Another Look at the "Mercator Effect" on Global-Scale Cognitive Maps: Not in Areas but in Directions

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The Mercator effect is the widespread and persistent belief among cartographers and others that people's global-scale cognitive maps are distorted in a particular way because of their exposure to world maps displayed with the common Mercator projection. In particular, such exposure has been claimed to lead people to believe that polar regions, such as Greenland, are much larger than they really are, relative to equatorial regions. Recent studies, however, have found no evidence for a Mercator effect on recalled areas for world regions. Given that a version of the Mercator projection known as the Web Mercator has been used for Web mapping in the last couple of decades, we carried out a replication with samples at two universities, but we also asked respondents to estimate great-circle directions ("as a jet would fly") from their home city to several other world cities. We again find no support for a Mercator effect on areas estimated from memory, but our novel collection of spherical direction estimates provides clear evidence of a Mercator effect (or that of a similar rectangular projection) on directional beliefs. These results confirm that cognitive maps are not unitary, analogue mental structures but collections of beliefs stored in different formats in separate mental structures that are not necessarily mutually coordinated and integrated. We also introduce a survey of map use that focuses on digital maps and their use for local versus global geographic inquiries. *Key Words: area estimation, cognitive maps, direction estimation, Mercator projection.*

One of the core ideas that teachers try to get across to students when introducing the topic of map projections is that projections are graphical lies—they do not and cannot show land or water features completely accurately in terms of one or more of the spatial properties of area, angle, distance, or direction (it is sometimes overlooked that projections always show discontinuities that do not exist on the planet or globe; Robinson et al. 1995; Kessler and Battersby 2019). At some point, students almost certainly get to hear about the most famous member of the family of cylindrical projections, the *Mercator projection* (technically not a geometric projection but a mathematical one). Created a half-millennium ago specifically for use in sea navigation, it has the property of showing *rhumb lines*—lines of constant compass direction—as straight lines on the flat map image.

Actually, Mercator's projection is more likely presented not as famous but as infamous. This is because the navigation functionality the projection gets by showing courses as straight lines that are not spherical straight lines—*geodesics* or lines of shortest distance on Earth's surface—requires it to greatly exaggerate the apparent areas of landmasses (water masses, too) as one goes toward the poles, relative to the landmasses near the equator. A view of the Mercator projection overlaid with an equal-area projection (the sinusoidal) in Figure 1 shows vividly that as one moves north or south from the equator, this exaggeration really picks up at about the 40° parallel and becomes downright huge beyond about 60°.

Given the impressive spatial distortion on a Mercator projection so readily apparent to even the untrained eye (Battersby 2009)—if not necessarily understood by the untrained mind—it has long been appreciated how inappropriate it is to use the Mercator projection as a general-purpose world map, such as in geography textbooks, on school walls, or in many media graphics. It is inappropriate because it potentially misleads map readers about the sizes of landmasses, particularly those of polar versus equatorial landmasses, a putative mental distortion sometimes termed the *Mercator effect*. Some writers have seen this as unintended miscommunication

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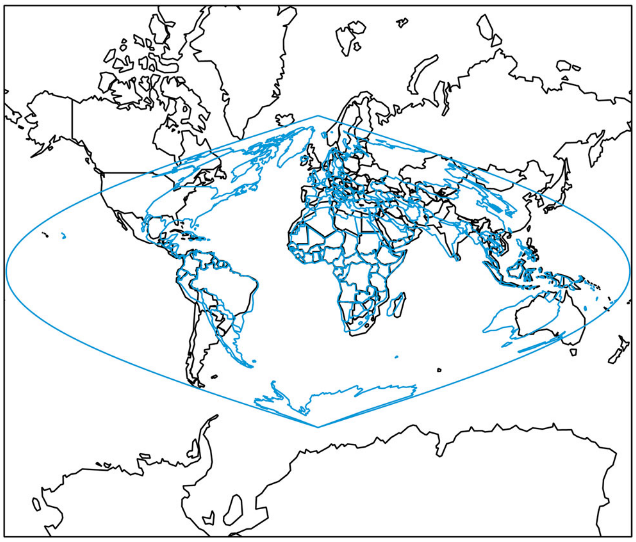


Figure 1. A sinusoidal (equal-area) world map (in blue) overlaying a Mercator projection clearly shows the areal distortions of the Mercator projection.

(Robinson 1990; Monmonier 1995, 2004; Saarinen, Parton, and Billberg 1996), whereas others have seen it as a sinister bit of intentional mental manipulation by naughty temperate-zone imperialists (Peters 1983; Wood 1992). Either way, critics deplore the Mercator projection's use for general-purpose world maps (see also Crampton 1994; Lumley and Sieber 2019).

Greenland probably provides the classic example (e.g., Battersby and Kessler 2012). It is uniquely well suited to play this role—one might refer to it as the Mercator effect's poster region—and like many geography instructors, we have referred to Greenland in numerous informal classroom demonstrations. It is a high-latitude landmass that stands out as a discrete landform surrounded by water, with a widely known name and identity. No other northern region that might provide a strong demonstration of the Mercator effect, such as Alaska, Russia, or Baffin or Ellesmere Island, has all of these characteristics. Only Antarctica in the Southern Hemisphere is adequately far from the equator—its area is even more relatively exaggerated on the Mercator than is Greenland's—but it cannot even be shown in entirety on that projection.

Thus it is understandable that Greenland so often gets compared to other landmasses to demonstrate the distorted impression of area supposedly induced by exposure to the Mercator projection. Often, Greenland's area is compared to South America or Africa, continents that straddle the equator. We ourselves have informally queried more than 1,000 students over the years about the size of South America in terms of "units of Greenland," and South America has typically been estimated as something like a third or half smaller than it actually is—over eight times the actual area of Greenland, but most people guess less than five.

We certainly agree with the critique that the Mercator projection should not be used for global-scale, hemispheric, or even continental maps in most situations (although the projection has some benefits at larger cartographic scales; see Battersby et al. 2014). That includes in most media and educational contexts at any level. The straight rhumb lines are of modest value for these applications, and the great relative area distortion of extreme-latitude regions is distinctly misleading to the eye (e.g., Lumley and Sieber 2019). Are they misleading to the mind, though?

In an earlier study (Battersby and Montello 2009), we attempted to find more systematic and comprehensive evidence for the Mercator effect. Using the psychophysical technique of magnitude estimation, research participants displayed virtually no tendency to estimate areas according to the pattern of a Mercator effect. Instead, their estimates correlated more closely with actual areas than with Mercator areas. Estimated areas were certainly not perfect, by any means; small regions were relatively overestimated and large regions were relatively underestimated. This was well described in terms of a standard psychophysical power function that was increasing but decelerating, with a positive exponent of 0.56. Not finding evidence for a Mercator effect on estimated areas, Battersby and Montello (2009) conjectured that there might have been such an effect in earlier times, when the Mercator was much more commonly used in media and educational contexts in the United States. Makers of educational and media maps, at least in the United States, had seemingly gotten the warning about using the Mercator projection and had mostly stopped using it by the time the research participants in Battersby and Montello were being exposed to world maps (Battersby [2006] discussed and provided evidence on projection popularity).

Battersby et al. (2014) observed, however, that Web mapping services had reintroduced the Mercator projection into mass culture in the United States (and elsewhere) through use of the Web

Mercator. Google began using the Web Mercator projection in 2005,[1] and other Web mapping services did the same at about this time. The Web Mercator is a variant of the Mercator projection that uses a spherical development of the ellipsoidal coordinates (Spatial Reference Organization 2014), but at most scales it looks indistinguishable from a standard Mercator: "From a perceptual standpoint Mercator and web Mercator projections can be considered the same" (Battersby et al. 2014, 88). There are technical benefits to using the Web Mercator for Web mapping involving the support of panning and zooming operations, but as Battersby et al. (2014) discussed, its reintroduction might have stimulated the return of a Mercator effect on users' minds, if one ever did exist.

Inspired by the possible return of a Mercator effect, Lapon et al. (2019) carried out an empirical replication of Battersby and Montello (2009) with samples from a Belgian university and two U.S. universities. Like the earlier study by Battersby and Montello, however, Lapon et al. (2019) again found that area estimates corresponded quite closely to actual areas, much more than to Mercator areas. The authors concluded that there was still no systematic evidence for a Mercator effect on estimated areas.

A Mercator Effect on Estimated Directions?

Apparent area is not the only spatial property of Earth's surface distorted by a Mercator projection (setting aside the discontinuity found in all projections). Indeed, the raison d'être of the Mercator is to distort "straightness" so that constant compass directions appear as Euclidean straight lines; consequently, most "straight" lines along the shortest path on the round Earth surface appear as curved lines on the projection. Perhaps mental representations of directional relationships at global scales might reveal a Mercator effect even if area estimates do not. Such an effect on directional knowledge would be shown if people believe that straight-line directions between places on Earth actually follow the straight-line relationships as shown on a Mercator map. Importantly, this would be true even if people are explicitly trying to indicate shortest-distance directions on the curved Earth surface.

