Chapter 10

Cognitive Perspectives on Cartography and Other Geographic Information Visualizations

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Abstract

Cartography is geographic cognition mapped. A major function of cartographic maps and other geographic information displays is to support human cognitive functions such as knowledge acquisition, reasoning, and problem-solving with geographic information—information that is explicitly tied to locations on the earth's surface. A host of research issues thus concern the ways that humans process geographic information from map displays. At the same time, the design of such geographic information displays typically involves a series of cognitive acts as well. In this chapter, we describe the basis for understanding cartographic map use and design as cognitive processes. We summarize research on human cognition of geographic information that involves creating, viewing, and reasoning with such displays. We also point to ongoing questions for future research, many stimulated by the technological developments in geographic information visualization.

1. Introduction

Maps matter. For thousands of years they have been made and consumed whenever location information is relevant for human understanding. Maps represent various views of the human and physical environment. They show visible and nonvisible geographical features and environmental processes, including weather patterns, plant distributions, human migrations, and locations for international sporting events. Maps are used to visually communicate world views, denote land ownership for collecting taxes, aid in warfare, uncover demographic relationships buried in population censuses, and help humans orient and navigate in known and unknown territories. For these and many other activities, geographic data from various sources and in diverse formats are collected, stored, processed, analyzed, and finally encoded visually by a cartographer to be presented to map users.

Maps are symbol systems designed to intentionally stand for portions of the earth surface, and the entities and events found there (Bertin 1967/83). Represented geographic phenomena may be relatively stable or quite dynamic. They may be visible or otherwise sensible by a person near the earth's surface, or they may not be: a mountain or a rate of HIV infection. As symbol systems, their purpose is to help people acquire, understand, remember, reason about, and communicate information concerning earth phenomena. All of these are cognitive states and processes; they also have components that are physical, social, economic, aesthetic, and so on. Maps are mental devices, in part, and their design greatly influences how they serve human understanding and behavior in this role.

Cognitive issues in cartography and geographic information visualization encompass the application of cognitive theories and methods to understanding maps and mapping, and the application of cartographic maps and mapping to understanding cognition[1]. The study of cognition is the study of knowledge structures and processes in sentient beings—humans, other animals, and intelligent machines (e.g., Wilson and Keil 1999). Cognition includes perception, learning, memory, thinking, reasoning and problem-solving, and communication (verbal, graphical, etc.). Therefore, the study of map design and map use is part of the cognitive sciences (Montello 2009). In humans, thinking and communicating about space, place, and environment are common cognitive acts, and maps often play a key role in these acts. Maps also influence human thinking and behavior. Cognitive research thus holds the promise of helping us tailor geographic information displays to the abilities and preferences of individuals and subgroups of people, and to assist people in thinking about their environment and their space-time behavior.

Maps play a part in cognition as complex symbol systems that convey spatial, thematic, and temporal information. They may convey this information authoritatively, relatively accurately, precisely, and comprehensively, but to some extent they always simplify, distort, and selectively present it. In fact, maps get much of their power as information tools from the fact that they simplify and distort reality (Kimerling, Buckley, Muehrcke, and Muehrcke 2012; Kraak and Ormeling 2011). But no matter how maps present information, they can misconvey information if map users fail to interpret map symbols or actively misinterpret them (Hegarty 2013; Liben and Downs 1992). Miscommunication can also happen if map makers employ map symbols inappropriately. Very abstract symbols—symbols that do not resemble what they stand for—can be hard to interpret. For instance, many people find contour lines difficult to understand (e.g., Shurtleff and Geiselman 1986). In contrast, iconic symbols—symbols that do resemble what they stand for—can be easy to overinterpret. For instance, information “landscapes” whose terrain surfaces represent nonspatial information such as intelligence reports can be intuitively understood, so much so that viewers may attribute properties of terrain to the information surface that do not apply (Fabrikant, Montello, and Mark 2010a).

Another potential challenge to making sense of maps is their perspective; when a map depicts the earth from the common vertical perspective, it must be transformed to match it with a horizontal or terrain-level perspective for tasks like wayfinding (Goldberg, MacEachren, and Korval 1992). Similarly, perhaps one of the richest challenges for human cognition is the issue of map projections. Projections necessarily introduce topological discontinuities in the earth's surface where there are none, and they distort one or more of the spatial properties of size, shape, distance, and direction (Olson 2006). These distortions are likely to lead to distorted ideas about the spatial layout of the earth's surface (Battersby and Montello 2009). Of course, how detrimental any of these miscommunications are will depend on various aspects of the context of the map use, such as what type of information is needed for a particular task, what are the consequences of the decisions being made with the map, and so on; it will also depend on characteristics of map users, such as their spatial abilities and education.

2. Historical Background

Cartographers have long recognized that maps influence a map reader's mind—maps are cognitive tools—and that the way a map is designed will affect how it influences the map user's mind. The historical roots of cognitive research in cartography were reviewed by Lloyd (2000) and Montello (2002). Some cartographers have probably long recognized that the way a map is designed will affect how it influences minds. Montello (2002) labeled this insight 'intuitive map psychology.' But the insight that maps are cognitive tools became a formal part of cartographic research and training only in the mid and late 20th century (Gilmartin 1992). Cartographers came to understand that map cognition could be approached systematically by applying the theories and methods of psychology and other cognitive sciences. These ideas were featured early on in the writings of the German cartographer, Max Eckert (1921/1925), but became especially prominent in the work of the American cartographer, Arthur Robinson (1952).

Three formal approaches to understanding maps from a cognitive perspective can be identified during the 20th century, continuing into the 21st. The most prominent and broad approach was "cognitive map-design research." This is concerned with how the design of maps influences human cognition, and how their design can be improved to make them easier to use, more effective, and so on. We focus on this approach in the present chapter, citing and discussing specific examples below. The second approach is focused on basic-science questions about map cognition; "map psychology" has as its goal the understanding of human perception and cognition of and with maps (e.g., Lloyd and Steinke 1984; Tversky 1997). Some of the work on map psychology is discussed in Section C of this Handbook. Finally, "map education research" is interested in improving education with maps and about maps (e.g., Liben and Downs 1989a; 1989b). Map education is discussed in Chapter 21 of this Handbook.

