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RESEARCH ARTICLE

Interactive maps: What we know and what we need to know

Robert E. Roth

Department of Geography, University of Wisconsin-Madison, WI 53706, USA

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Abstract: This article provides a review of the current state of science regarding *cartographic interaction*, a complement to the traditional focus within cartography on cartographic representation. Cartographic interaction is defined as the dialog between a human and map, mediated through a computing device, and is essential to the research into interactive cartography, geovisualization, and geovisual analytics. The review is structured around six fundamental questions facing a science of cartographic interaction: (1) *what* is cartographic interaction (e.g., digital versus analog interactions, interaction versus interfaces, stages of interaction, interactive maps versus mapping systems versus map mash-ups); (2) *why* provide cartographic interaction (e.g., visual thinking, geographic insight, the stages of science, the cartographic problematic); (3) *when* should cartographic interaction be provided (e.g., static versus interactive maps, interface complexity, the productivity paradox, flexibility versus constraint, work versus enabling interactions); (4) *who* should be provided with cartographic interaction (e.g., user-centered design, user ability, expertise, and motivation, adaptive cartography and geocollaboration); (5) *where* should cartographic interaction be provided (e.g., input capabilities, bandwidth and processing power, display capabilities, mobile mapping and location-based services); and (6) *how* should cartographic interaction be provided (e.g., interaction primitives, objective-based versus operator-based versus operand-based taxonomies, interface styles, interface design)? The article concludes with a summary of research questions facing cartographic interaction and offers an outlook for cartography as a field of study moving forward.

Keywords: cartographic interaction, interactive maps, geographical user interfaces, science of interaction, interactive cartography, geovisualization, geovisual analytics

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1 Introduction

Cartography commonly is defined as the art and science of mapmaking and map use. Although stemming from artisan roots, cartography emerged as a legitimate scientific discipline following the Second World War in the wake of growing interest in empirical map design research and, more broadly, the quantitative revolution within geography. The guiding philosophy during what Robinson [230] called the "Golden Era of Cartography" was functional design, or the scientific generation of cartographic design guidelines based upon the perceptual and cognitive limits of the intended map user. This approach to cartographic research gave rise to the *communication model*, which describes the map as a conduit through which a message can be passed from the mapmaker to the map user [19, 144, 231]. The few empirical insights derived within cartography were supplemented with research on visual communication from advertising, art, education, and psychology in order to recommend general cartographic design guidelines for avoiding interruptions in this message transmission. Although the communication model largely has fallen out of favor due to concerns from practical/applied [179, 207] and critical/social theory [110, 293] perspectives, the design and use guidelines generated during this era remain the backbone of the modern cartographic curriculum [183, 192]. Today, many scholars frame their research as *cartographic representation*, continuing the Robinson-era investigation into how maps work from a perceptual and cognitive standpoint (i.e., how maps are seen and understood) while also accounting for the map user's situated experiences (i.e., how maps become imbued with meaning) [16, 157].

In this article, I approach a complementary topic to cartographic representation, one that is increasingly central to cartography specifically and GIScience generally: *cartographic interaction*, or how maps are manipulated by the map user. In the following, the term "interactive" is used rather than "dynamic" to distinguish display updates evoked by the user (interaction) from display updates evoked by the system (such as animation, a form of cartographic representation). The digital revolution and subsequent information age together have prompted changes that are as numerous as they are fundamental to the ways in which maps are produced and consumed, with interactivity being among the most significant of these new possibilities [65, 208]. As Harrower [111] writes, "The Golden Age of Cartography is now." As an example, Figure 1 provides a pair of radial categories proposing a shift in the central map prototype as a result of emergent digital information technologies. Figure 1a, originally published by MacEachren [157] in 1995, illustrates the "analog map" using degree of abstraction and map scale as the motivating characteristics. Prototypical maps in the Figure 1a categorization include a planimetric reference map of county roads, an oblique reference map of terrain, and a thematic map of AIDS incidence. In contrast, Figure 1b illustrates the "digital map" using web dissemination and cartographic interaction as the motivating characteristics [237]. Prototypical examples in the Figure 1b digital map categorization include digitally-native road maps for navigation either in-car (e.g., GPS-based systems) or online (e.g., Google Maps, MapQuest), digital globes (e.g., Google Earth, an example of a map that would be peripheral in Figure 1a due to the degree of realism), and thematic atlases that include print and digital versions (e.g., the National Geographic Atlas of the World). Although many conclusions can be inferred from the Figure 1 exercise, it is evident that maps providing some degree of interactivity are growing in popularity. It can be expected that cartographic interaction only will become more fundamental as the central map prototype continues to shift from analog to digital.