There is a fairly substantial body of scientific literature on people's knowledge of directional relationships in environmental and geographic spaces at a large range of spatial scales (e.g., Ridgley 1922; Loftus 1978; Gould and Able 1981; Hintzman, O'Dell, and Arndt 1981). Our interest in this research is with directional knowledge at the global scale. Although countless classroom exercises have probably asked students to estimate the locations of world cities as part of exams in geography courses, a dozen or so studies have reported the results of locational tasks at the world scale as part of general and systematic research (e.g., Ryan and Ryan 1940; Wise 1975; Tversky 1981; Moar and Bower 1983; Beatty and Tröster 1987; Friedman and Brown 2000; Friedman et al. 2005). These studies have asked research participants (typically students) to perform tasks such as matching cities to countries or placing them on outline maps. The studies have had various purposes, including examining patterns of locational knowledge at global scales as a window into the cognitive organization and processing of spatial information. None made comparisons to Mercator patterns of directional knowledge, however, or presented their results in a manner that allows one to examine possible projection patterns. In a particularly relevant study, Anderson and Leinhardt (2002) studied subjects of varying levels of expertise on their understanding of different map projections, including the Mercator. They discussed directional rhumb lines on a Mercator projection, including the way "shortest-distance" lines on the globe are shown on the Mercator. They had subjects draw lines on Mercator maps of the world or the Americas to show the "shortest actual distance" between several pairs of cities, located in both hemispheres. The paper presented only percentages correct, based on scoring whether drawn lines were within an inch of the correct line; it presented no detailed mean angles for the lines. Overall, their results provide fairly clear evidence that people struggle with this task but people with more geography training perform better.

Our own intuitions are consistent with the findings of Anderson and Leinhardt (2002). We anticipate that most people would struggle to estimate spherical geodesic directions between places on Earth with much accuracy and that even trained people would have to explicitly intellectualize the task. Indeed, we wonder how well most people could do this even while looking at a globe. None of the existing research on directional knowledge at global scales has requested estimates of the spherical

(Earth-surface) directions between cities, nor has any focused on the role of particular map projections in explaining these subjective beliefs about directions. If people do struggle to indicate spherical directions, it is still interesting to ask how they do it. We investigate that in this article.

There is an interesting wrinkle to having people estimate directions at the global scale: There are two correct directions from any base city to any target city.[2] This is true whether estimates are based on spherical or flat representations, although we expect more consistently preferred directions for pairs of cities on a flat representation that have one straight-line connector that crosses the projection discontinuity and one that does not. The spherical straight line from any city to any other is a segment of a single great circle, such that if the correct direction from one city to another in the eastward direction is 46.0°, as it is from Columbia, South Carolina, to London (with due north as 0° and due east as 90°), the correct direction to the west is simply the opposite direction, 226.0°. There are also two answers when pointing on a flat representation such as a Mercator projection, but they are generally not just opposite directions. The Mercator straight-line (rhumb-line) direction between two cities depends on the latitude difference between the two cities and the distance between them. For example, the Mercator direction from Columbia to London in the easterly direction is 73.4°. In the westerly direction, however, it is 275.0°, not the opposite of 253.4°. The availability of two correct directions from any city to any other, no matter the geometry of the representation from which they are extracted, raises intriguing and rather perplexing substantive questions we address in our study. Given the choice to point to the east or to the west of one's home city to indicate the direction to other cities, is there a preferred direction? How likely are respondents to point in the direction in which the target city is closer? Will we see a bimodal distribution of estimated directions with some city pairs and just a unimodal distribution with other pairs?

This Study

In this study, we attempt again to find evidence for a Mercator effect on people's judgments of region areas estimated from memory. That is, we carry out a replication of our earlier study (Battersby and Montello 2009) with a couple of extensions. Given that we explore whether exposure to a version of the Mercator projection on Web maps might be responsible for the reemergence of a Mercator effect on spatial knowledge at the global scale, we develop and administer a map use survey that asks about participants' use of maps for local versus global tasks, especially digital Web maps. Clearly, people might not usually use Web mapping sites to view the entire globe or large portions thereof, and if they do not, the Web Mercator cannot be expected to have any new effects on spatial beliefs.

Like Battersby and Montello (2009), we used the conterminous United States as the standard area for magnitude estimation, but to increase the generality (external validity) of our results, we also had half our participants use Greenland as the standard area. After all, any specific landmass has a particular size, shape, and location that might influence how it is treated mentally in an area estimation task. Greenland, being the "Mercator poster region," is of special interest to examine as a standard, allowing us to collect estimates of the area of the conterminous United States. Also, to increase the generality of our results, we sampled respondents from both the University of California, Santa Barbara (UCSB) and the University of South Carolina (USC) in Columbia, on the opposite coast of the conterminous United States. Our main innovation, however, is to collect spherical direction estimates to world cities, allowing the first systematic empirical investigation of whether there is a Mercator effect on judgments of directions, rather than just on areas.

Methods

Participants

A total of 160 students (eighty from UCSB, eighty from USC) participated at the two study sites, with forty females and forty males at each. At UCSB, participants were students from one of several undergraduate geography courses; they received a small amount of course credit for their participation. Data were collected over three separate academic terms (about nine months). Although they were students in geography classes, the great majority of participants were not geography majors. Their mean age was 19.2 years (range = 18–25 years). One female participant from UCSB was dropped from further analyses, because she estimated all regions to have single-digit areas (when she had been given a modulus value of 1,000 units). At USC, participants were students in a large undergraduate introductory geography course; data were collected on a single day. Like the UCSB participants, the great majority of USC participants were not geography majors. Their mean age was 19.1 years (range = 18–23 years). They participated voluntarily without compensation, as part of a classroom exercise.

Regions

We tested the same twenty-seven regions we had examined in our 2009 work (Battersby and Montello 2009). All of these are countries, except Alaska, Greenland, the conterminous United States, and Antarctica. We chose these regions to sample across a variety of region sizes, latitudes, and longitudes. Our regions are depicted on both the sinusoidal projection (which is equal-area) and, for comparison, a Mercator projection in Figure 2. They are also listed in Table 1, along with their actual areas (in square kilometers) and "modulus areas," which are each region's area calculated relative to the modulus number of 1,000 provided for the standard region.

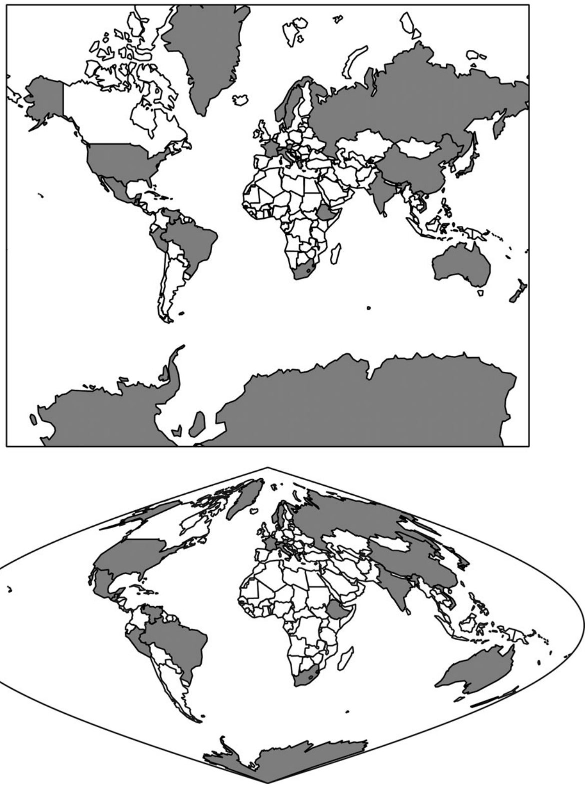


Figure 2. A Mercator map of the regions for which we had participants estimate areas is shown at the top; a sinusoidal (equal-area) map of the same regions is shown below that.

Tasks

Participants performed four tasks: region knowledge, area estimates, direction estimates, and map use survey.

Region Knowledge. Participants rated their "knowledge of each" of the twenty-seven world regions by circling a number from zero to ten, with zero being described as no knowledge and ten as extensive knowledge. To reduce the risk of order effects, we presented the regions to different participants in one of ten different randomized orders. Each of the ten order sequences was administered to eight different participants at each study site, balanced across standard regions and task order (described later).

Area Estimates. Participants estimated the areas of each of the twenty-six regions in Table 1 other than the region they used as a standard, either Greenland or the conterminous United States. Participants used the psychophysical technique of magnitude estimation to estimate areas by supplying a number they believed represented the area of the region relative to a standard quantity, the numerical value of which is called a modulus (see Gescheider 1997). Half of the participants estimated regions in terms of the area of Greenland; we told them to assume that Greenland had an area value of 1,000 units (i.e., its modulus value was 1,000). We provided an example: "If you think that Canada is twice the size of Greenland, you would estimate its size as 2,000 units." Participants were told to estimate areas accurately but without spending too much time on each one and to make their best guess if they were unsure or even if they did not know the region at all. The other half of the participants estimated regions in terms of the area of the conterminous United States ("lower forty-eight"); we also told these participants that the standard had an area value of 1,000 units. We provided the same example of Canada but with respect to the conterminous United States. Whichever standard was used, regions were presented in the same randomized order as participants had received for their knowledge ratings.

