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Brief article

The Earth is flat when personally significant experiences with the sphericity of the Earth are absent

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ABSTRACT

Participants with personal and without personal experiences with the Earth as a sphere estimated large-scale distances between six cities located on different continents. Cognitive distances were submitted to a specific multidimensional scaling algorithm in the 3D Euclidean space with the constraint that all cities had to lie on the same sphere. A simulation was run that calculated respective 3D configurations of the city positions for a wide range of radii of the proposed sphere. People who had personally experienced the Earth as a sphere, at least once in their lifetime, showed a clear optimal solution of the multidimensional scaling (MDS) routine with a mean radius deviating only 8% from the actual radius of the Earth. In contrast, the calculated configurations for people without any personal experience with the Earth as a sphere were compatible with a cognitive concept of a flat Earth.

1. Introduction

It was a long and difficult journey for humankind to prove, accept and establish the concept of a spherical Earth. As long as humans were not able to explore the Earth from a non-geocentric perspective, they had to estimate the radius of this spheroid on basis of typical phenomena associated with a spheroid. Around 240 BC, Eratosthenes of Cyrene, for instance, integrated the knowledge of the distance between the cities of Syene and Alexandria with the different angles of elevation of the sun at these places. The outcome of this simple trigonometric calculation was a remarkably accurate estimation of the Earth's radius with a deviation of <1% (Dutka, 1993).

Besides these classic findings later validated by modern science, the spherical nature of the Earth is also visible to the naked eye. In his book *On the Heavens*, Aristotle already called attention to certain arguments favoring a spherical Earth. He described, for instance, the phenomenon of the circular shadow of the Earth on the moon during the lunar eclipse which is observable at all elevations of the moon—an effect that cannot emerge from a shadow cast by a round disc but only by a spheroid (Kuhn, 1957). Other directly visible phenomena are, inter alia, that objects traveling towards the horizon are increasingly covered from the bottom to the top until their full invisibility, or the simple fact that the horizon is slightly bent.

Today, there is neither a rational debate nor fruitful discussion on the pros and cons of the concept of the Earth as a sphere—it is a scientific truth in the physical sciences. But what about the cognitive model of the Earth? Do people really use the concept of a spherical Earth in everyday life? When we explicitly asked undergraduates ($n = 120$), none of them believed in a flat world. It is well known that explicit, forced-choice questioning produces an increase

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of scientifically correct responses and the report of more internal consistent models (Vosniadou, Skopeliti, & Ikospentaki, 2004). This could be explained by the fact that people tend to simply retrieve explicitly learnt knowledge in such situations. Thus, this way of asking only validates the high degree of common-sense regarding this issue, but does not provide any insights into the deeper cognitive representation of the Earth.

Cognitive research has invested much effort to obtain cognitive representations of geographical relations, which are known as "cognitive maps" (Tolman, 1948). Such cognitive maps can be interpreted as the cognitive representation of a geographic map containing systematic as well as fluctuating cognitive distortions. Cognitive maps can be retrieved directly by map reproductions (e.g., Hirtle & Jonides, 1985). Yet, this has the practical limitation of participants' drawing abilities and the cognitive limitation that participants might not be able to construct a coherent map from scratch. Indirect retrieval of cognitive maps are much more cognitively impenetrable. They can be realized by estimation of directions (e.g., Glicksohn, 1994), estimations of alignments relative to adjacent geographical units (Friedman & Brown, 2000), or the measurement of cognitive distances (Montello, 1991).