Map design and use were widely recognized as a process of communication during the 1960s and 1970s (Board 1981; Taylor 1983). That is, maps became understood as "channels" that transmit information from a source (the world) to a recipient (map reader). The cartographer was said to "encode" information about the world he or she wanted the map reader to "decode," which would depend on the "message" the cartographer wanted to transmit. It was also understood that this transmission could contain "noise." All of this was standard semiotic theory (see below), but during the heyday of this model, the communication process was seen by some as not just formal but as mental or cognitive (Lloyd 1993; Robinson and Petchenik 1976). As time progressed, however, scholars came to recognize that the communication model was grossly misleading in suggesting that maps deliver neat packages of meaning from the mind of the cartographer to the mind of the reader. Maps contain many different messages that a reader might extract from them, including some the cartographer never intended. Further, the information that map readers glean will depend critically on what they already know, what their map reading abilities are, what they are trying to achieve when they use the map, and so on. “Maps don’t communicate knowledge, they stimulate and suggest it” (Montello 2002, p. 292).

Knowledge generation and space-time behavior are literally dependent on the eyes and the spatio-temporal information processes of the beholder, and this is also dependent on the map readers’ geographic information use context (Wilkening and Fabrikant 2011). Hegarty (2013) suggests three possible ways map displays might influence learning geographic information and generating knowledge from it. First, well-designed maps—those saliently depicting task-relevant information—might serve as ‘cognitive prosthetics’ for map users with limited internal spatial visualization capacity. Second, a minimal basic capacity to internally visualize geographic information is necessary for a user to take advantage of map displays of any sort. Third, Hegarty argues that map displays can augment the internal visualization capacity of all users, regardless of their individual cognitive skill base, and thus augment their geographic knowledge acquisition. Nevertheless, research suggests that individual differences can play a decisive role in map-based learning (Liben 2009) and decision making (e.g., Wilkening and Fabrikant 2013). Some cognitive cartographers might even accept today that individual differences among users could be an equally (if not more) critical factor, compared to cartographic design, for geographic knowledge generation and decision making with map displays (Griffin et al. in press); this perhaps much to the chagrin of professional cartographers!

The research tradition of the cognitive study of cartography continues today with the recognition of the study of geographic information and systems as a science, i.e., GIScience (Goodchild 1992). From its inception in the 1980s and, especially, 1990s, GIScience incorporated cognitive aspects of geographic information as one of its core concerns (Mark and Frank 1991;

Montello 2009). One of the clearest examples and major domains of cognitive GIScience has always been seen to be the study of cognitive aspects of cartography, or more broadly, "geographic information visualizations"—variously shortened to "geovisualization" or even "geoviz" (Fabrikant and Lobben 2009).

3. Cartographic Design as a Cognitive Process

Maps are products of design. They only communicate effectively and efficiently when they are well designed—visually attractive, clear, engaging, comprehensible, consistent, complete, logical, properly annotated, focused on relevant information, and so on. The data transformation and visual encoding processes that take place when creating maps involve systematically selecting and arranging visual elements—such as point symbols, colors, text—to convey messages for a particular use context to a particular audience (Figure 1). The result of cartographic design is thus the whole spectrum of visual forms on map displays, ranging from abstract geometric symbols to photorealistic 3D immersive virtual environments.

However, cartographic design and geographic information visualization more broadly is not simply about solving a graphical layout problem. Cartographers are somewhat like engineers: They conceive, innovate, and create graphic solutions to solve particular visualization problems, often under various conflicting communication goals and/or constraints, and always with a given context and particular class of map reader in mind. Regardless of the use context (e.g., private data exploration by domain specialists or communication of known facts to a broad audience), the end goal of the cartographer is to communicate efficiently and effectively through graphic means. One goal may be to uncover patterns of ice cream consumption buried in a complex spatio-temporal database concerning a particular ice cream producer. Another goal may be to communicate plans for an atomic waste site to concerned citizens at a town hall meeting. Yet another may be to locate the boundaries of a new country in a way that satisfies all interested nations. But while the main goal for assigning graphic symbols to data is to facilitate effective and efficient communication, aesthetics and art are also integral parts of the visualization design process.

<Insert Figure 1>

Regardless of the goal of a map and the context of its use, cartographic design is a complex conceptual (generalization), graphic (symbolization), and technical (reproduction) process (Dent 1999). Rarely will cartographers find a single best solution for the communication problem. Typically, after negotiating various conflicting goals and constraints (the format of the visualization, scale and resolution, reproduction and dissemination, economics), one selects an appropriate design solution from a large, multidimensional solution space, understanding that another solution may exist that would work even better.

The cartographic design process involves systematically transforming data perceived or measured in the world, then conceptualized within a spatial-temporal data model into a visual-spatial model, usually in the form of a two-, three-, or four-dimensional graphic display. This process is typically performed by applying scientific (i.e., systematic, transparent, and reproducible) methods as well as aesthetic expressivity and intuition. It is characterized well in leading textbooks of cartographic practice (Dent 1999; Kraak and Ormeling 2011; Slocum 2009). "The art in cartography is the cartographer's ability to synthesize the various ingredients involved in the abstraction process into an organized whole that facilitates the communication of ideas" (Dent 1999, p. 17).

3.1 Semiotics

Human communication generally involves symbol systems. The symbols on a map image are expressed through graphical marks which depict figures and patterns. The ways that variations in these graphical symbols encode variations in represented properties of the earth and its phenomena are referred to as “visual variables.” The cartographic scholar Bertin (1967/1983) is well known for originally laying out a systematic analysis of visual variables. They include such graphical elements as location, size, color value, color hue, texture, orientation, and shape. Symbolization on geographic visualizations must clearly, legibly, and unmistakably communicate essential features and characteristics of mapped phenomena and processes. The symbols refer to tangible and intangible phenomena, processes, and relationships, including abstract concepts. So how do we systematically communicate knowledge through graphic marks? How do we logically and coherently link data to graphics? The systematic study of signs and symbols and how they relate to meaning is the study of semiotics.

<Insert Figure 2>

Modern semiotics was developed independently by the Swiss linguist De Saussure and the American philosopher Peirce (MacEachren 1995). De Saussure distinguished between two components of a sign/symbol: the *signifier*, which in maps is a set of graphical marks on the map image, and the *signified*, which is the concept or idea to which the graphical mark refers. Peirce decomposes signs/symbols into a triad of three relations (Figure 2). He refers to De Saussure’s signifier as the *sign-vehicle*, and his signified as the *interpretant*; Pierce adds the phenomenon or property in the real world, which he calls the *referent*. For example, a patch of blue color on a map might be the sign-vehicle, the concept of an ocean would be the interpretant, and the Pacific Ocean would be the referent.