Direction Estimates. Participants estimated directions from their location city (Santa Barbara or

Table 1. Actual areas and modulus areas for each region used for the region knowledge and area estimation tasks, ordered from smallest to largest

Region	Area (km^2)	Modulus area (conterminous United States)	Modulus area (Greenland)
Denmark	41,104	5	19
Switzerland	41,854	5	20
Austria	82,869	11	39
Guatemala	109,829	14	52
North Korea	122,847	16	58
Greece	125,515	16	59
New Zealand	267,214	34	126
Italy	301,101	39	142
Norway	305,866	39	144
Vietnam	322,743	41	152
Japan	370,727	47	175
Sweden	442,246	57	209
Spain	503,250	64	238
Venezuela	913,485	117	431
Ethiopia	1,134,156	145	535
South Africa	1,219,930	156	576
Peru	1,296,605	166	612
Alaska	1,499,145	192	708
Mexico	1,953,851	250	922
Greenland	2,118,140	271	1,000
India	3,153,010	404	1,489
Australia	7,694,273	985	3,633
Conterminous United States	7,809,158	1,000	3,687
Brazil	8,493,132	1,088	4,010
China	9,366,190	1,199	4,422
Antarctica	12,277,658	1,572	5,796
Russia	16,897,294	2,164	7,977

Columbia) to eleven other world cities (in alphabetical order): Anchorage, Alaska; Bangkok, Thailand; Cairo, Egypt; Cape Town, South Africa; London, England; Moscow, Russia; Rio de Janeiro, Brazil; Rome, Italy; Santiago, Chile; Sydney, Australia; and Tokyo, Japan. The cities were identified by their name, including the country (or region, in the case of Anchorage) in which they are located. Participants estimated directions by drawing a straight line from the center of a pointing circle (the center represented their location, either Santa Barbara or Columbia) in the direction to the named city (Figure 3). Specifically, they were told to "Indicate the direction you would head out to fly from Santa Barbara [Columbia] to the city asked about, following the shortest straight-line path between them, along the surface of the Earth (as jets typically fly)." These instructions were designed to elicit spherical geodesics if participants knew them. As with the other tasks, we attempted to reduce order effects in the direction estimates by presenting

Direction from **Santa Barbara** (in the center) to **Sydney, Australia**:

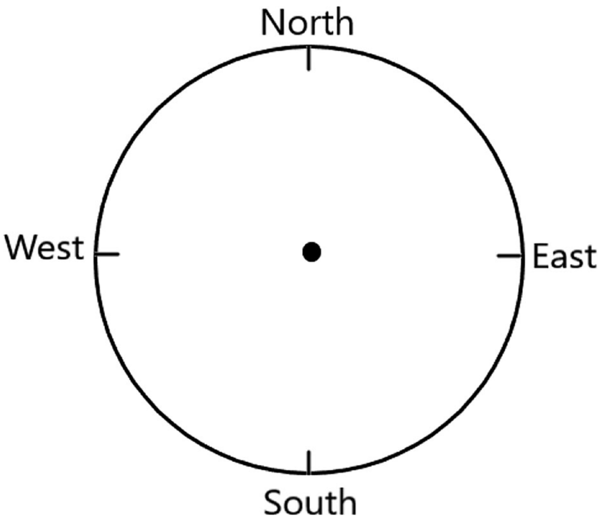


Figure 3. Example pointing circle used for direction estimates task, as administered to University of California, Santa Barbara students. For University of South Carolina students, "Santa Barbara" was replaced by "Columbia."

the eleven cities in one of ten different randomized orders. Each of the ten orders was again administered to eight different participants at each site.

Map Use Survey. Participants filled out a map use survey we created for this research. The survey asks people to report how often they use maps, what kinds of maps they use, and for what tasks, particularly distinguishing between tasks involving "global" or "local" areas. The short survey consists of nine questions; it is presented in the Appendix.

Procedure

Participants read and signed an informed consent to begin the experiment. All participants then carried out all four tasks: region knowledge, area estimates, direction estimates, and map use survey. Area estimates were always collected right after region knowledge ratings. Half of the participants performed these two tasks first, followed by direction estimates; the other half performed the direction estimates task first, followed by the region knowledge/area estimates tasks. All participants filled out the map use survey as their final task. Each of these task orders was counterbalanced with the use of either Greenland or the conterminous United States as the standard for the area estimates. The materials for each task were printed on 8.5 × 11-inch paper and stapled in the proper order for each condition. At UCSB, participants were tested individually or in small groups of up to four individuals in a lab testing room. At USC, participants were tested as a single large group in a classroom. At both sites, a participant took about thirty to forty minutes to complete the entire procedure.

Results

Estimated Region Areas and Knowledge Ratings

To compare region knowledge and area estimates as performed by research participants at the two research sites, we used the multivariate approach to repeated measures for all twenty-seven regions, including Greenland and the conterminous United States (region was a within-case factor) across both sites (site was a between-case factor), using a rejection probability of 0.05. Knowledge ratings of the regions significantly differ from each other, $F(26, 127) = 39.40$, $p < 0.0001$, as expected. Knowledge ratings do not differ as a main effect of site, however, $F(1, 152) = 2.47$, *ns*, or of the interaction of site and region, $F(26, 127) = 1.37$, *ns*, so we collapse across the two sites in Table 2.

We then compare area estimates from the two sites for the twenty-five regions other than the standards of Greenland and the conterminous United States (which only half of the participants at each site estimated). Of course, area ratings differ substantially across the twenty-five regions, $F(24, 127) = 8.24$, $p < 0.0001$. Area estimates do not differ across the two sites, though, $F(1, 150) = 1.15$, *ns*, nor do they vary as a function of the interaction of region and site, $F(24, 127) = 1.37$, *ns*. We thus carried out all further analyses of area by combining across UCSB and USC, with a total of 159 participants.

When we analyzed the combined area estimates, we find that they differ by the standard region used to estimate them (both converted to kilometer units). Estimated areas based on a standard of the conterminous United States average over 600,000 km^2 (13.7 percent) larger than those based on Greenland; this substantial difference is significant, $F(1, 150) = 16.73$, $p < 0.0001$. This is not a novel finding, nor is it likely particularly substantive theoretically—it has long been known that the absolute magnitudes of entities in an estimation set relative to the magnitude of a standard will influence the magnitudes of estimates (Poulton 1968; Baird 1970). Other things being equal, we expect that a larger standard will lead to larger estimates overall; in our case, the conterminous United States is about 3.7 times larger than Greenland. We also find a significant interaction of region by standard, $F(24, 127) = 1.85$, $p < 0.05$. Just six of the twenty-five regions were estimated to be larger with Greenland as standard, averaging only about 250,000 km^2 larger. In contrast, the nineteen regions estimated to be larger with the U.S. standard are over 1 million km^2 larger. The six estimated as larger with Greenland range from small regions to large and from lower latitude regions to upper latitude; we see no pattern to explain these variations.

We next calculated the power equation to summarize the psychophysical function between estimated and correct area, standard practice in psychophysics. We calculated these for each individual participant, averaging to obtain the mean slope and scaling constant across participants. As we reviewed earlier, we expected the power functions

Table 2. Knowledge ratings, correct areas, mean estimated areas, and relative estimated areas for the twenty-five test regions and two standard regions

Region	Knowledge[a]	Correct area (km^2)	Estimated area[b]	Relative estimated area[c]	Mercator inflation factor[d]
Denmark	2.4	41,104	2,228,020	54.2	3.2
Switzerland	3.0	41,854	2,020,721	48.3	2.1
Austria	2.6	82,869	2,054,588	24.8	2.2
Guatemala	2.2	109,829	1,761,537	16.0	1.1
North Korea	3.6	122,847	2,347,629	19.1	1.7
Greece	3.8	125,515	2,048,200	16.3	1.7
New Zealand	3.2	267,214	2,440,194	9.1	1.8
Italy	5.0	301,101	2,696,853	9.0	1.9
Norway	2.3	305,866	2,685,449	8.8	5.5
Vietnam	3.3	322,743	2,065,198	6.4	1.1
Japan	4.5	370,727	3,195,751	8.6	1.6
Sweden	2.5	442,246	2,576,380	5.8	4.9
Spain	4.8	503,250	2,809,853	5.6	1.7
Venezuela	2.4	913,485	2,178,433	2.4	1.0
Ethiopia	1.9	1,134,156	1,740,005	1.5	1.0
South Africa	3.7	1,219,930	4,162,268	3.4	1.3
Peru	2.6	1,296,605	1,943,424	1.5	1.0
Alaska	5.0	1,499,145	3,097,667	2.1	5.4
Mexico	6.1	1,953,851	5,049,014	2.6	1.2
Greenland	2.2	2,118,140	4,556,644	2.2	16.4
India	4.1	3,153,010	7,431,223	2.4	1.2
Australia	5.0	7,694,273	8,402,605	1.1	1.2
Conterminous United States	6.5	7,809,158	6,025,348	0.8	1.7
Brazil	3.9	8,493,132	6,345,742	0.7	1.1
China	5.1	9,366,190	12,416,637	1.3	1.6
Antarctica	3.6	12,277,658	15,006,597	1.2	56.7
Russia	4.0	16,897,294	22,068,159	1.3	4.9

Note: Regions ordered by correct area, from smallest to largest.