Montello (1991) defines cognitive distances as "mental representations of large-scale environmental distances that cannot be perceived from a single vantage point" (p. 101). This definition reveals the fundamental problem of cognitive distances. Given that they cannot be seen fully from one point at one time, people have to estimate large-scale distances using different heuristics. For instance, distortions arise from hierarchical structures of cities, areas or continents: people tend to overestimate the location of hierarchically higher-ordered elements to the disadvantage of nested elements: for instance, Chicago and Rome are at the same latitude (42°N), although Chicago is cognitively located much more north of Rome (Tversky, 1981) due to at least two heuristics: (a) Chicago is located in the north of the USA and Rome is located in the south of Europe; as the USA and Europe are thought to be approximately aligned on the same area of latitudes, Chicago is dislocated north of Rome; (b) Chicago has hard winters and is located near Canada, a country known for its cold climate; Rome is a sunny and hot city, not very far from Africa, a continent associated with deserts and a hot climate; the general heuristic for climates suggests: cold means north, hot means south; consequently, Chicago must be north of Rome. While the general distortive nature of cognitive maps was found to be relatively impenetrable by expertise (Friedman & Montello, 2006), research in the domain of social cognition shows strong overlaying effects of social attitude. Carbon and colleagues showed that negative attitudes, for instance towards the German reunification (Carbon, 2007; Carbon & Leder, 2005) or towards the war in Iraq (Carbon, 2010) systematically change the cognitive distances between places like the Western and the Eastern part of Germany or Europe and the USA, respectively. Although systematic as well as unsystematic cognitive distortions are observable, humans are able to estimate areas (e.g., Battersby & Montello, 2009; Brown & Siegler, 1993) or distances (e.g., Carbon, 2007) impressively well. This is documented by high correlations between estimated and actual measures of .82 up to .93 in the given studies, qualifying such estimations as a relatively valid measurement.

2. The current study

To investigate the cognitive representation of the Earth, the current study made use of an indirect method, i.e., distance estimations (cognitive distances). To be able to measure deviations from a flat vs. a spherical concept of the Earth, we asked our participants to estimate large-scale distances between different cities all over the world and submitted these distances to a specific spherical multidimensional analysis with variations in radius.

2.1. Methods

2.1.1. Participants

Forty-four participants ($M = 26.9$ years, range: 19–71; 33 female) took part on a voluntary basis. All were naïve to the purpose of the study and none of them had specific expertise or training in geography or astronomy; additionally, when asked explicitly, none of them believed in a flat world. As explained in the *Results* section, the sample was split in two groups, one including people who had personal experience with the Earth as a sphere, the other including people who had none of such personal experiences.

2.2.2. Design and procedure

The study consisted of two parts: (1) Estimation of all possible distances between six cities situated on different continents: Berlin (Europe), Cape Town (Africa), Los Angeles (North America), Rio de Janeiro (South America), Sydney (Australia) and Tokyo (Asia). The 15 distance estimations (see Fig. 1) were randomized across participants and had to be estimated in kilometers. (2) After completion of the estimation task we asked the participants a series of questions regarding their traveling experience, geographical and topographical knowledge, self-assessments of their knowledge and the diameter of the Earth, in order to gain insight into predictors for different cognitive representation of the Earth. We also asked whether they could "honestly" imagine the Earth travelling around the sun and the Earth as a sphere. The last task for the participants was to answer the question whether they had ever personally experienced the Earth as a sphere; if so, they were asked to describe this situation in detail. All items asked are listed in Table 1. The testing was conducted individually and took less than 20 min per participant.

2.2. Results and discussion

The estimated (=cognitive) distances were submitted to a multidimensional scaling to obtain a configuration of the cities that showed the least disparities between the actual physical distances and the estimated ones. To estimate the cognitive radius of the Earth, we employed a special multidimensional scaling algorithm in the Euclidean 3D space

