reoriented' to the North, which is easy to recognize since the texts are upside down after the reorientation.

The importance of viewpoint as a determinant of values and cultural meanings of the direction is exemplified by early Chinese maps. These representations took the perspective of one person, the emperor, sitting in his capital city in the north, up in the map and looking down to his subjects. Consequently, these rectangular maps, although they may seem north-oriented, were oriented to the South, the primary direction of the Chinese compass [31].

The origin of the North as a primary direction is astronomical and goes back to ancient times. For the civilizations living on the northern hemisphere the regular observation of celestial movement offered a structure for a cosmic, both celestial and terrestrial reference frame of long-term stability. Using geographical latitudes and longitudes to describe the inhabited world the Alexandrian geographer, *Eratosthenes* constructed a world map in the 3rd century BC. The reason why his map was north-oriented was the eminent role the celestial pole played in early Greek astronomy: the imaginary point marked the direction of the rotational axis of the celestial sphere.

In the *gnomon* world model (6th c. BC) the length of the Sun's shadow depended on the inclination of the celestial axis to the plane of the horizon of the observer. This inclination was called '*enklima'* in early Greek terminology [32]. Scholars realized that it was the equivalent of geographical *latitude*, which was measured from the plane of the Equator. *Oikoumene*, the inhabited world in classic geography, was located on the northern hemisphere, and it was described by geometrical, abstract data in the Antiquity. In the *Geography* of the 2nd-century Alexandrian scholar, *Claudius Ptolemy*, the world map was constructed with the imaginary, northern point as a real center for the geometric construction of parallels. It is due to the fundamental influence of Ptolemy's work that the North became the cardinal direction in Renaissance geography.

However, orientating *all types* of maps to North became a convention only in the 17-18th century, when modern cartography was born in the Enlightenment. Due to higher precision optical instruments, *astronomical* and geodetic measurements became accurate enough to provide a rigid geometric basis for more detailed, regional maps. Small scale world maps, medium scale *topographic maps* and detailed cadastral plans were constructed according to the same intellectual framework, now regularly with North at the top. Medium-scale topographic maps allowed navigation in *environmental spaces* and were made first for the military. From the 19th century similar maps, allowing field navigation, appeared in geographical education and were used widely by the public [33]. By the 20th century elementary geography schoolbooks instructed generations in map use and it became the common knowledge that north was *always* at the top of the maps. At the same time, as maps were printed, circulated and used as cognitive tools, the world was seen from this naïve geographical perspective.

II. The 'You Are (A)where' Experiment

A. The location of the experiment

After our virtual navigation experiment [34] the location of the real world experiment was carefully selected at the Lágymányos Campus of the Eötvös University. This is part of a relatively new complex on the western side of river Danube, dominated by two massive buildings. The experiment site was halfway between the Northern and Southern main buildings, in a practically open field.

The location of the site allowed good visibility at a smaller, *vista space* on campus. However, of the salient landmark of the city but the Danube was visible. Note that the general course of the river is north-south - except for the short section right at the campus. Here the *river changes its course* and flows from north-east to south-west. This deviation (25-35° East from true north) made the location of the experiment suitable for testing the sense of north in the human cognitive structure.

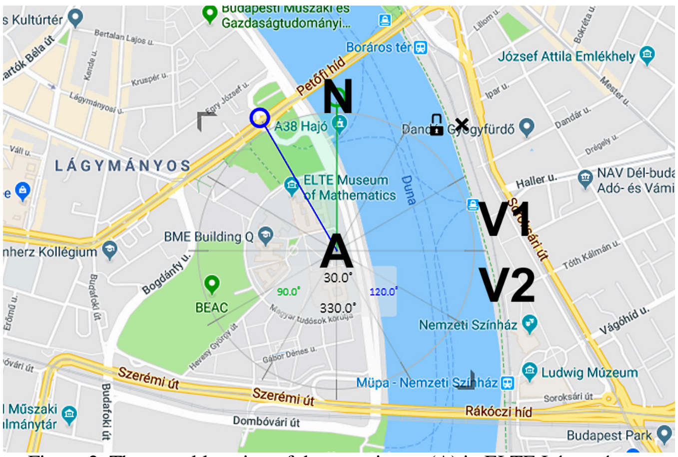

Figure 2. The actual location of the experiment (A) in ELTE Lágymányos Campus, Budapest. True North (N), the approximate viewing direction of test group 1 (V1) and group 2 (V2) are marked.

Our hypothesis was that in the smaller scale, *vista* space, where the river bank and the floating boats etc. were well visible, the test subjects would use this landmark (a *border* according to Lynch's mental map terminology [35]), and would consider it as a *north-south* structural axis of the city. Consequently, at the first test in our pointing experiment we expected a significant deviation (c. 30-40°) West from true North. As the location in the vista space was surrounded by higher buildings, with an architecture adjusted to the orientation of the river, the geometry of the space could reinforce or guide geometry-based reorientation. To reduce any bias introduced by the orientation of the experimental table, the table/ sheet of paper was reoriented with +\- 10 degrees after each recording.

In the second series of marking directions of cities the scale of the space was *geographical* [36]. We expected subjects to change their previous, egocentric reference frame for a geographical one with a north-oriented coordinate system.