[a] 0 is *no knowledge*, 10 is *extensive knowledge*.

[b] Translated to square kilometers by setting correct area of standard, Greenland or conterminous United States, to 1,000.

[c] Estimated area divided by correct area.

[d] Mercator area of region relative to its actual area, taking area at equator as baseline of 1.0.

with either standard region to have positive slopes less than 1.0, reflecting positive but decelerating relationships; participants estimated larger regions to be larger but decreasingly so as the correct region area gets larger (a nonlinear increase in estimates as region area increases). That is, we expected larger regions to be relatively underestimated compared to smaller regions and smaller regions to be relatively overestimated compared to larger regions. In fact, we found just this pattern, with considerable compression of area estimation as regions get larger:

$$\text{EstArea} = 30.9(\text{ActArea})^{0.386}. \qquad (1)$$

Although the slope of the power function was a little larger with the larger standard (as one would expect), it is very similar for both standards and did not differ significantly, $t(157) = 1.33$, *ns*.

Relation of Area Estimates to Mercator Areas. Our central question concerning area estimates concerns whether they reveal a Mercator effect, wherein the estimated areas of regions near the poles are exaggerated compared to regions closer to the equator. A straightforward way to address this is simply to correlate each participant's estimated areas for each region with his or her correct areas and then with his or her areas as depicted on a Mercator projection. We did this for each participant across the twenty-five regions not including the two standard regions; we then averaged these correlations across participants. The correlation of estimates with correct areas is a rather strong 0.76, whereas the correlation with Mercator areas is a much weaker 0.42. This is statistically significant by a test for the difference of dependent correlations

(Steiger 1980), $z(157) = 6.47$, $p < 0.0001$. The fact that the actual areas of the regions in our set correlate 0.53 with their Mercator areas means that larger regions on Earth tend fairly strongly to be larger regions on Mercator projections. Given how accurately our participants estimated region areas, the correlation of their estimates with Mercator areas is almost entirely due to the coincidental fact (at least psychologically) that larger Mercator regions tend strongly to be larger regions on Earth. There is very little variance in our area estimates requiring explanation by a hypothetical Mercator effect. Furthermore, whether based on Greenland or on the conterminous United States, the two correlations are virtually identical, within 0.01 of each other.

Another way we looked for a Mercator effect in our data was by taking the individual region as the unit of analysis rather than the individual participant. To do so, we calculated an index that expresses the degree of relative over- or underestimation of areas for each region:

$$\text{Relative EstArea} = (\text{EstArea}/\text{ActArea}). \quad (2)$$

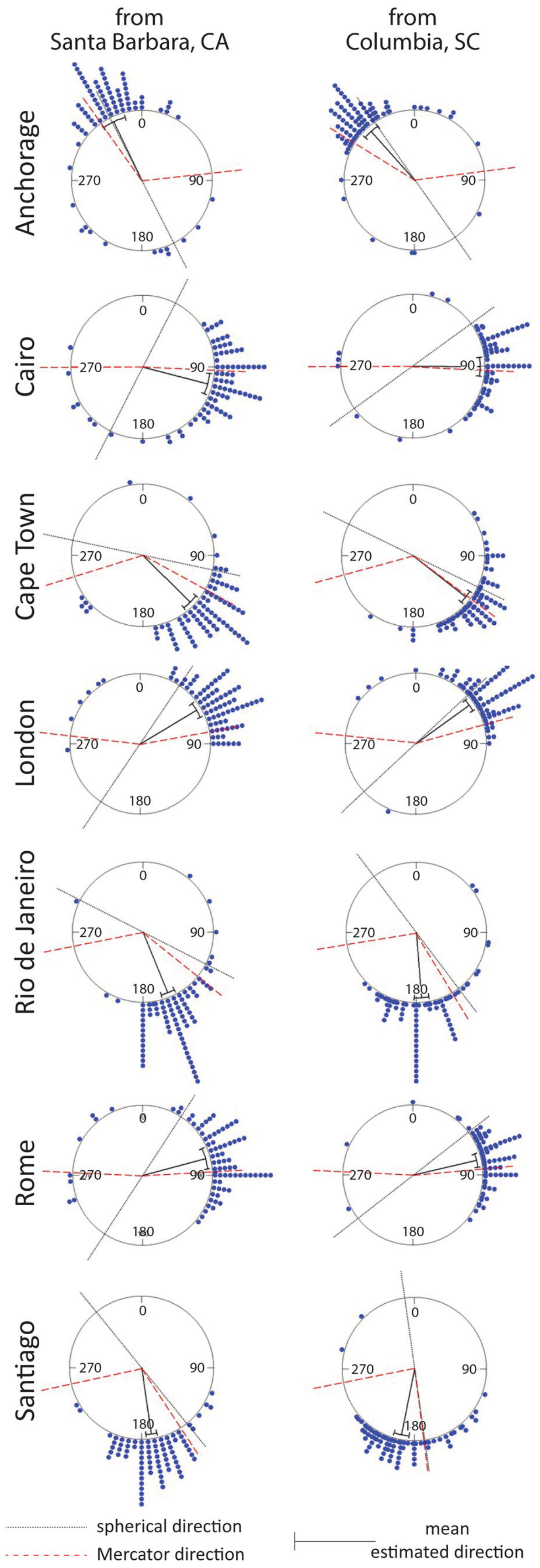
These are shown in Table 2. Table 2 also presents an index we call the Mercator inflation factor (MIF), indicating the area of a region on a Mercator projection relative to its actual area on the Earth's surface. The MIF takes the area of Earth's surface at the equator as a baseline of 1.0; because no region on the planet spans an area solely along the equator, all regions have some Mercator expansion—an MIF >1.0—if only slightly. If a Mercator effect accounts for a sizable portion of variance in area estimates, the index of relative estimated area should correlate substantially and positively with the MIF. That is not what we found, however: The correlation is actually small and negative at –0.13. If, instead, our data reflected much more a psychophysical tendency for small areas to be recalled as relatively larger and large areas as smaller, we would expect relative estimated area to correlate negatively with correct area. Although the power function is nonlinear, it is monotonic and we found a linear correlation of −0.39. Like the correlations of area estimates with Mercator areas based on participants, the correlations of relative estimated area with MIF based on regions revealed virtually no Mercator effect in our area estimates.

Relation of Area Estimates to Knowledge Ratings. Before turning to our direction estimates to look for evidence of a Mercator Effect, we consider how the pattern of estimated areas might depend on how much our participants claimed to know the various regions. Of course, one expects that estimates will be more accurate with better known regions, a region's size certainly being one thing a person is likely to know about a region if anything is known. We find only weak evidence for this, however. Because the great majority of estimates are overestimates, more accurate relative estimation (i.e., relative estimated area in Table 2) is a lower number, closer to 1.0. So we expected that relative estimated area would be smaller for regions known better. When we correlated within participants how well they report they know a region with how relatively accurately they estimated its area, we found a negative correlation, but only −0.15.

We can take another approach to address how knowledge relates to estimation accuracy by organizing area estimates according to two groups of participants: participants who claimed knowledge of a given region above the sample's median knowledge for that region and those who claimed knowledge below the median. We then looked at the correlations of estimated areas for each region with their correct areas and with their MIF, but we did this separately for those with above- and below-median knowledge of that region. The correlation of estimated with correct areas was very high and virtually identical for both groups of participants: 0.96 for those who claimed above-median knowledge (n ranges from fifty-nine to seventy-eight participants) and 0.95 for those who claimed below-median knowledge (n ranges from forty-three to seventy-six participants). We found that the estimates of below-median participants correlated a bit better with the MIF (0.49) than those of above-median participants (0.41), but both are much weaker than the correlations with correct areas.

Estimated Directions

We next analyzed estimated directions, using the Oriana software for circular statistics (Kovach 2011). Unlike the other tasks performed by participants, we clearly expected direction estimates to differ from the two study sites of UCSB and USC, given that the correct directions to world cities are not the same from the two sites (although they are mostly quite close). Therefore, we analyzed the estimates



from each site separately; given other things being equal, errors in estimating directions vary as a function of the correct direction (e.g., Montello et al. 1999).

The circular distributions for estimated directions from Santa Barbara and Columbia to each target city are graphed in Figures 4 and 5. As we discussed earlier, there are two correct directions from any base city to any target city. In Figures 4 and 5, we show both correct directions for each type of representation (spherical and Mercator) for each target city, separately for the two sites of Santa Barbara (SB) and Columbia (C). The spherical correct answers are shown with a dotted black line bisecting each directional circle, with the easterly answer to the right and the westerly answer to the left. The Mercator correct answers are shown in the figures with two dashed red lines emanating as radii from the center, one easterly and one westerly. Mean directional estimates are shown with solid black radius lines capped by 95 percent confidence interval bars.

These circular graphs reveal striking patterns of direction estimates. For all target cities at both testing sites, significant values for Rao's Spacing Test (Batschelet 1981) indicate nonuniform distributions: Participant estimates were more clustered than likely by chance alone. Furthermore, it is clear that most of the distributions are unimodal, with a single preferred answer direction. Graphed in Figure 4, these seven cities include Anchorage, Cairo, Cape Town, London, Rio, Rome, and Santiago. The single mean vectors on these graphs have mean lengths larger than 0.70 at both testing sites (0.0 indicates a uniform distribution around the circle; 1.0 indicates complete agreement on a single direction).