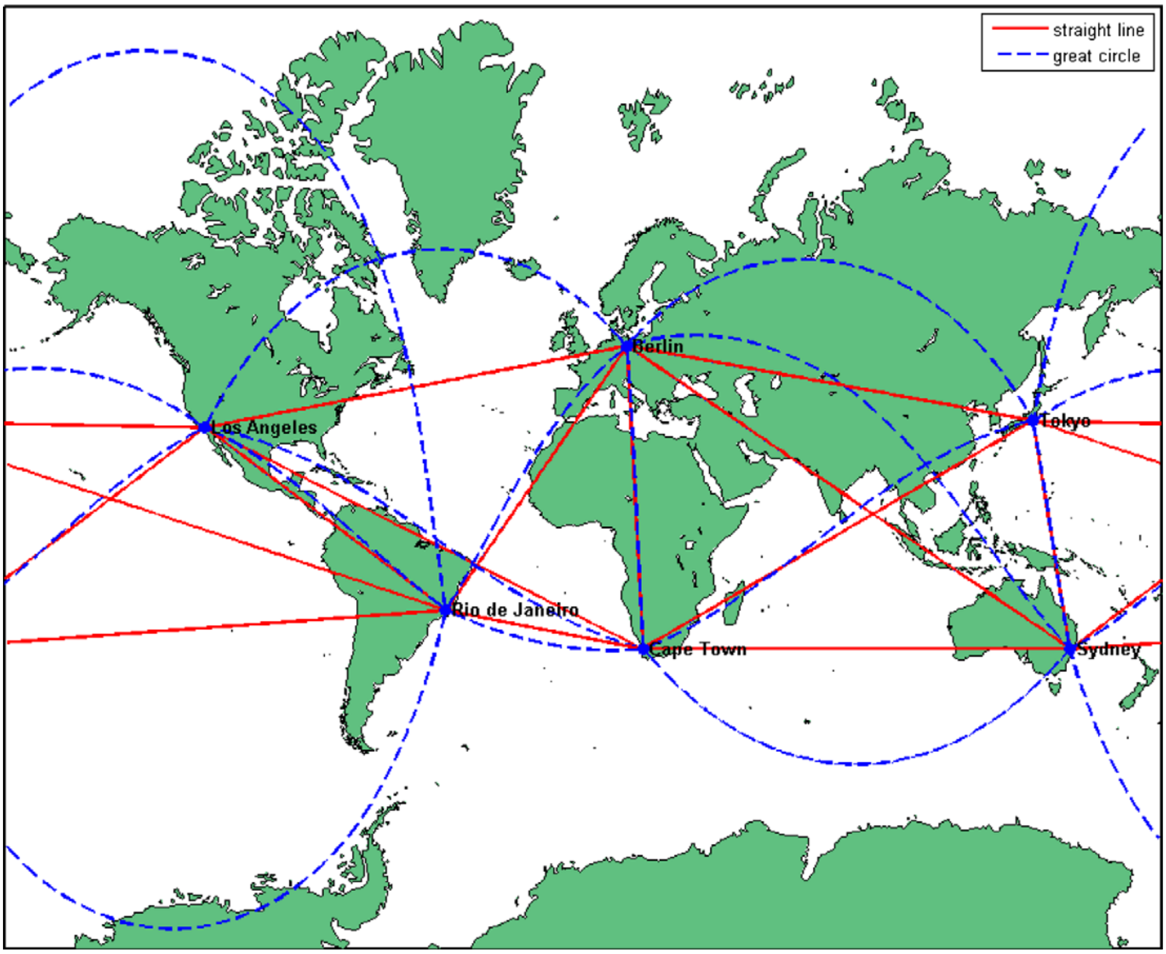

Fig. 1. Illustration of the disparity of "straight lines" (full red lines) and "great circle" lines (orthodromes; slashed blue lines), which serve as the analogue of straight lines in spherical geometry. As map a typically and widely used Mercator projected map was used, which is a cylindrical map projection presented by Flemish geographer Gerardus Mercator. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with the important constraint that all cities have to lie on the same sphere, following the logic of all places being located on a same-sized globe. A simulation was run that calculated the respective 3D configurations of the city positions for a wide range of radii. As there is no standard procedure for spherical MDS (Cox & Cox, 1991), we interpreted the estimated distances as geodesic distances on a sphere and calculated the respective direct, Euclidean distance in a 2D space. As already pointed out by Bronstein, Bronstein and Kimmel (Bronstein, Bronstein, & Kimmel, 2005; Bronstein, Bronstein, & Kimmel, 2007), such a spherical solution is advantageous over a plain or unconstrained 3D solution. This was iteratively done for radii from 4800 to 10000 km in steps of 10 km. The direct 2D distances were submitted to a non-classical multidimensional scaling algorithm (Matlab R2008b's *mdscale* routine). As a measure of goodness-of-fit we used the metric S-Stress (Scaled-Stress), which is the squared stress, normalized with the sum of 4th powers of the dissimilarities. The metric S-Stress is defined for a value range of 0–1 with 0 indicating a perfect fit, while "excellent", "good" and "fair" fits are achieved by values of 0.025–0.049, 0.050–0.099, and 0.10–0.19, respectively (Hair, Anderson, Tatham, & Black, 1998).