4. Perception, Cognition, and Emotion in Map Reading and Interpretation

The information encoded in maps, of course, is generally not decoded by machines, but by people (and any machine decoding of maps that does happen is due to programs written by people). Human spatial cognition is a well-researched area, yielding at least half a century of research into our understanding of the spaces around and in front of us (e.g., chapters in Section C). From the users' perspective, a geographic information display involves three entities: the earth surface space that is represented, the visible space of the display, and the mental processing of both by the user. To design better geovisualizations, therefore, researchers have proposed that it helps to know about users' understanding of both the earth space and the display space, and the way users attempt to integrate their understanding of the two.

4.1 Basic Cognitive Processes Relevant to Map Displays

4.1.1 Perception and Attention. Perception, the processing of the immediately experienced world around us, is dominated by vision for most humans. A large area is devoted to it at the rear of the brain. Hence it is hardly surprising that geographic visualizations are a powerful means of understanding spaces too large to fully experience in a single moment or glance. Certain key aspects of human perception and attention help explain why some visualization designs work better than others. Visual attention is obviously influenced by the design of the graphical marks which depict figures and patterns on maps (we discuss these "visual variables" below). But users' prior expectations will often be more powerful in directing where users look, and what they notice and interpret there. Thus, although visual salience has been a widely researched area of attention in recent decades, and lends empirical credence to many basic cartographic design principles, it is now clear that a user viewing a map display with any kind of prior agenda in mind will approach acquiring information from the display differently than will a relatively passive research participant; this will happen even subconsciously and as quickly as the first second or two of viewing (Davies, Fabrikant, and Hegarty 2015; Henderson, Malcolm, and Schandl 2009). This “top-down” influence on the user’s attention and perception reminds us, as cartographers have long claimed, that good design can never proceed without knowing, as far as possible, the users’ likely tasks and expectations (Board 1981; Robinson and Petchenik 1976).

An interesting attentional phenomenon known as “pop out” is relevant to map design. Now well established empirically, pop out describes a strong expression of stimulus saliency relative to its surroundings, where a feature or pattern seems almost to reach out of the display and grab the map viewer. You may have experienced this when looking at an array of similar items, such as in a store display, when the specific item you need or one which is in the wrong place suddenly stands out far more obviously than its visual characteristics alone would predict. Clearly, this phenomenon will be of service when viewing a multi-purpose cartographic map, crowded with symbols. A few decades of psychology experiments (usually with relatively abstract items such as letters or geometric shapes) have led to consensus on a model of attention to explain human visual search processes in real world scenes and information displays (Triesman and Gelade 1980; Wolfe and Horowitz 2004).

4.1.2 Spatial Memory. The brain integrates information from the senses with existing knowledge and expectations, which can influence our perception and attention before we even begin to look at a map (Lloyd 2005). The brain allows us to mentally visualize and manipulate our memorized knowledge about a space, partly by reusing the same pathways that we use to perceive physical stimuli in the world (Finke 1985). This mental visualization allows us to imagine, anticipate, and recall changes in the scene in front of us, at a variety of spatial scales—both what we expect to see next when turning the corner on a familiar route, and what will become visible if we zoom in on or pan a digital map display.

Debate has raged for some decades (Block 1981) as to whether mental images themselves are manipulated to solve visualized spatial problems, or whether the information is calculated based more on propositional (symbolic, expressible in language) representations, as in a computer. In reality, our brains appear to store both spatial and propositional information about experienced spaces, and seem to draw on multiple sources and pathways depending on the specific task. This 'messier' view of spatial cognition has been demonstrated both by behavioral and neuroscience data (Wolbers and Hegarty 2010), though more popular accounts tend to greatly simplify the picture. Even with the smaller pictorial spaces typical of maps and computer screens, there is evidence that spatial memory may encode both a visual image and a less precise (possibly propositional) record, along the lines of "the road was a bit to the left of the grid line" (Lansdale 1998). Thus, our memory for a studied map probably becomes simplified or abstracted in a way similar to our memory for environmental spaces (Newcombe, Huttenlocher, Sandberg, Lie, and Johnson 1999).

In fact, there are specific, systematic ways in which we mentally misrepresent geographic and environmental-scale spaces. These specific distortions may then affect users' expectations when they try to view a map display of a familiar area. For instance, like a topological subway map, our mental representations tend to simplify routes to straight, parallel, orthogonally intersecting lines, even where neither the local culture nor the urban layout fit exactly with such a "grid" view (Davies and Pederson 2001; Tversky 1997). At the same time, though, there is no guarantee that those memorized route segments and intersections will have been correctly integrated into the real topology, nor that an accurate overview will have been gained of its shape. In addition, unlike most cartographic maps, humans often prioritize awareness of landmarks over other aspects of an environment, even in situations where the local geometry or broader topography would be more useful (Denis, Michon, and Tom 2007; Peebles, Davies, and Mora 2007; Richter and Winter 2014). For these reasons, it may be quite a surprise for someone immersed in or already familiar with a given environment to view a map of it for the first time. In such a scenario, it seems likely that the presence of familiar landmarks and/or names could help map viewers to quickly locate themselves, and to relate the depicted features to known geographic entities such as roads, buildings, woods, or rivers.

In many other scenarios, however, users of map displays may have no knowledge of nor interest in the specific locations being depicted: They simply have a job to do with the information depicted in the visualization and can perform their tasks without concern for its relationship to perceptible real-world landscapes (Davies 2002). Here, basic map design principles (such as Bertin's, discussed below) would be more relevant to effective map use than correspondence with a known reality.

4.1.3 Reasoning With Maps. People use maps to reason about earth-referenced phenomena. Geovisualizations are powerful aids to reasoning and problem-solving because they exploit the properties of the visual-spatial perceptual system, particularly the nearly simultaneous availability of rich spatial and nonspatial information they provide. They do this by shrinking large portions of the earth's surface, and exploiting the abilities of the visual system and working memory, to efficiently extract spatial relationships and hold them in thought (MacEachren 1995; Montello, Waller, Hegarty, and Richardson 2004).