In contrast, at both testing sites, answers to four of the target cities (Bangkok, Moscow, Sydney, Tokyo) appear bimodally distributed (Figure 5). When calculated on the distribution as a whole, the mean vector length for each of these four targets is

Figure 4. Circular frequency distributions of estimated directions for the seven target cities that display unimodal distributions, separately for Santa Barbara and Columbia. The solid black lines are mean estimated directions, with 95 percent confidence intervals shown. The dotted black line bisecting each circle shows the easterly and westerly correct spherical answers (i.e., the geodesic on Earth's surface). The dashed red radius lines show the easterly and westerly correct Mercator answers. Due north is 0°, east is 90°, south is 180°, and west is 270°.

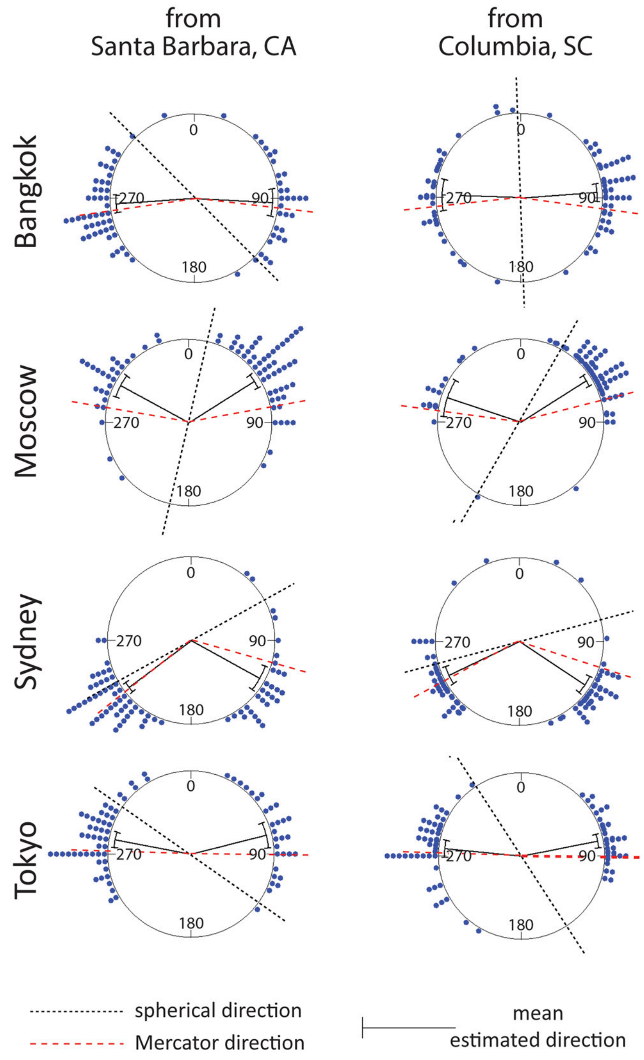


Figure 5. Circular frequency distributions of Estimated Directions for the four target cities that display bimodal distributions, separately for Santa Barbara (SB) and Columbia (C). The solid black lines are mean estimated directions, with 95 percent confidence intervals shown. The dotted black line bisecting each circle shows the easterly and westerly correct spherical answers (i.e., the geodesic on Earth's surface). The dashed red radius lines show the easterly and westerly correct Mercator answers. Due north is 0°, east is 90°, south is 180°, west is 270°.

smaller than 0.60 from either testing site (for the estimates to Moscow from Columbia, it is 0.67). Thus, we calculated and graphed two mean vectors for each of these targets, one based on estimates to the east (0°–180°) and the other on estimates to the west (180°–360°; two answers of exactly 0° and one of 180° are omitted from these calculations).

Whether unimodal or bimodal, it is clear that the average participant, from whichever site he or she estimated directions, was unable successfully to estimate spherical directions, despite being carefully instructed to do so. We see this by comparing the mean vectors for the estimates to the closer of the two correct directions, one Mercator and one spherical. Of the fourteen unimodal distributions (two from each of the seven sites in Figure 4), eleven reveal mean estimates that are nearer to the Mercator direction than to the spherical direction. The mean vectors for all targets (from both sites) average 28.3° from the spherical direction but only 15.8° from the Mercator direction. Of the sixteen bimodal distributions (four from each of the four sites in Figure 5, one for east and one for west), all sixteen reveal mean estimates that are nearer to the Mercator directions than to the spherical directions. Averaging over all bimodal targets from both sites, mean vectors are a full 52.6° from the spherical directions but only 11.0° from the Mercator directions.[3]

Of course, it is difficult to discriminate whether mean estimates are closer to the correct spherical or Mercator directions when the two correct directions are very near each other. When we restrict our analyses to targets for which the two correct directions diverge considerably, the results are especially clear and distinctive. Across all targets from both sites, the difference between the correct spherical and Mercator directions ranges from 1.2° to 95°, and the mean is 38.8°. When we look only at the fourteen trials where the difference between spherical and Mercator directions exceeds this 38.8°, we find that all mean vectors for the estimates are closer to Mercator directions than to spherical directions. In the Mercator case, the error averages only 12.2°; in the spherical case, the error averages a very substantial 60.0°.

It is also striking how similar the patterns of direction estimates are at the two sites of UCSB and USC. This might suggest not only a similarity between the two groups of students but, more notable, between the cognition of global-scale directions from two different testing sites more than 2,000 miles apart (both are at about 34° north latitude). To formally compare the magnitudes of errors in pointing from the two sites, we calculated absolute (unsigned) errors of estimated directions from correct Mercator directions; errors for bimodal distributions are based on a combination of the east and west correct values, as appropriate. Applying the multivariate approach to mixed analysis of variance designs, the target city is a within-case factor (eleven targets), and the testing site is between-case (two sites). Not surprising, absolute errors significantly vary across the eleven target cities, $F(10, 144) = 11.00$, $p < 0.0001$. Importantly, errors did not differ as a function of the interaction between site and target, $F(10, 144) = 1.47$, *ns*. This means that we found no evidence that patterns of absolute errors across the target cities differed when estimating directions from Santa Barbara versus from Columbia. Overall error was 3.5° greater from Santa Barbara (27.5°) than from Columbia (24.0°), $F(1, 153) = 3.79$, $p < 0.05$, as a main effect; error was lower at twelve of the fifteen trials from Columbia.

Map Use Survey

Finally, we compare the relation of responses to the map use survey to area and direction estimates.[4] Although possible answers to five of the questions are not strictly interpretable as metric scales (i.e., they are not interval or ratio), all answers can be interpreted as following quantitatively ordered scales. Thus, for significance testing (not precise quantitative interpretation), it is valid to translate the answers into numerical values ranging from 1 to 5 or 1 to 7. In fact, although responses to different questions vary significantly from each other, they do not differ across the two sites, $F(1, 151) = 2.27$, *ns*, nor does the pattern of differences across questions vary as a function of research site—there is no interaction of question and site, $F(12, 140) = 0.95$, *ns*.

As an exploratory approach to addressing whether there are relations between survey responses and patterns of area and direction estimates, we examined the correlations of map use survey responses with five spatial estimation measures: the relative over- or underestimation of region areas, the correlation of estimated areas with actual areas, the correlation of estimated areas with Mercator areas, the absolute errors of direction estimates from spherical values, and the absolute errors of direction estimates from Mercator values. Only two of these correlations even exceeded 0.20. Participants who reported they looked at maps of places on Earth more often had a modest tendency to estimate directions to cities with less error, both spherical ($r = -0.22$, $p < 0.01$) and Mercator ($r = -0.27$, $p < 0.001$), than those reporting less map viewing. In particular, however, none of the correlations of the spatial estimation variables with Question 8 about formal training in cartography or Question 9 about knowledge of projections even exceeded 0.10.

Discussion

We again found no evidence for a Mercator effect on people's estimated areas of world regions from across the range of Earth's latitudes, largely replicating the relatively recent findings of Battersby and Montello (2009) and Lapon et al. (2019). Our results are based on systematic psychophysical methods (specifically magnitude estimation) rather than the anecdotal, piecemeal demonstrations that might have provided informal support over the decades for the intuition of a Mercator effect on people's subjective beliefs about region areas. We think this intuition is entirely reasonable, but it is apparently false. At our testing sites in both California and South Carolina, estimates of areas did not look much at all as if participants based their beliefs on past experiences looking at the sizes of regions on a Mercator projection. On that projection, regions more polar than 40° latitude north or south would be greatly exaggerated in size, relative to the regions between 40° north and south, including regions near or at the equator. When we correlated region estimates with different measures of region areas, whether calculated across regions or across participants, we found that the estimates correlate considerably more with the actual region areas on Earth's surface than with areas as depicted on a Mercator projection.