The shift in central prototype from Figure 1a to Figure 1b indicates a possible "cartographic revolution" that has been 20+ years in the making. With the increased awareness or general adoption of many digital cartographic technologies, it is possible that we are nearing the terminus of this revolution, rather than being directly in its midst. While technological developments in interactive mapping have been spectacular, cartographic science thus far has failed to keep pace with practice. In this article, I argue that cartographic science must expand its reach to provide actionable knowledge about and practical guidelines for the design and use of this new generation of interactive maps. Cartographic research also should suggest new opportunities for the application of interactive mapping, creating a positive feedback loop of expansion and vitality between science and practice. Cartographic growth, however, should not be at the expense of established research on cartographic representation. Instead, traditional cartographic questions need to be reevaluated—and readily accepted cartographic guidelines reconsidered—in the context of an interactive, digital environment [5, 89, 146]. We need a unifying structure to incorporate the affordances of the digital revolution into cartography without jettisoning the pillars of twentieth century cartographic research.

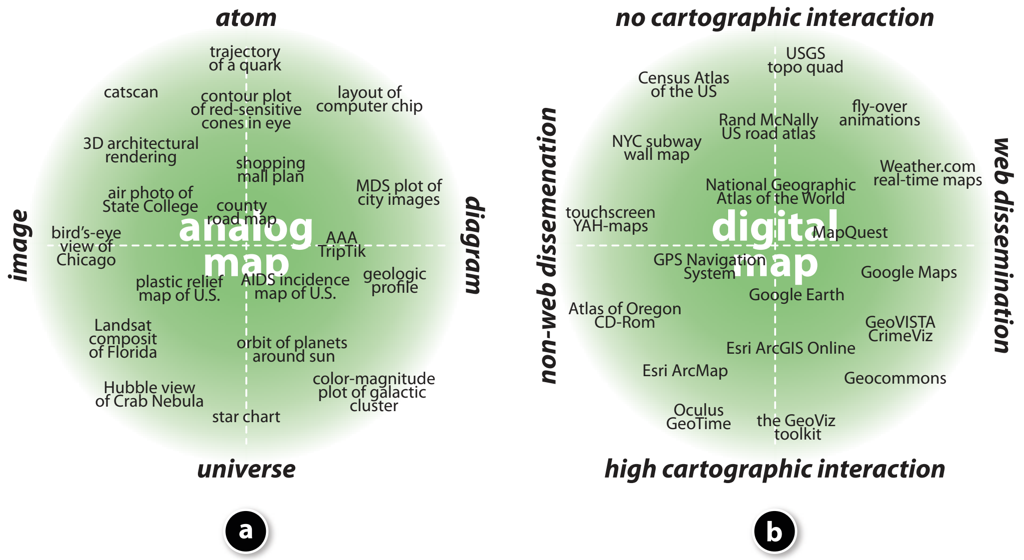

Figure 1: The shifting prototypical map as a result of the digital revolution and information age. Radial categories have a central prototype (i.e., the first example that comes to mind), with non-prototypical examples bearing family resemblance to the central prototype according to non-arbitrary, motivating characteristics [149], which often are represented graphically as orthogonal axes. (a) A radial categorization of the analog map using motivating characteristics important to cartographic representation, redrawn from MacEachren [157]. (b) A radial categorization of the digital map using motivating characteristics important to cartographic interaction. In the article, a broad and inclusive definition of the "analog map" as well as the "digital map" or "interactive" map is used, following prototype theory.

Figure 2 organizes the breadth of research topics covered by this growing cartography according to two continua: cartographic representation versus cartographic interaction and mapmaking versus map use. Cartographic research can be focused primarily on cartographic representation, primarily on cartographic interaction, or on the influence each has on the other and their combined synergy. Further, and following the classic distinction in cartography between mapmaker and map user, cartographic research can examine how the representations or interactions should be designed by cartographers, how these representations and interactions should be employed to support user goals and objectives, or how they should be altered under the increasingly common scenario when the mapmaker is the map user. Modifications of Figure 2 are provided to suggest the primary emphasis of five important thrusts of research related to cartography: the communication model (Figure 2b), critical cartography (Figure 2c), interactive cartography (Figure 2d), geovisualization (Figure 2e), and geovisual analytics (Figure 2f); the Figure 2 annotations should be interpreted as fuzzy boundaries, with these research thrusts ultimately blending into a coherent whole.

The purpose of this article is to provide a review of the current state of science regarding cartographic interaction, identifying important research goals and, where possible, summarizing initial insights towards these goals. There is a concentrated, and growing, set of research articles examining digital interactions that are explicitly cartographic in nature. Yet, research on cartographic interaction remains incomplete. Like Robinson [230] in his early writing on cartographic representation, I offer this review on cartographic interaction in hope to "impart an appreciation of what and how much we do not yet know" and ultimately to motivate a deeper inquiry into the nature of cartographic interaction. In the following review, research in cartography is supplemented by secondary sources on interaction from the disciplines of GIScience, human-computer interaction, information visualization, and visual analytics. It is likely that such external theoretical frameworks and empirical evidence need to be rethought when applied for cartographic interaction in the same way that past scholars have rethought broader research on communication and design when treating cartographic representation.