As to person variables we were primarily interested in a variable that was diagnostic for dissociate conceptual models of the earth. From a methodological perspective, none of the variables we asked for was suitable for splitting groups—except for the last one about the personal experience of the earth as a sphere. Splitting by the other variables was not possible as they (a) were not dichotomous and (b) showed no bi-modal distributions regarding their answer levels. So any group splits on this basis would have been problematic in terms of arbitrariness. From a theoretical perspective, we also were very much focused on the item on the personal experience with the Earth as a sphere, as one can test for the significance of such personal experiences on the formation and change of conceptual models. People who had personally experienced the Earth as a sphere (6 female, 10 male subjects), at least once in their lifetime (e.g., "Yes, once. When I looked at the sea, I saw that the horizon was curved"), were assigned to the group of people with personal experience with the Earth as a sphere. People who had *not* reported such experiences (e.g., "No, never") or even negated such experience to be possible at all (e.g., "Of course, not: I am not an astronaut, so it is impossible to experience the sphericity at all") were assigned to the group of people (15 female, 1 male)

Table 1
Demographic data of the participants classified as having no personal experience vs. having personal experience with the Earth as a sphere. For all knowledge items the correct answer is given in box brackets to give an impression of the deviations. Group comparisons refer to the comparison of means of the respective item between the group of people with vs. without personal experience with the Earth as a sphere.

Item	[correct answer]	$M_{\text{personal experience}}$	$M_{\text{no experience}}$	Group comparison		
				Type of statistics	*p*-Value	Effect size
Age of participants (years)	–	29.5	25.6	*t*-Test	.4350	*n.s.*
Female: Male participants (*n*:*n*)	–	10:6	15:1	*Chi*^{2}	.0325	*r* = .179
1. How often have you flown with an airplane (subsections counted as single flights) (*n*)	–	12.9	21.1	Mann–Whitney-U	.3461	*n.s.*
2. How often have you travelled to another continent? (*n*)	–	2.7	1.9	Mann–Whitney-U	.7774	*n.s.*
3. How large is the diameter of the Earth? (km)	[12,756]	13,977	21,831	*t*-Test	.0941	*n.s.*
4. What is the longest possible direct distance between 2 points on the Earth? (km)	[20,037]	21,880	27,033	*t*-Test	.4728	*n.s.*
5. How long does an average jet plane travel (assuming a non-stop flight) around the globe? (h)	[47.15]	37.81	48.75	*t*-Test	.3648	*n.s.*
6. Given the curvature of the Earth, how far is the sight from the Zugspitze, Germany's highest mountain? (km)	[194.43]	237.67	293.44	*t*-Test	.7808	*n.s.*
7. How much is the altitude of the highest peak (Mount Everest) in relation to the Earth's radius? (%)	[0.139]	29.462	13.750	*t*-Test	.2333	*n.s.*
8. (Assuming you are not standing on an elevated place:) How far can you still see the silhouette of an object as large as a human due to the curvature of the Earth if you have perfect sight (and perfect vision)? (km)	[9.14]	44.75	16.14	*t*-test	.4016	*n.s.*
9. How good do you think your geographic knowledge is? (1 = 'very bad' to 7 = 'very good')	–	2.69	2.81	*t*-Test	.7937	*n.s.*
10. Please answer honestly: Can you imagine that the sun is not going "down", but the Earth is rotating around the sun? (1 = 'very bad' to 7 = 'very good')	–	5.06	5.44	*t*-Test	.5424	*n.s.*
11. Please answer honestly: Can you imagine that we all live on a sphere (=Earth)? (1 = 'very bad' to 7 = 'very good')	–	5.13	4.75	*t*-Test	.5745	*n.s.*