For reasons of some historic–geographic interest, polar regions on our planet tend to be larger than equatorial regions. By itself, this is not relevant to specific patterns of distortions in people's cognitive maps, but it does help us explain patterns of variation in area estimates without need to reference a Mercator effect. Although the Mercator projection has largely disappeared in the United States from widespread usage in educational and media settings, its reintroduction (in Web version) on mapping sites such as Google Maps has apparently not reintroduced a Mercator effect on subjective areas, if it ever did exist. Although it would be valuable to extend data collection efforts like ours and those of Lapon et al. (2019) to participants in other parts of the world than the United States and Western Europe, the clear lack of a Mercator effect on subjective region areas recalled from memory that we found with several hundred participants at different sites leads us to doubt that a Mercator effect on recalled areas is likely to exist anywhere under any conditions of systematic retrieval, except perhaps with very naive respondents who have just viewed a Mercator projection.

In stark contrast to their area estimates, when we asked participants to estimate directions to world cities from their testing site, explicitly requesting that they follow the spherical shortest distance routes, we found clear evidence that participants did base their direction estimates on a Mercator projection or some other flat projection from the rectangular family. We clearly found that people’s estimated directions do not follow geodesic directions on the spherical Earth. Especially for the target cities whose actual spherical and Mercator directions from the testing sites differ greatly, we found that all mean directions are closer to the Mercator directions than the spherical directions, by about 50° on average. Especially striking evidence for the predominance of a planar pattern of direction estimates comes from our finding that when direction estimates tend to display a bimodal pattern, they are definitely the bimodal directions we see on a Mercator projection, not the ones we see on Earth itself. These results hold at both testing sites.

Our data thus reveal no Mercator effect on subjective areas at all but a conspicuous Mercator effect on subjective directions. Clearly, a single mental representation—a unitary cognitive map—is not used to answer both types of questions. Montello (1992) argued that violations of Euclidean geometry in spatial estimations, such as when internal angles of direction estimates between three points do not sum to 180°, or even violations of metric geometry more broadly, such as violations of symmetry in distance estimates, are evidence that cognitive maps are not unitary, coordinated spatial representations. They do not support an explanation of unitary, coordinated representations that are non-Euclidean or nonmetric, as some have claimed (for demonstrations and theoretical claims about these distortions, see Cadwallader 1979; Sadalla, Burroughs, and Staplin 1980; Baird, Wagner, and Noma 1982; Golledge and Hubert 1982; Moar and Bower 1983).

Likewise, the notion of a “cognitive graph” (Chrastil and Warren 2014) appropriately highlights that environmental spatial representations encode topological connections (albeit, metrically weighted) and not fully elaborated metric representations, but it still underemphasizes the disjoint, partially uncoordinated, and nonintegrated nature of spatial representations at large scales. In this respect, we see that cognitive maps (or graphs) are more like “cognitive atlases,” with various spatial representations not necessarily integrated and at a common, coordinated scale (Stea and Downs 1970; Kuipers 1982; Carbon and Hesslinger 2013).

Furthermore, although our data do not demonstrate this as definitively, we doubt even that different estimates of a single type (i.e., different area estimates or different direction estimates) are based on unified, coordinated representations. Our results are most consistent with a conception of cognitive maps that recognizes that they are not even stored in a single mode or format. This is beyond even a cognitive atlas—it is more like a “cognitive collage” of representations encoded spatially, pictorially, verbally, numerically, and so on (Tversky 1993).

Friedman and Brown (2000), in explaining the pattern of latitude estimates they found for world cities, claimed that people employ *plausible reasoning processes* that combine analogue perception-based representations (images or spatial mental models) with other formats, including verbal, whenever a task allows or stimulates the use of multiple sources of knowledge. The “fundamental assumption of this framework is that people use whatever information is at hand to aid their judgment and decision-making processes and that what is ‘at hand’ may change with a variety of factors” (Friedman and Brown 2000, 217). Brown and Siegler (1993) similarly accounted for patterns of people’s estimates of country’s populations and areas (although with no investigation into a Mercator effect; see also Collins and Michalski 1989).

Our study was not designed to determine the information or experience on which our participants did base their estimates of region areas if it was not viewing world Mercator maps. Our participants could have seen written lists of region areas, but we find that implausible. Nor do we know of any other information such as population size or media prominence that would account for the accuracy of area estimates our participants displayed (the correlation of estimated to actual areas was 0.76). Our participants based their area estimates on either exposure to globes, exposure to equal-area flat projections such as the sinusoidal, or exposure to non-equal-area projections, the area exaggerations of which they were able to decode.

In this respect, Carbon (2010) had participants report on their personal experiences with the Earth as a sphere. They estimated distances between cities on different continents, which were subjected to a multidimensional scaling (MDS) algorithm that solved for locations on the surface of a sphere. Further, Carbon carried out simulations of these distance estimates for solutions on spheres with different radii. He found that the distances estimated by participants who reported having had personal experience of a spherical Earth (e.g., by witnessing the curve of the horizon) were optimally modeled by MDS solutions of the surface of a sphere with a radius only 8 percent away from that of the actual planet. Distances estimated by participants who reported no personal experience with a spherical Earth were optimally modeled by a flat (nonspherical) MDS solution. This is intriguing, but it is also plausible that participants who reported personally experiencing a spherical Earth were different in other ways that could explain these results. Carbon did ask his participants to self-report their level of geographical knowledge, which did not discriminate those who had personally experienced the Earth as spherical from those who had not.

The claim that the Mercator projection influences the projection of the cognitive map assumes that areas are distorted while viewing a Mercator map, which a person naively accepts as true and then stores as inaccurate in memory. As we cited earlier, we know of two studies (one by one of us) in which people were tested on their impressions of areas while actually looking at a Mercator map (Battersby 2009; Lumley and Sieber 2019). It is intriguing that both of these papers present evidence that people do show a perceptual Mercator effect on estimated areas. The Battersby paper, in particular, very clearly and explicitly told participants that "some spatial properties (such as area) may be distorted due to projection from the Earth … onto a map that is flat. You are being asked to estimate actual areas on the surface of the earth, not their projected size on the map" (she did not, however, mention the name "Mercator" or any of its specific properties). Nonetheless, she found that participants viewing a Mercator map made estimates that greatly exaggerated a couple of the landmass areas that are greatly exaggerated on a Mercator. Although our interest in this study is solely on a Mercator effect on existing beliefs in memory, we believe that a carefully designed study that combines judgments made from memory with judgments made during perception, with perceptual instructions to estimate either "actual" or "apparent" areas, could further illuminate this issue. At this point, it appears that there is a Mercator effect on areas in perception, but either people transform these perceptions to remove them from memory or, more likely, they do not rely on memories of looking at Mercator maps to make their judgments of areas from memory in the first place. Clearly, issues concerning how people learn about global spatial properties and how this influences their spatial beliefs are worthwhile questions for future research.

Our participants reported using Web mapping mostly for local-scale spatial problems, but this tendency was not related to whether they estimated areas or directions to follow a Mercator pattern. Although our participant samples might have been a little more cartographically sophisticated than the average lay person, they definitely included many relatively cartographically naive participants and no cartographic experts. The participants in Anderson and Leinhardt's (2002) study did include cartographic experts, however, and they did find stronger correlations of expertise with the ability to produce spherical geodesics. A broader, more variable sample of respondents to our survey might be interesting in this respect.

Instead of a Mercator effect on estimated areas, we once again found that a power function describes our results well, wherein small regions are relatively overestimated in comparison to large regions, which are relatively underestimated (e.g., Kerst and Howard 1978). Collapsing across our two testing sites, we found a considerable compression in area estimates for our set of regions—estimated region areas equal actual region areas raised to the power of 0.39 (and multiplied by a constant of 30.9). We also found very weak but significant tendencies for regions reported as better known to be more accurately estimated and for regions reported as less known to be estimated more closely to Mercator values, but neither tendency shows regions to be estimated more closely to Mercator areas than to actual areas. Such a Mercator effect simply is not present in area estimates based on memory, though it is starkly evident in areas as visually perceived on that projection. It would be valuable to further explore the relationship between perceived and conceived areas by having people estimate "actual" and "apparent" areas of regions while looking at a Mercator projection.

These results beg the question of why the informal Greenland demo we cited earlier in this article has seemed so robustly over the decades to indicate a Mercator effect in memory for global region areas. We hypothesize that the power function might explain this. Earlier, we noted informally observing students underestimating South America's relative size with respect to Greenland by a factor of something like two to four. Table 2, however, shows an MIF for Greenland of 16.4. South America is not listed there, but a few countries in this mostly tropical continent are listed there, along with their very slight MIFs. In fact, South America overall has an MIF of less than 2.0. The empirically observed relative exaggeration of Greenland's estimated area, even in informal demonstrations, is not nearly as large as its actual relative exaggeration on a Mercator projection. Instead of a Mercator effect, the power function whereby large regions (like South America) are relatively underestimated compared to smaller regions (like Greenland) could account for the results of countless informal demonstrations.

In contrast, estimated directions apparently do reveal the influence of past exposure to Mercator or similar rectangular projections. As we discussed in the introduction, there are generally two correct directions straight from a city to any other city on Earth, whether that straight-line direction is spherical or Euclidean. Our participants, however, clearly showed a preference to indicate directions to seven of the eleven target cities much more in one of the two correct alternative directions than the other. That is, their direction estimates to seven cities were largely unimodally distributed. For the other four cities, however, a substantial portion of the participants appeared to choose one of the two alternatives, whereas the other portion chose the converse—the direction estimates of this portion were largely bimodally distributed.