Philosophers in the Western tradition have talked about reasoning for centuries as a logical and rational process, and cognitive psychologists modeled human cognition for decades as if it were something like a logical computer program (Wilson and Keil 1999; Zalta 2012). But in the last three or four decades, psychological researchers have explored models of human reasoning that recognize the influence of biases, emotional states, and suboptimal probabilistic reasoning—in short, processes that would have previously been considered "irrational" but are efficiently heuristic in many contexts (Gigerenzer and Goldstein 1996 Plous 1993). In fact, clever cartographers have exploited this heuristic shortcutting throughout history in order to manipulate impressions—to "propagandize" (Monmonier 1991)—as well as to facilitate interpretation of the map. For example, water bodies shaded in blue can be rapidly detected on a map. This is true even though we know from experience that water almost never appears to be uniformly blue in the real world, if blue at all.

An expression of human reliance on heuristic reasoning in the context of geovisualizations is the role of visual salience in influencing inferences drawn from displays. Geovisualizations can, intentionally or inadvertently, mislead viewers into drawing inaccurate or oversimplified conclusions, even when the information presented is entirely accurate and fair, and the display observes good basic design principles. Large areas of a bright color will attract attention and be more memorable, thus becoming more available during recall. This is true even if the areas are actually less important (e.g., due to relatively sparse populations or less economic significance) and even if the viewer knows this. Therefore, well-trained cartographers normalize raw counts to be shown in enumeration units, to allow map readers to visually compare statistical information when mapped into statistical areas of unequal size (i.e., with choropleth maps). Similarly, to show statistical information at a global scale, cartographers choose a map projection that preserves relative size relationships of areas, so that they can be visually compared.

Likewise, the choice of colors, or the size and prominence of key features, can create an over-simplified but visually powerful impression which viewers cannot easily overcome when trying to interpret the map, even if they are informed about the coded categories via a well-labelled legend (Borland and Taylor 2007). Depending on the intended message, cartographers will choose an appropriate data classification scheme from the many that are available. Each classification scheme will have a direct visual effect on the data pattern in a statistical map, e.g., a scheme might highlight clusters of similar data values, or emphasize the contrast between high and low values (Slocum 2009).

Indeed, the very mapping of delineated categories can itself "lie." After the UK's 2016 "Brexit" referendum, in which the electorate narrowly voted to leave the European Union, a commonly published two-colored map of voting patterns showed a 'leave' vs 'remain' outcome for each voting district, implying that the vote reflected stark geographic divides (see the upper map in Figure 3). In this map, a general 'leave' trend in England and Wales was claimed to contrast starkly with Scotland and Northern Ireland's general 'remain' trend (e.g., Armstrong 2016). Based on this, nationalist movements in the latter two regions pressed their case for independence, while reporters endlessly investigated why a given town or region "voted in" or "voted out" (e.g., Jamieson 2016; McKenna 2016). In reality, the counting units were not areas but individual votes, of which 51.9% voted 'leave' and 48.1% 'remain'. More subtly designed maps showed that the advantage to either side was typically under 15% in any district. Indeed, the population-weighted cartograms in Figure 3 show this and show that the closeness of the result was influenced far more by English voters (especially in London) voting to remain in the EU than by the relatively few Scottish and Northern Irish voters. Thus, the post-referendum rhetoric of geographic division may have been misleading, when these divisions were in fact less important than education level, social class, political beliefs, and age (Hobolt 2016).

<Insert Figure 3>

As part of the very purpose of maps is to simplify the world, Monmonier (1991) pointed out that "Not only is it easy to lie with maps, it's essential" (p. 1). This is no less true—perhaps even more true—in the current age of digital mapping and dynamic imagery. Cartographers sometimes need to lie to overcome flaws in the human visual system. For example, people perceptually underestimate the apparent areas of map symbols in graduated symbol maps (Flannery 1971). Good cartography software nowadays will provide a method for scaling circles, based on a psychophysical function that approximately accounts for this underestimation.

Yet map displays will still communicate particular pieces of information at the expense of others, and incorrect inferences by users cannot easily be anticipated by cartographers. Perhaps end users should have more control over the visualizations themselves, so they can make more appropriate design choices with greater awareness of their impact. But this is probably unrealistic: Studies by Hegarty and her colleagues have suggested that novice map users will not make less biased design decisions, let alone task-optimized ones (Hegarty, Smallman, and Stull 2012; Hegarty, Smallman, Stull, and Canham 2009). Many mapping agencies across the globe are increasingly providing raw geographic datasets or mapping services on their map portals, rather than finished maps. In a digital world, psychophysical functions and cognitive principles may thus be directly encoded into the algorithms that adaptively serve maps on an online mapping portal, depending on the data request, use context, or target audience. Cartographic design expertise can thus help reduce the impact of human reasoning biases but never remove them altogether.

4.1.4 Emotion. Emotion (affect, mood, etc.) is also relevant to map perception and cognition. Emotion and cognition are intertwined, both functionally and experientially. Our beliefs and knowledge influence, and are influenced by, what we feel. Certain information can lead to an emotional response and certain emotional responses can motivate us to attend to certain aspects of the world (Griffin and McQuoid 2012). Relevant emotional responses to maps include positive ones such as aesthetics and preference, and negative ones such as stress and anxiety (e.g., Thoresen et al. 2016). Although human emotions can be complex and subtle, a scientific analysis decomposes emotional states into two main dimensions: evaluation (hedonic tone) and activity level (arousal) (Russell 1980). Sometimes, a third dimension of potency (control) is included. An important concept that involves emotion is the concept of attitude, which is a belief about something combined with an affective response to this belief. For instance, one might have an attitude that getting robbed is likely in certain mapped area of a city and a feeling of fear to visit those areas.

Clearly, features and events displayed on maps can evoke emotional responses, whether they are true or not. The way phenomena are graphically displayed can stimulate or attenuate emotions, such as using bright versus muted colors to represent a potential environmental hazard (Muehlenhaus 2012). Even the choice of map projections can influence emotional responses, because different projections make different places appear to be closer or more connected (Gilmartin and Lloyd 1991). Emotions can also affect how maps are used, as when stress restricts attention and impairs spatial decision-making from maps used, for example, in air traffic control situations (Maggi, Fabrikant, Imbert, and Hurter 2016) or during emergency evacuation. This is an active area for cognitive cartographic research (Burigat and Chittaro 2016; Klippel, Freksa, and Winter 2006).