without personal experience with the Earth as a sphere; twelve people did not answer this item at all and were thus excluded from all analyses related to this variable.

In order to rule out (on the basis of the data we have) that the differences we found with respect to personal experience with the Earth as a sphere were not simply based on a third variable, we looked for systematic differences between both groups regarding variables such as the accuracy of geographical estimation (e.g., estimation of the diameter of the Earth), the degree of subjective geographical knowledge or the travel experience. Table 1 shows that both groups did not differ in any of the items they were asked for. Note: on average, both groups did also answer the knowledge items with high accuracy, with the exception of one item which was answered extremely deviant by both groups: the altitude of the Mount Everest in relation to the Earth's radius was massively over-estimated.

The stress values of the multidimensional scaling routine in a spherical space showed a clear optimal radius for the people who had personally experienced the Earth as a sphere. On average, this group showed a cognitive radius of $r = 5860$ km, which is pretty near to the actual mean radius of the Earth, being $r = 6371$ km. Interestingly, people who had *never* personally experienced the Earth as a sphere showed no specific best fitting radius. The larger the simulated radius was, the better the overall fit of the configuration proved to be. Fig. 2 illustrates these findings including the stress values for real distances, which show a perfect fit with a radius of 6371 km. This corresponds with the true radius of the Earth.

As a sphere with $r \to \infty$ is in fact a plane, the distance estimations of the group of participants which had never personal experienced the Earth as a sphere are compatible with a configuration in a 2D space. Importantly, although these participants reported to have a spherical image of the earth when explicitly asked about it (see item 11; Table 1), failed to demonstrate a concept of the Earth as a sphere when indirect measures such as estimating large distances were used. When such higher cognitive processes were required, they based their estimations on a simple cognitive concept, that of a flat Earth.

From Table 1 we can demonstrate that probable candidates of triggering a spherical model of the Earth that were assessed in this study (e.g., geographical knowledge, travel experience) were not associated with one of the two groups. Besides a higher rate of males in the group of individuals with personal experience with the Earth as a sphere, none of the items showed any significant difference between the groups. This is quite compatible with the finding of "mental walls" (Carbon & Leder, 2005)—overestimations of distances between cities belonging to different parts of Germany (East and West)—whose existence does not seem to depend on geographical knowledge or travel experience. Within the scope of the present study we can therefore only speculate about determinants of the development of the conceptual model of the Earth as a sphere.

From the literature we know that children as well as adults indeed construct an intuitive understanding of our world based on their everyday life experiences (Vosniadou