The factor that appears to explain these patterns is the relative distance to a target city in the two directions from Columbia or from Santa Barbara. Distributions for a given target city were unimodal when the target city was much closer in one direction than the other; that is, when the distance in the two directions was very unequal. From Columbia, the seven cities that revealed a unimodal distribution were the seven most unequally far away in the two alternative correct directions, and for all seven of these cities the preferred alternative was in the closer direction. The longer direction to these seven cities was 8.2 times further than the shorter direction. In contrast, the four cities that revealed a bimodal distribution were the four most equally far away in the two alternative correct directions, the longer direction to these four cities being only 1.6 times further than the shorter.

The role of relative distance to a target city in determining whether directions estimated from memory are uni- or bimodal provides further evidence that our participants employed a flat, Mercator-like mental representation to determine directions to world cities. The centering of the projection is critically important in this regard. Figure 6 shows directions to the four bimodal target cities from Columbia on a Mercator projection centered in four ways that are common alternatives for North American users like our participants. As the centering of the map varies, choosing the direction that follows the path staying within the frame of the image causes the preferred direction to switch between easterly and westerly. Paths to target cities that are nearly equally distant in both the easterly and westerly directions will cross the periphery of the projection, depending on the centering of the projection. Paths to target cities that are much further away in one of the two directions, either easterly or westerly, do not cross the periphery of the projection for any of the plausible centerings. This would not happen if direction estimates were based on a spherical, globe-like mental representation (or a nonimagistic verbal representation). It is notable that these observations reflect the distorting influence of the discontinuity in projections we mentioned earlier that is often unrecognized explicitly as a distorting influence.

The fact that relative distance operates a little differently in the pattern of direction estimates from Santa Barbara actually further supports this interpretation. From Santa Barbara, two of the seven cities that revealed a unimodal distribution were not among the seven most unequally far away in the two alternative correct directions, although for all seven the preferred estimated direction was, again, the closer alternative. The longer direction to these seven cities was 4.0 times further than the shorter direction. The two unimodal cities that were among the most equally far away from Santa Barbara (but not Columbia) were Cairo and Cape Town. These two cities are both in Africa; Figure 6 shows that these two cities are to the east of Santa Barbara in all centerings but the Pacific-centered Mercator, not very common in the United States. At the same time, two of the four cities that revealed a bimodal distribution from Santa Barbara were not among the four most equally far away in the two alternative correct directions. These two bimodal cities were Tokyo and Sydney. Both are closer to Santa Barbara across the Pacific Ocean, and this body of water is highly salient for Santa Barbara students (it is outside their window). Nonetheless, in two of the four centerings in Figure 6, Tokyo and Sydney are reached without leaving the periphery of the image by going east across the Atlantic rather than west.

With the prevalence of digital maps, the Web Mercator (and all other projections) can be panned to wherever people want to center it. Just as cartographers from particular parts of the world have always preferred certain centerings over other centerings, however, we assume that nonspecialists in various parts of the world will still prefer to center global maps more in some ways than others (not to mention preferring north-up alignments). These preferences likely include centering, or at least avoiding splitting, one's home region. This would vary across the globe. Other than residents of Oceania in the Pacific and perhaps oceanographers, however, we assume that Earth's people would generally prefer to split the world somewhere in the Pacific Ocean. People's preferred centerings when using global Web mapping would be interesting research to pursue.

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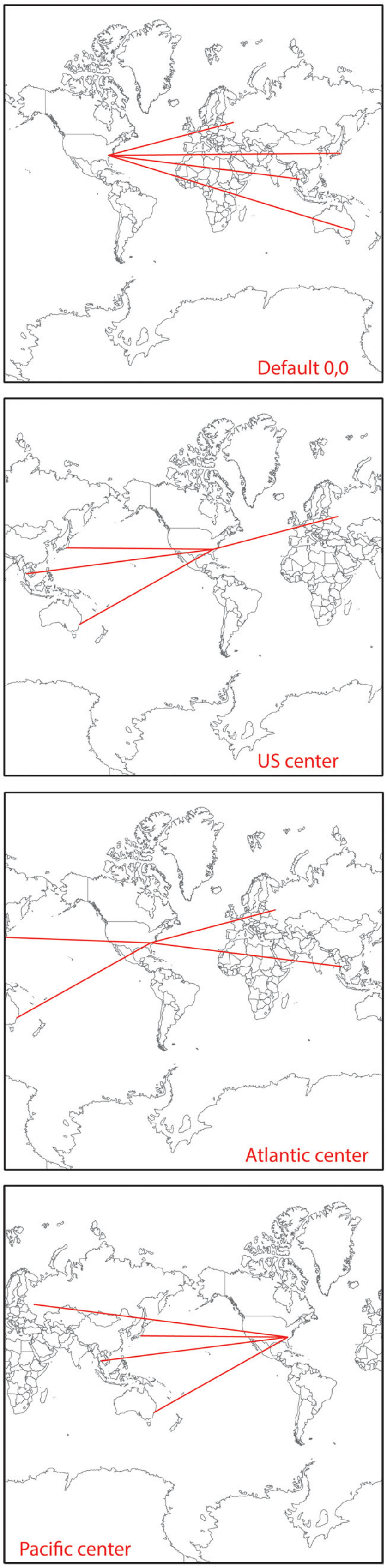

Figure 6. Directions to the four bimodal target cities from Columbia on a Mercator projection centered in four ways that are common for North American users like our participants. As the centering of the map varies, choosing the direction that follows the path staying within the frame of the image causes the preferred direction to switch between easterly and westerly.

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Notes

1. In August of 2018, Google switched to an orthographic (globe-like) projection. In late 2019, Google apparently made another change, returning to the Web Mercator as their default projection (and limiting the extent of zooming out to just less than the entire Earth). The Google interface, however, provides a button just above the location and zoom buttons to switch to the globe-like projection if preferred.
2. The exception is pointing from any base city to its antipode, in which case the correct answer is any of the infinite number of great circles on Earth that go through the base city!
3. Even though restricting bimodal distributions to one semicircle of responses in our analysis necessarily reduces overall mean error, compared to using the entire circle of responses in unimodal distributions, we still find that errors from spherical directions on the bimodal distributions are quite large.
4. Because of space limits, we do not present the general results for the survey here, but they are available from the first author.

References

Anderson, K. C., and G. Leinhardt. 2002. Maps as representations: Expert novice comparison of projection understanding. *Cognition and Instruction* 20 (3):283–321. doi: 10.1207/S1532690XCI2003_1.

Baird, J. C. 1970. *Psychophysical analysis of visual space*. New York: Pergamon.

Baird, J. C., M. Wagner, and E. Noma. 1982. Impossible cognitive spaces. *Geographical Analysis* 14 (3):204–16. doi: 10.1111/j.1538-4632.1982.tb00069.x.

Batschelet, E. 1981. *Circular statistics in biology*. London: Academic.

Battersby, S. E. 2006. Distortion of area in the global-scale cognitive map: A geographic perspective. PhD diss., University of California, Santa Barbara.

Battersby, S. E. 2009. The effect of global-scale map-projection knowledge on perceived land area. *Cartographica: The International Journal for Geographic Information and Geovisualization* 44 (1):33–44. doi: 10.3138/carto.44.1.33.

Battersby, S. E., M. P. Finn, E. L. Usery, and K. H. Yamamoto. 2014. Implications of Web Mercator and its use in online mapping. *Cartographica: The International Journal for Geographic Information and Geovisualization* 49 (2):85–101. doi: 10.3138/carto.49.2.2313.

Battersby, S. E., and F. C. Kessler. 2012. Cues for interpreting distortion in map projections. *Journal of Geography* 111 (3):93–101. doi: 10.1080/00221341.2011.609895.

Battersby, S. E., and D. R. Montello. 2009. Area estimation of world regions and the projection of the global-scale cognitive map. *Annals of the Association of American Geographers* 99 (2):273–91. doi: 10.1080/00045600802683734.

Beatty, W. W., and A. I. Tröster. 1987. Gender differences in geographical knowledge. *Sex Roles* 16 (11–12):565–90. doi: 10.1007/BF00300374.

Brown, N. R., and R. S. Siegler. 1993. Metrics and mappings: A framework for understanding real-world quantitative estimation. *Psychological Review* 100 (3):511–34. doi: 10.1037/0033-295X.100.3.511.

Cadwallader, M. T. 1979. Problems in cognitive distance: Implications for cognitive mapping. *Environment and Behavior* 11 (4):559–76. doi: 10.1177/0013916579114007.

Carbon, C.-C. 2010. The Earth is flat when personally significant experiences with the sphericity of the Earth are absent. *Cognition* 116 (1):130–35. doi: 10.1016/j.cognition.2010.03.009.

Carbon, C.-C., and V. M. Hesslinger. 2013. Attitudes and cognitive distances: On the non-unitary and flexible nature of cognitive maps. *Advances in Cognitive Psychology* 9 (3):121–29. doi: 10.2478/v10053-008-0140-y.