4.2 Summary of Research on Cognitive Aspects of Map Use

In his historical review of cognitive research in cartography, Montello (2002) summarized many empirical map-design studies, for example on the perception of map symbols (see also Gilmartin 1992). These include studies of the perception of the size of proportional-area symbols, such as graduated circles (e.g., Flannery 1971). Many psychophysical studies have been done on such symbols (Castner 1983; Chang 1977); psychophysical methods are described below. Other studies have looked at the perception of gray-tone values (e.g., Kimerling 1975), color hue and saturation (e.g., Olson and Brewer 1997), and the perception of type fonts and lettering for maps (e.g., Bartz 1970). Especially common have been studies on perceiving elevation and landforms from topographic maps, including those symbolized with isolines (contours), hachures, and shaded relief (e.g., Eley 1987; Phillips 1984; Potash, Farrell, and Jeffrey 1978).

MacEachren (1995) authored the most comprehensive review of cognitive cartographic research that had been conducted up to that point in *How Maps Work*. It summarizes cognitive and perceptual research by cartographers, psychologists, and others, and links it to the semiotics of geovisualizations. Not just a review of empirical studies, however, MacEachren's book presents extensive material on the basic psychology of perception and cognition as it is relevant to understanding map design and use. He also discusses cartographic communication, noting that maps do not "contain" and "transmit" their messages to users, but stimulate ideas and inferences by interacting with the prior beliefs of those users.

In an effort to develop comprehensive scientific foundations for academic geovisualization research, almost two decades ago members of the International Cartographic Association provided a research agenda for cognitive and usability issues in geovisualization, focusing on the implications of development in computing software and hardware that they believed would lead to profound new ways of displaying, analyzing, and sharing geographic information (Slocum et al. 2001). These new possibilities include images that are:

(a) truly 3D (stereopsis, VR),

(b) moving (animations),

(c) nonvisual (sonifications, tactile maps, smell and taste),

(d) interactive (slider bars, zoom, pan),

(e) customizable (variable or theme selection), and

(f) based on nonspatial information (spatializations, interface metaphors).

These “maps” would appear online, distributed and shared on the World Wide Web and across a broad, international user base, or privately, on small cellphone screens. They would be location-enabled with GPS, so that information systems would know where the user was when requesting information. The authors further recognized that user issues, including individual differences among users, would perhaps be even more important than with traditional flat and static cartography. Thus, the possibility of individually tailored interfaces, intelligent defaults, options for flexible displays, and improved user education would become increasingly relevant. Without cognitive and usability research, however, Slocum and colleagues argued that many developments would be ineffective or even counterproductive to the goals of effective knowledge construction and sharing. They identified six relevant research themes: (1) geospatial virtual environments, (2) dynamic representations, including animated and interactive maps, (3) metaphors and schemas in interface design, (4) individual and group differences among users, (5) collaborative geovisualization, and (6) evaluation research. Finally, Slocum et al. recommended these research themes needed to be tackled via an interdisciplinary effort that included, at least, cartographers and geographic information scientists (GIScientists), cognitive scientists, usability engineers, and computer scientists.

Since 2001, geoviz researchers have in fact pursued the themes set out by Slocum et al. (2001). A great deal of cognitive work has been conducted on (or with) virtual environments, but work has mostly involved desktop systems that do not include actual body locomotion and has almost entirely been conducted by psychologists interested in basic questions about spatial orientation and learning, not geographic information display (Ambinder, Wang, Crowell, Francis, and Brinkmann 2009; Chabanne, Péruch, and Thinus-Blanc 2003; Waller, Beall, and Loomis 2004; Wraga, Creem-Regehr, and Proffitt 2004). A rare exception comes from work like that reported by Shelton and Hedley (2002), who demonstrated the effectiveness of an augmented reality system in teaching about earth-sun relationships. Other studies have looked at animated or interactive maps (Griffin, MacEachren, Hardisty, Steiner, and Li 2006; Harrower and Fabrikant 2008; Lobben 2008; Shipley, Fabrikant, and Lautenschütz 2013), individual and group differences among map users (Lobben 2007; Wilkening and Fabrikant 2013), and collaborative geovisualization (Jankowski and Nyerges 2001). Especially productive areas have been cognitive and human factors work on metaphors in interface design, particularly on information spatializations (Fabrikant et al. 2010a; Fabrikant, Montello, Ruocco, and Middleton 2004; Moore and Bricker 2015), and continued research evaluating display formats and techniques, some of which are made newly feasible by technological developments (Fabrikant, Rebich Hespanha, and Hegarty 2010b; Koua, MacEachren, and Kraak 2006).

4.3 Map Cognition by Children

The potential difficulties people have in interpreting maps (e.g., scale, projection, abstractness) show up glaringly when we consider map understanding and use by children. There is a fairly large body of cognitive research on how and how well children of different ages (mis)understand cartographic maps and how they might be taught to understand them properly (Liben and Downs 1992; Newcombe and Huttenlocher 2000; Uttal 2000). This work has included a longstanding interest in education with and about maps (see Chapter 21). A debate took place, most actively during the 1990s, about the nature and development of children's understanding of maps. One side (Blaut 1997; Blaut, Stea, Spencer, and Blades 2003; Landau 1986) argued that young children (ages 3–5) understand aerial photographs and simple map-like representations because they have a "natural" ability at mapping. The other side (Liben and Downs 1997) argued that children demonstrate difficulties and confusions when attempting to understand maps because the development of mapping skills such as symbolic correspondence and the transformation of spatial perspectives are difficult and require somewhat extended development over childhood. In fact, although some abilities to make and understand map-like symbols are present earlier than a strict Piagetian interpretation would suggest, and mapping probably should be introduced earlier in school than has been widely believed, evidence supports that there is a suite of different skills involved in mapping that take time and experience to develop (Davies and Uttal 2007; Liben 1999). Various literature documents that even adults find some mapping tasks difficult (Liben 2009); interpreting contour lines is one example.

4.4 Empirical Methods in the Study of Map Perception and Cognition

Over the years, various empirical methods have been used by cognitive geovisualization researchers, mostly derived from behavioral sciences like research psychology. Traditional methods employed in cartographic research include psychophysical ratio and magnitude scaling and estimation (e.g., Castner 1983; Chang 1977; Flannery 1971; Kimerling 1975); the assessment of response time and accuracy (e.g., Dobson 1983; Eley 1987; Fabrikant et al. 2010a; Potash et al. 1978); and surveys and interviews, such as about whether a user likes a particular display, and whether administered in verbal, numerical, or graphical format (e.g., Bianchetti 2016; Roberts, Newton, Lagattolla, Hughes, and Hasler 2013). But besides these traditional and long-used methods, cognitive geovisualization researchers have recently been applying some newer methods, or at least reapplying some traditional methods in different ways.