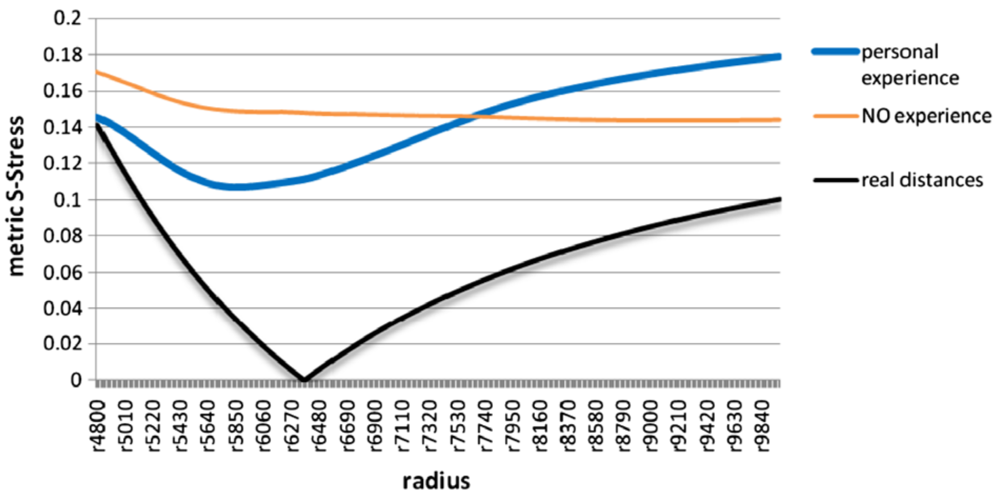

Fig. 2. Metric S-Stress values (the lower the value the better the fit; 0 indicates a perfect fit) for the two empirical groups (with personal experience with the Earth as a sphere vs. no such experience) and the real distances with varying radii of the based sphere.

& Brewer, 1992). An extreme position would be that personal experience with the Earth as a sphere could trigger an instant conceptual change from the concept of a flat to a spherical Earth. Such a non-monotonic change can happen when the learner resubsumes a domain of experience under a conceptual system which had been originally developed for another domain (Ohlsson, 2009). As pointed out by Vosniadou (2007), to initiate such a conceptual change a restructuring of "naive, intuitive theories based on everyday experience and lay culture" (p. 47) towards scientific knowledge is needed. In the realm of the present study, we could argue in favor of such restructuring, but should modify the condition when restructuring is effective for the present case: scientific knowledge of the Earth *plus* personal experience in terms of a moment of deep insight—Vosniadou (1991) already mentioned this important step within her instruction framework for restructuring conceptual models by underlining the meaning of counter-intuitive personal experiences. To personally experience the Earth as a sphere might be such an event of personal importance.

A more moderate position would claim that one single event of personal significance such as the personal experience of the Earth as a sphere might change sub-models of the whole mental model or might create a "synthetic" mental model (Vosniadou, 2007) consisting of different self-consistent models. When children were tested for their mental models of the Earth, Vosniadou and Brewer (1992) identified such synthetic models in conceptual development. For instance, about two thirds of first graders adhered to a "dual earth" or "mixed" mental model. In the "dual earth" model (Vosniadou, 1991), people think of two distinct Earths, a flat and stable one inhabited by humans and a spherical one which is an astronomical object rotating in the universe, separated from everyday living. Other developmental scientists (e.g., Straatemeier, van der Maas, & Jansen, 2008) favor the idea of mental models which continuously increase their consistency when additional experiences and knowledge are added. In the context of the present study, we cannot argue for or against any of these positions. It is, however, clear that the specific way of how we ask for or investigate mental models changes the usage or even the nature of the mental model in itself (Stark, 2003). Although none of our participants believed in a flat world when asked directly, the ones who had no personal experience with the Earth as a sphere showed cognitive distances which are quite compatible with such a view.

2.3. Conclusions

The result of the present study does not only address an important question of the history of humanity on the sphericity of the Earth and the specific radius of this spheroid. It is particularly important for the theory of cognitive representation and the development of mental models. The dissociation of the two groups researched here, the one with and the other without any personal experience on the given topic, underlines the significance and importance of personal experiences for building up a coherent mental model of a physical system. It also illustrates that humans often possess incoherent, so-called fragmented mental models (Straatemeier et al., 2008): while they may explicitly state that the Earth is spherical, they implicitly use a flat Earth model when large-scale distances have to be estimated. It is important to note that this flatness does not necessarily arise from the conventional presentation of the Earth on flat maps—Battersby and Montello (2009) only recently demonstrated that, for instance, the commonly used Mercator projection does not necessarily lead to typical area distortions accompanied by this type of projection. The reason for such a fragmented mental model might be in the general cognitive inability to imagine a complex mental model—here the spherical Earth—in a coherent sense if significant personal experience with it is missing.

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