Chrastil, E. R., and W. H. Warren. 2014. From cognitive maps to cognitive graphs. *PLoS ONE* 9 (11):e112544. doi: 10.1371/journal.pone.0112544.

Collins, A. M., and R. Michalski. 1989. The logic of plausible reasoning: A core theory. *Cognitive Science* 13 (1):1–49. doi: 10.1016/0364-0213(89)90010-4.

Crampton, J. 1994. Cartography's defining moment: The Peters projection controversy, 1974–1990. *Cartographica: The International Journal for Geographic Information and Geovisualization* 31 (4):16–32. doi: 10.3138/1821-6811-L372-345P.

Friedman, A., and N. R. Brown. 2000. Reasoning about geography. *Journal of Experimental Psychology: General* 129 (2):193–219. doi: 10.1037/0096-3445.129.2.193.

Friedman, A., D. D. Kerkman, N. R. Brown, D. Stea, and H. M. Cappello. 2005. Cross-cultural similarities and differences in North Americans' geographic location judgments. *Psychonomic Bulletin & Review* 12 (6):1054–60. doi: 10.3758/BF03206443.

Gescheider, G. A. 1997. *Psychophysics: The fundamentals*. 3rd ed. Mahwah, NJ: Erlbaum.

Golledge, R. G., and L. J. Hubert. 1982. Some comments on non-Euclidean mental maps. *Environment and Planning A: Economy and Space* 14 (1):107–18. doi: 10.1068/a140107.

Gould, J. L., and K. P. Able. 1981. Human homing: An elusive phenomenon. *Science* 212 (4):1061–63. doi: 10.1126/science.7233200.

Hintzman, D. L., C. S. O'Dell, and D. R. Arndt. 1981. Orientation in cognitive maps. *Cognitive Psychology* 13 (2):149–206. doi: 10.1016/0010-0285(81)90007-4.

Kerst, S. M., and J. H. Howard, Jr. 1978. Memory psychophysics for visual area and length. *Memory & Cognition* 6:327–35. doi: 10.3758/BF03197463.

Kessler, F. C., and S. E. Battersby. 2019. *Working with map projections: A guide to their selection*. Boca Raton, FL: CRC.

Kovach, W. L. 2011. *Oriana–Circular statistics for Windows, version 4*. Pentraeth, UK: Kovach Computing Services.

Kuipers, B. 1982. The "map in the head" metaphor. *Environment and Behavior* 14 (2):202–20. doi: 10.1177/0013916584142005.

Lapon, L., P. De Maeyer, N. Vanhaeren, S. Battersby, and K. Ooms. 2019. Evaluating young people's area estimation of countries and continents. *ISPRS International Journal of Geo-Information* 8 (3):125. doi: 10.3390/ijgi8030125.

Loftus, G. R. 1978. Comprehending compass directions. *Memory & Cognition* 6 (4):416–22. doi: 10.3758/BF03197474.

Lumley, S., and R. Sieber. 2019. Web maps for global data visualization: Does Mercator matter? *Spatial Knowledge and Information Canada* 7 (1):5.

Moar, I., and G. H. Bower. 1983. Inconsistency in spatial knowledge. *Memory & Cognition* 11 (2):107–13. doi: 10.3758/BF03213464.

Monmonier, M. 1995. *Drawing the line: Tales of maps and cartocontroversy*. New York: Holt.

Monmonier, M. 2004. *Rhumb lines and map wars: A social history of the Mercator projection*. Chicago: University of Chicago Press.

Montello, D. R. 1992. The geometry of environmental knowledge. In *Theories and methods of spatio-temporal reasoning in geographic space*, ed. A. U. Frank, I. Campari, and U. Formentini, 136–52. Berlin: Springer. doi: 10.1007/3-540-55966-3_8.

Montello, D. R., A. E. Richardson, M. Hegarty, and M. Provenza. 1999. A comparison of methods for estimating directions in egocentric space. *Perception* 28:981–1000. doi: 10.1068/p280981.

Peters, A. 1983. *Die neue Kartographie/The new cartography (in German and English)*. Klagenfurt, Germany and New York: Carinthia University and Friendship Press.

Poulton, E. C. 1968. The new psychophysics: Six models for magnitude estimation. *Psychological Bulletin* 69 (1):1–19. doi: 10.1037/h0025267.

Ridgley, D. C. 1922. The teaching of directions in space and on maps. *The Journal of Geography* 21 (2):66–72. doi: 10.1080/00221342208984113.

Robinson, A. H. 1990. Rectangular world maps—No! *The Professional Geographer* 42 (1):101–4. doi: 10.1111/j.0033-0124.1990.00101.x.

Robinson, A. H., J. L. Morrison, P. C. Muehrcke, A. J. Kimerling, and S. C. Guptil. 1995. *Elements of cartography*. 6th ed. New York: Wiley.

Ryan, T. A., and M. S. Ryan. 1940. Geographical orientation. *The American Journal of Psychology* 53 (2):204–15. doi: 10.2307/1417416.

Saarinen, T. F., M. Parton, and R. Billberg. 1996. Relative size of continents on world sketch maps. *Cartographica: The International Journal for Geographic Information and Geovisualization* 33 (2):37–47. doi: 10.3138/F981-783N-123M-446R.

Sadalla, E. K., W. J. Burroughs, and L. J. Staplin. 1980. Reference points in spatial cognition. *Journal of Experimental Psychology: Human Learning and Memory* 6 (5):516–28. doi: 10.1037/0278-7393.6.5.516.

Spatial Reference Organization. 2014. *SR-ORG Projection 6864—EPSG:3857*. http://spatialreference.org/ref/sr-org/6864/.

Stea, D., and R. M. Downs. 1970. From the outside looking in at the inside looking out. *Environment and Behavior* 2 (1):3–12. doi: 10.1177/001391657000200101.

Steiger, J. H. 1980. Tests for comparing elements of a correlation matrix. *Psychological Bulletin* 87 (2):245–51. doi: 10.1037/0033-2909.87.2.245.

Tversky, B. 1981. Distortions in memory for maps. *Cognitive Psychology* 13 (3):407–33. doi: 10.1016/0010-0285(81)90016-5.

Tversky, B. 1993. Cognitive maps, cognitive collages, and spatial mental models. In *Spatial information theory: A theoretical basis for GIS*, ed. A. U. Frank and I. Campari, 14–24. Berlin: Springer. doi: 10.1007/3-540-57207-4_2.

Wise, J. H. 1975. Student deficiency in basic world knowledge. *Journal of Geography* 74 (8):477–88. doi: 10.1080/00221347508980548.

Wood, D. 1992. *The power of maps*. New York: Guilford.

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Appendix: Map Use Survey

This survey is part of a research project investigating how often people use maps, what kinds of maps they use, and for what tasks. The survey asks about your use of traditional (paper/printed) maps and online digital maps. It also compares your use of maps of *global geographic areas* (like continents, regions, or the whole earth) or *local geographic areas* (like states, cities, or neighborhoods). This short survey should take no more than 5 minutes. Your responses are anonymous and completely confidential.

Your sex: F M Other/Decline
Your age: _________
Today's Date: ______________

1. How often do you look at maps of places on Earth?
   a. once or more per day
   b. almost daily
   c. once a week
   d. once or twice a month
   e. once every 2 months
   f. more than once a year, but less than every 2 months
   g. once a year or less
2. Of all the times you look at maps, what percentage do you look at maps of *global areas* and what percentage do you look at maps of *local areas*? (should sum to 100%)
   global areas (0–100%): __________ local areas (0–100%): ___________
3. Of all the times you look at maps of *global areas*, what percentage do you use online digital maps (e.g., Google, Bing, or Yahoo Maps) and what percentage do you use printed/paper maps? (should sum to 100%)
   online maps (0–100%): __________ paper/printed maps (0–100%): ___________
4. Of all the times you look at maps of *local areas*, what percentage do you use online digital maps (e.g., Google, Bing, or Yahoo Maps) and what percentage do you use printed/paper maps? (should sum to 100%)
   online maps (0–100%): __________ paper/printed maps (0–100%): ___________
5. Of all the times you use online digital maps of *local areas*, what percentage do you use them primarily for getting directions to some place vs. using them for other purposes (such as virtual exploration, learning geographic facts, etc.)? (should sum to 100%)
   getting directions (0–100%): __________ other purposes (0–100%): ___________
6. Online digital maps (e.g., Google, Bing, or Yahoo Maps) are a good resource for looking at information about *global areas*.
   a. strongly agree
   b. agree
   c. neither agree nor disagree
   d. disagree
   e. strongly disagree
7. Online digital maps (e.g., Google, Bing, or Yahoo Maps) are a good resource for looking at information about *local areas*.
   a. strongly agree
   b. agree
   c. neither agree nor disagree
   d. disagree
   e. strongly disagree
8. How much formal training have you had in maps and cartography?
   a. none
   b. one class lecture or light reading/study on maps and cartography
   c. several class lectures or moderate reading/study on maps and cartography
   d. one course or significant reading/study on maps and cartography
   e. extensive study of maps and cartography
9. The topic of map projections concerns how the round Earth surface is flattened into a map image. How much do you know about map projections?
   a. nothing
   b. only a little
   c. a moderate amount
   d. quite a bit
   e. a great deal