4.4.1 Gaze direction and eye movements. Since the early 1970s (Steinke 1987), cartographic researchers have explored recording a map viewer's gaze direction and eye movements as a source of data. This method is based on the notion that (sighted) people will look at what interests them in the visual field. The center of the visual field (the fovea of the eye) is the area of highest resolution vision, so people "foveate" the part of the visual field to which they wish to direct attention or the part that attracts attention (often nonconsciously). Tracking eye direction is thus a way to track visual attention over time. A researcher may be interested in where gaze stops for a several moments ("fixations") or the path over which gaze moves over time ("scan paths"). Although cartographic researchers explored the use of eye-movement recordings as early as the 1970s, the technique was difficult and costly, and was strongly criticized for being atheoretical (Montello 2002). It fell out of favor for a decade or more. Recently, technological and theoretical developments have led to a renaissance of eye-movement recording as a basic tool in the cognitive cartographic toolbox. For example, it has been used to study interactivity and the operation of varying perceptual salience of different features on map displays (Çöltekin, Heil, Garlandini, and Fabrikant 2009; Fabrikant et al. 2010b). Recently, mobile eye tracking has been explored. For example, Kiefer, Giannopoulos, and Raubal (2014) measured travelers' eye movements while they walked around a city with a map.

4.4.2 Web analytics. Since the 1990s, map viewers began to look at maps on their computer screen. Today, map images are probably most often accessed on the World Wide Web. As viewers click on links and travel from page to page, they leave a rich record of their viewing patterns that can potentially provide data for cognitive studies of maps. These records include the number of visitors to a page, the amount of time a viewer stays on a page, and the links which are clicked on. These records can be retrieved from web server log files or from page tagging, based on cookies attached to users. A cartographic example of web analytics comes from Ooms et al. (2015).

4.4.3 Brain scanning. As discussed in Chapter 9, researchers have begun to recognize the relevance to geographic problems of understanding the role of the brain in the mental and behavioral structures and processes of space, place, and environment. The fast-expanding field of cognitive neuroscience is increasingly being seen as relevant to cartographic science (Lobben, Lawrence, and Olson 2009; Lobben, Lawrence, and Pickett 2014). Its major method of collecting data is brain scanning. The most popular scanning technique for cognitive neuroscience is functional magnetic resonance imaging, fMRI. This technique allows researchers to scan the healthy brain activity of alert human research participants at relatively high spatio-temporal resolution. It records oxygenation of blood in brain cells, which corresponds to energy use by these cells, which in turn reflects cell activation during cognitive activity, such as thinking about patterns on a map. Other techniques used in cognitive neuroscience but largely waiting to be applied to cartography include computerized tomography (CT, formerly CAT), positron emission tomography (PET), electroencephalogram (EEG), event-related potential (ERP), and transcranial magnetic stimulation (TMS). The latter is noteworthy insofar as it applies a strong magnetic field to the surface of the brain to temporarily induce electric activity in one area of the cortex. In this way, it induces a transient interruption of normal activity in an area of the brain.

4.4.4 Physiological measures. Researchers interested in emotional responses to cartographic displays have started to explore the measurement of physiological responses of the body during map use (Griffin and McQuoid 2012). As we mentioned above, a prototypical situation is the use of maps during emergency egress, characterized both by time pressure and spatio-temporal uncertainty. Potential measures include pulse rate, blood pressure, body temperature, and skin conductance. The latter reflects changes in electrical conductance of the skin due to perspiration, a common effect of the stress response.

5. Conclusions and Outlook

The design of maps and other geovisualizations doubtless has many implications for geographic perception, thinking, reasoning, and emotions concerning features, events, and states of the world. Geovisualizations provide a very important symbolic source of spatial and nonspatial knowledge (beliefs) about the world, as highlighted in many chapters of this *Handbook*. The implications of geovisualizations as symbolic sources of knowledge run in both directions—geographic information and the means of its communication influences cognition, and existing knowledge influences how geographic information is interpreted and should best be communicated. The critical nature of this relationship may arise no more obviously than with the issue of how to effectively communicate data quality or uncertainty (MacEachren et al. 2005; Slocum, Cliburn, Feddema, and Miller 2003; Yao and Jiang 2005), such as uncertainty in predictions about climate change. While there are several proposed ways to depict data uncertainty, there is only a little research in the geovisualization community on essential questions about how people should and do make use of uncertainty metadata to make decisions.

A continuing question concerns how widespread the influence of cognitive research has been on the design of displays that people actually make and use, e.g., commercial atlases, mapping websites, or in-vehicle navigation systems? That is, how successful is cognitive research on geovisualization—indeed, cognitive research in all areas of GIScience (as in Chapters 8 and 11)—as applied science? In his historical overview of cognitive research up to 2000, which included interviews with several prominent academic cartographers, Montello (2002) concluded that it had not been very successful to that point, and he considered reasons why basic cognitive research on map design had not readily translated to application (cf. Petchenik 1983). True, Montello noted that the large GIS company Esri had just implemented “Flannery scaling” to let mapmakers accommodate perceptual effects in their graduated circles, and this is still implemented in ArcGIS. He also cited nascent applications of Brewer’s work on a system for choosing color schemes for maps, originally to accommodate color blindness (“ColorBrewer”). Brewer and her colleagues have continued to develop this system (Brewer, Hatchard, and Harrower 2003) and it is now available in most important data analysis and mapping packages (including R, MATLAB, ArcGIS, etc.) (http://www.personal.psu.edu/cab38/ColorBrewer/ColorBrewer_updates.html).