B. Participants

Thirty-six participants took part in the experiment (12 female). Their age ranged from 18 to 24 (M = 19.97, SD = 1.36), their vision was, or corrected to, normal. All participants were bachelor students of ELTE Eötvös Loránd University. Their vision was normal or corrected to normal and they were all right-handed. Some of them were born and lived in Budapest, while others spend much shorter time in the capital, but they all knew the city and the locations of its major landmarks. Our subjects represented a rather homogenous group of young Hungarians with very similar education and, because of their interest in geography, they have seen many maps and were familiar with map orientation and simple wayfinding tasks. Prior to the Task 1 participants were given a short explanation about the experiment and they gave a written informed consent. They were all volunteers and the experiment data we collected and analyzed did not include any personal information. The experiment was carried out in accordance with the Declaration of Helsinki. In the end we acknowledged their cooperation, praised the achievement and expressed our gratitude for their help and they all departed with positive feelings.

C. Procedure

For the experiment we used a stylish, antique measuring table, an old surveying instrument of the topographer, standing on a tripod. The table was horizontal and its orientation was systematically changed +/-10 degrees from North in order to compensate the effect of regular geometry on graphic representation. In the middle of the table we fixed a sheet of paper, where a large dot indicated the place of our experiment in any mental space, and an around 18 cm-diameter circle was drawn by gray dotted line, symbolizing the horizon. Test subjects were explained that this structure is the framework of a '*You-Are-Here*' type map.

They were asked to imagine that their position was the black dot in the center of the circle. Next they were asked to draw a straight line from the center to the horizon in the direction of the true *North*. Using color pens they followed the procedure when they indicated the imagery directions of various *landmarks* in Budapest (e.g. Heroes' Square). After the first test run we changed the sheet of paper and asked subjects to draw the directions of different major *cities* in Europe (e.g. Paris) and beyond (e.g. Cairo) in *geographical space*. In the end we asked them to once again mark the direction of North on the same sheet of paper.

When planning the experiment our primary concern was to design a paradigm as simple as possible to make our subjects able to solve the actual tasks in c. *two minutes*. As the experiment required field work during the spring semester we wanted to include as many interested students as possible during the short breaks between lectures. Unfortunately, for the unusually rainy weather in May, the student group had to work under cold and wet conditions under a large umbrella that saved but the experiment records and the test subject. With all the preparations and including the final act of offering participants a chocolate bar the duration of the whole procedure was c. 6 -7 minutes per person.

III. Results

A. Data processing and analysis

For brevity data processing and analysis are presented together below. We used R (3.6.0) statistical software and JASP 0.9.2 for modelling. First, we tested whether participants were influenced (misoriented) by the availability of the Danube as a potential landmark-cue for the North direction. We compared the pointing errors to the two references (North, Danube) in a Bayesian paired samples t-test (M_{Real} = 15.61 (SD = 22.56), M_{Danube} = 43.06 (SD = 21.81), $BF10$ = 6.294e+6, *error %* = 6.321e-10). This analysis showed that the errors were significantly smaller in comparison to the real North direction than to the one that could have been suggested by the river.

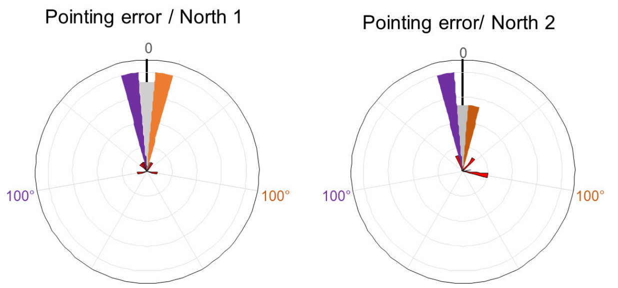

Figure 3. Distribution of the pointing errors in the two spatial tasks

Based on this results we used the pointing errors relative to the geographic North as dependent variable. In the next step of the analysis, we were interested whether Gender or Habitation had any effect on pointing errors. Therefore, we performed Bayesian modelling in a Multivariate Repeated Measures ANOVA design, where on top of the null-model, the following terms were introduced:

- Measurement: Sense of direction North was collected before (pre-test) and after (post-test) the experiment.
- Gender
- Habitation in Budapest was considered as a binary variable; 'True' was used when the person lived in Budapest and 'False' when his/her primary address was not Budapest

The choice of the modelling technique was motivated by the ability of explicitly comparing potential underlying models. Hence, all main effect models were constructed along with all the two and three-way combinations. This yielded a total of 19 models to evaluate (including the null-model containing only the intercept). We defined uniform priors, and all models entered with a prior likelihood of 0.53 into the comparison. The analysis showed that the most likely model given the data was the one that contained only the term of 'Lives in Budapest' ($P(M|data)$ = .270, BFM = 6.647). The effect showed that participants living longer time in Budapest showed significantly smaller errors in the sense of North than at participants staying there for shorter periods (see Figure 4).

Figure 4 The effect of time spent in the city

We did not find any model, including either the Gender or the Measurement factors that would have been more or comparably likely. Indeed, the difference between pre-test and post-test measurements in a planned contrast test were shown to support weakly the hypothesis of no significant difference between the pre- and post-test sense of North in our sample (BF_{01} = 3.707, *error %* = 9.962e-7, 95% CI: [-0.458, 0.170]).

IV. Conclusions

In our experiment, we were interested if there is a difference in the orientation frame between a smaller scale, physical environment and geographical space. In our pointing experiment we found that participants had generally good sense of North direction that was not influenced by the visible, but misleading cues of geometry and/or the deceptive course of the river. This result means that participants had an active mental representation of the wider spatial context of the city.

This cognitive map, although with apparent individual differences [37], was available already in the first test when they pointed to North, and it did not require exposure to the later experimental conditions. We did not find any gender differences, but there was strong effect of habitation: local participants more accurately pointed to North. This results supports the hypothesis of learned components underlying the knowledge of North in egocentric navigation.

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