Nonetheless, this still seems like fairly limited application. The question of why this is so limited and how this can be changed remains intriguing for cognitive researchers of maps and other geovisualizations, and maybe a challenge for some. Admittedly, it is difficult to say with complete accuracy how much basic cognitive research has influenced production mapping and mapping software. In particular, it is not clear how much private companies and government agencies have carried out research for internal uses, or how much they have implemented academic, industry, or agency research in their products. They have likely carried out at least simple usability testing, of varying systematicity, and probably continue to. Such work might be considered cognitive research, although simply asking tests users to make coarse judgments of preference for one design over another, or express opinions about what would or would not work well in cartographic design does not connect much to cognitive theory (and according to work like that of Hegarty et al. [2009], expressed opinions are of dubious validity in this case). Still, we see some evidence for a trend of increasing application for cognitive research, especially as the reality of geovisualization continues to go so far beyond traditional flat and static cartographic images. We also expect the increased use of newer empirical methods such as mobile eye tracking, physiological measures, and brain scanning to portend exciting breakthroughs in our understanding of the psychological science of maps that may well facilitate successful application. In any case, basic-science research that attempts to understand cognitive aspects of maps and other geovisualizations remains interesting and, we think, worthwhile as an intellectual endeavor. Numerous citations in this chapter show how influential this work has been in academic cartography for decades, and that it remains so.

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Footnotes

[1]For further information, see the Commission on Cognitive Issues in Geographic Information Visualization of the International Cartographic Association on the Web at: http://cogvis.icaci.org

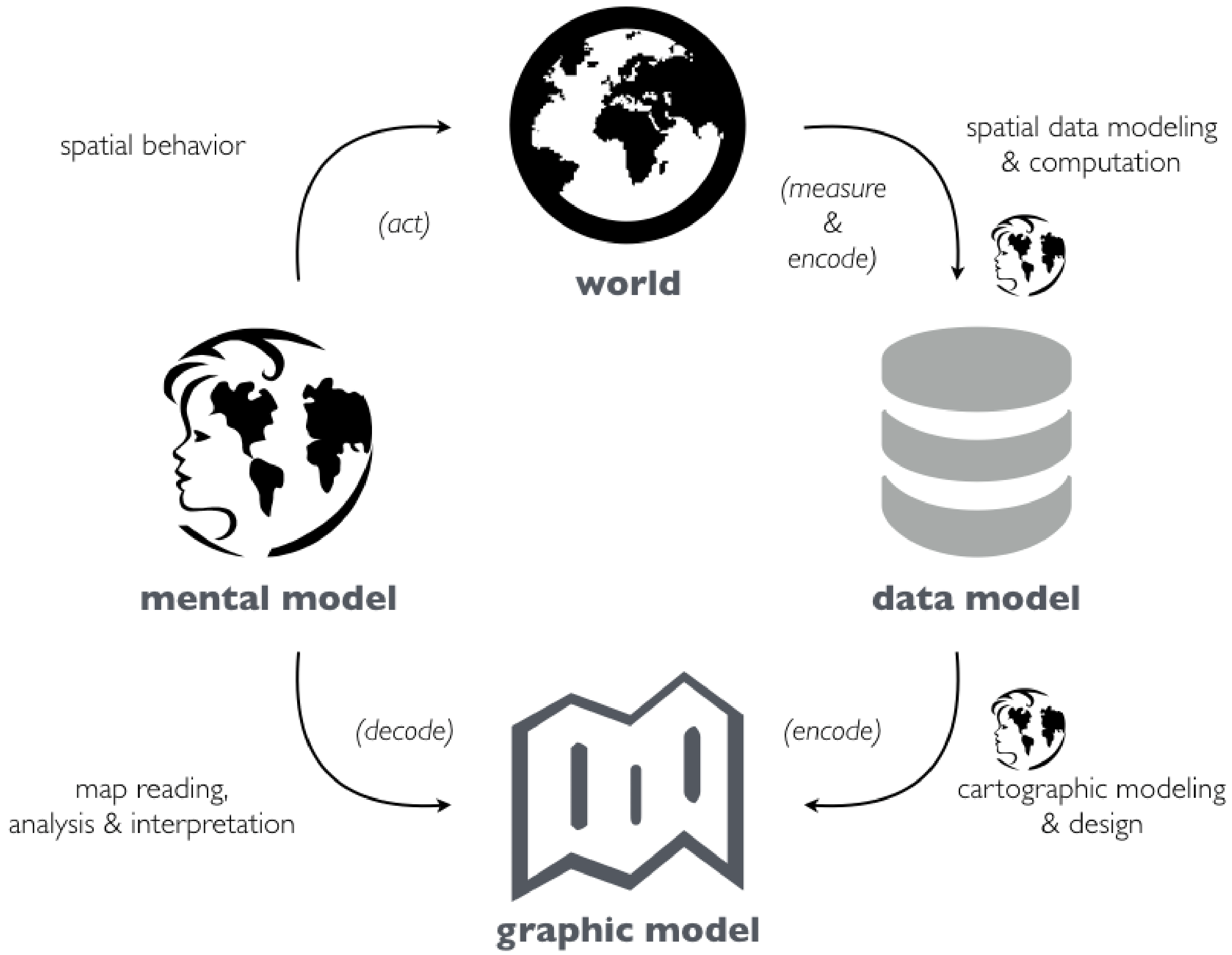

Figure 1. A simple representation of the cartographic abstraction process.

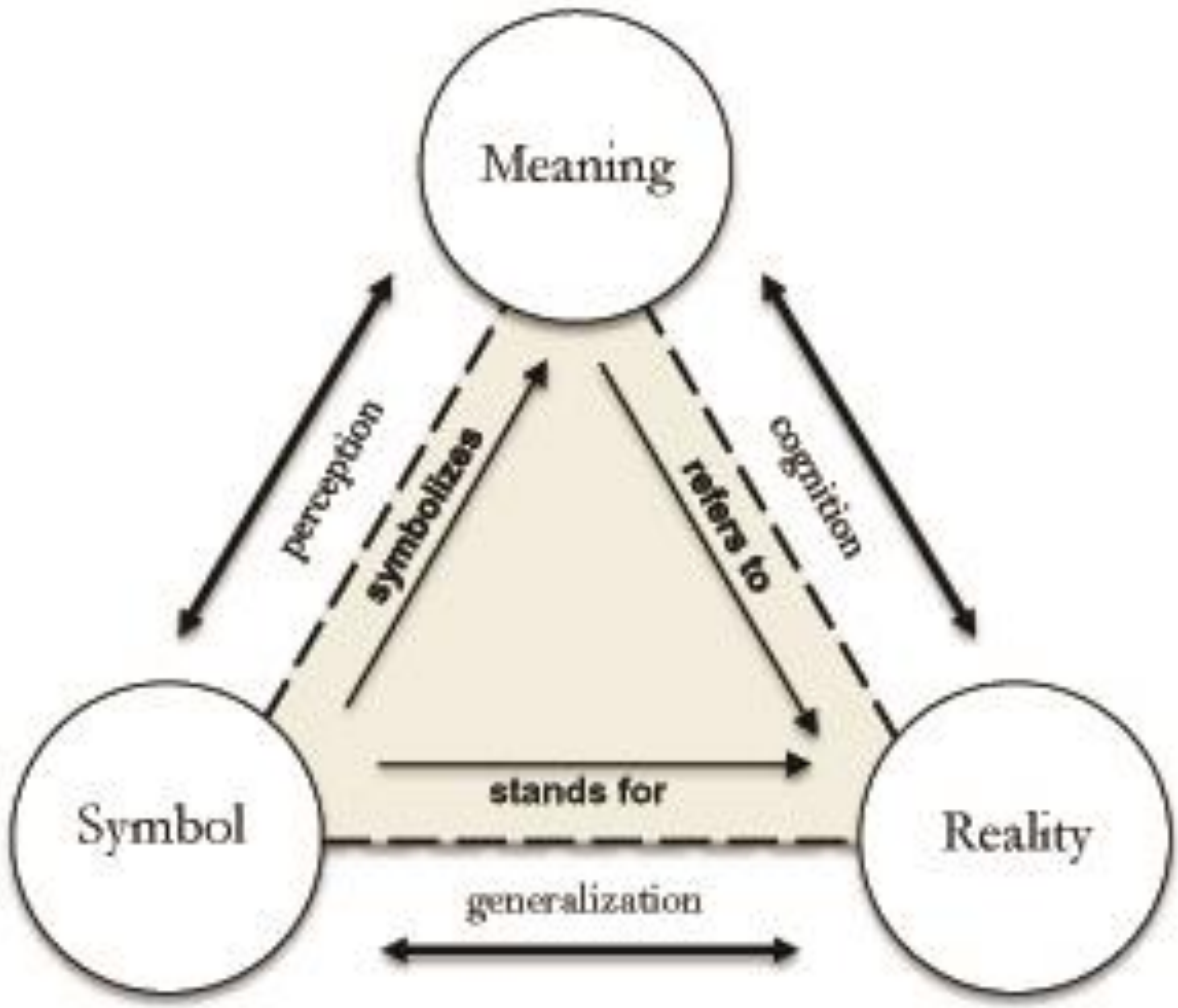

Figure 2. The cartographic representation of meaning: The Peircian semiotic triangle (after MacEachren 1995).

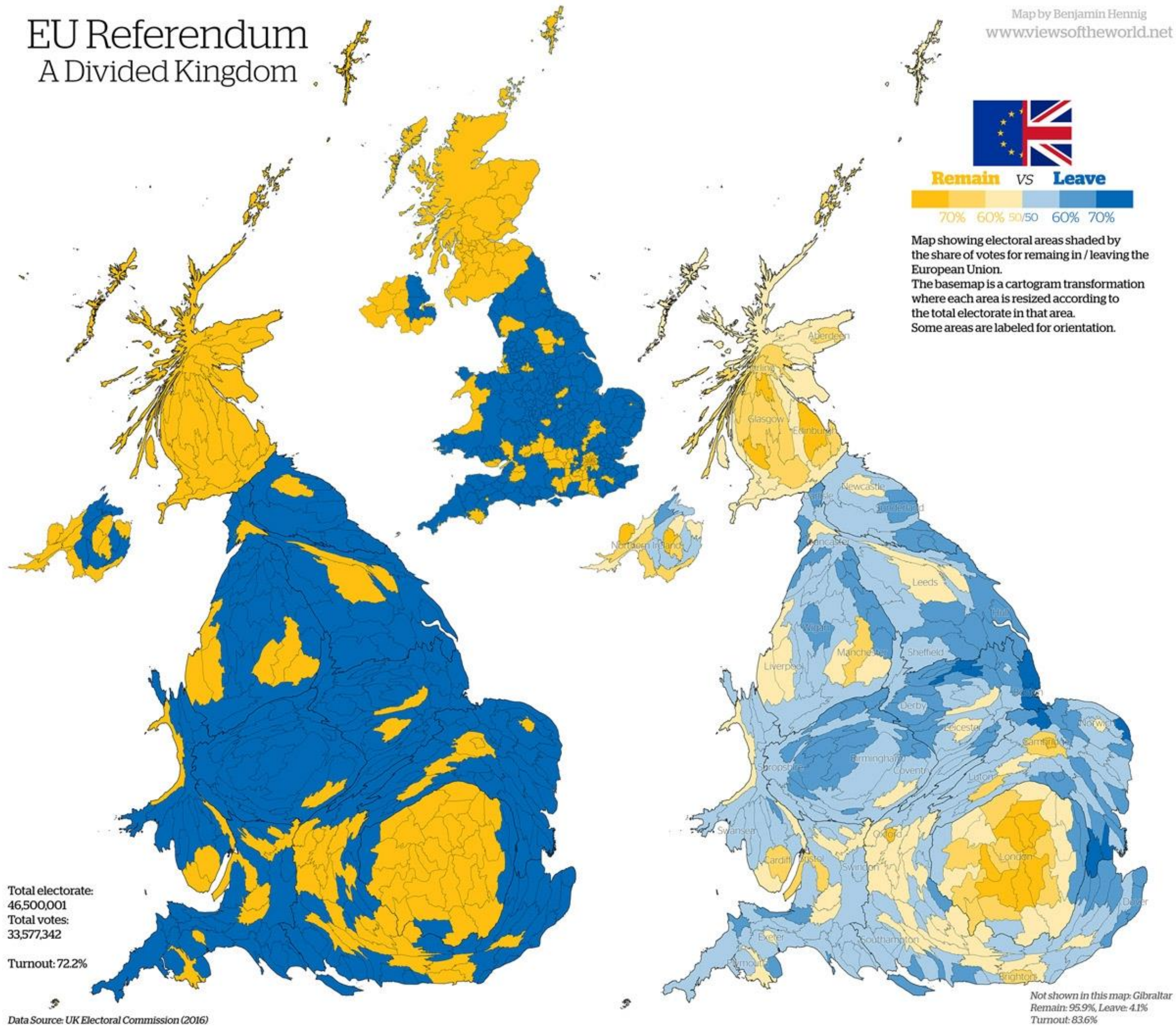

Figure 3. Cartogram of the 2016 Brexit vote in the United Kingdom (Hennig and Dorling 2016) (used with permission).