The remainder of the article is organized according to six key themes, or *fundamental questions*, facing a science of cartographic interaction identified during the review process: (1) what is cartographic interaction? (2) why provide cartographic interaction? (3) when should cartographic interaction be provided? (4) who should be provided with cartographic interaction? (5) where should cartographic interaction be provided? and (6) how should cartographic interaction be provided? The following sections provide a synopsis of what we know, and offer preliminary suggestions on what we need to know, about each fundamental question regarding cartographic interaction. For reference, Table 1 (provided at the end of the article) defines each of these fundamental questions and enumerates the set of associated research questions exposed in the review. Throughout the review, the focus is primarily on the current state of *science* regarding cartographic interaction to parallel and reinforcing an equivalent effort of establishing a science of interaction in the related fields of information visualization and visual analytics [212, 270]. The final section offers comments regarding both the *art* and *ethics* of cartographic interaction, and cartography overall.

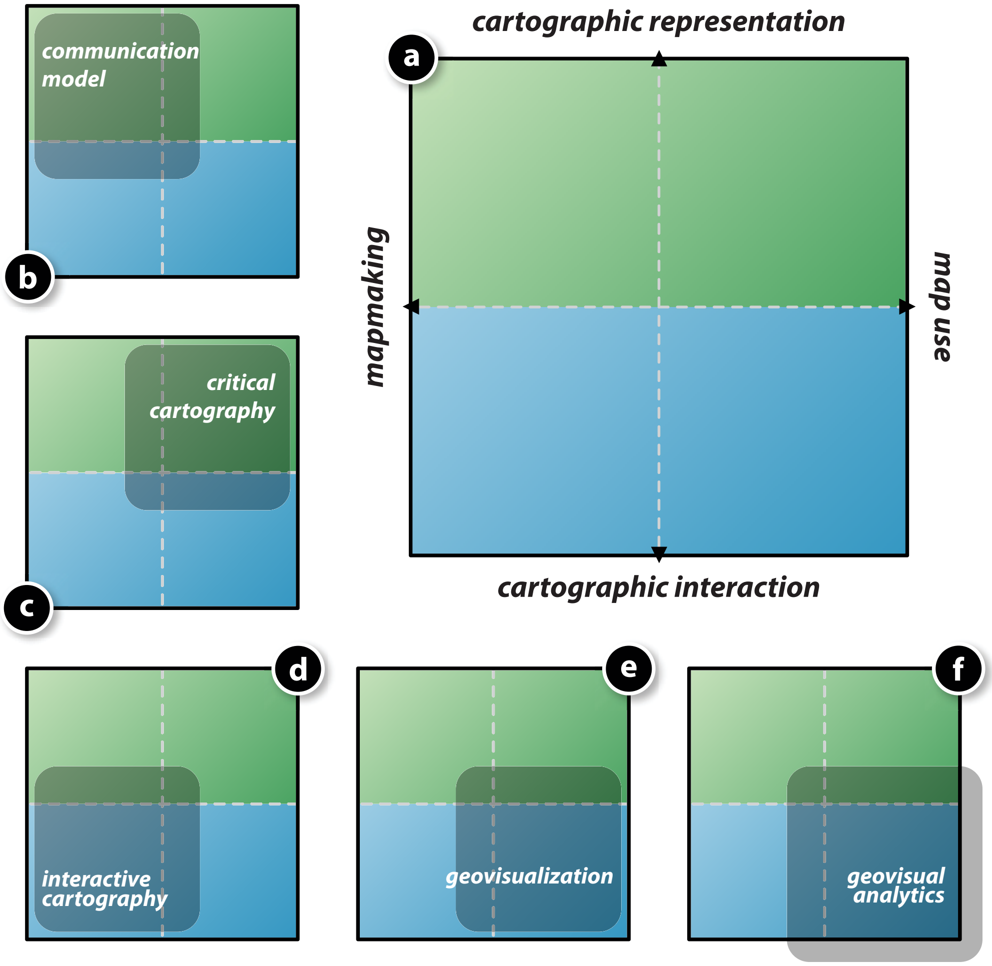

Figure 2: The breadth of research topics related to a growing cartography. (a) Research in cartography can be characterized along the dimensions of *cartographic representation* versus *cartographic interaction* and *mapmaking* versus *map use*. The inset drawings suggest the general topical breadth of the research thrusts of: (b) the communication model, (c) critical cartography, (d) interactive cartography, (e) geovisualization, and (f) geovisual analytics.

2 What is cartographic interaction?

An important starting point is to define the meaning of cartographic interaction in the context of cartographic research (i.e., *what?*, Table 1). Numerous scholars have argued that paper maps and map sketches are interactive [16,61,168,208,294] and that the way in which humans interact with analog representations should inform the design of cartographic interfaces [33, 91, 94, 148, 263]. However, a digital environment affords a wider array of interaction forms for manipulating cartographic representations, with the kinds of interactions provided through the interactive map limited only by the objectives of the map user, the skill set of developer, and the input, processing, and display limits of the hardware [87]. In the following, the term *cartographic interaction* is defined as the dialogue between a human and a map mediated through a computing device (Figure 3) to emphasize digital interactions [13, 33, 208, 237, 297]. As explained in Roth [238], such a definition is not a renewed attempt at the communication model (Figure 2b), which imposes a one-way conversation metaphor, but rather an acknowledgement that the human and map are equals in the cartographic interaction, each holding the ability to affect change to the other.

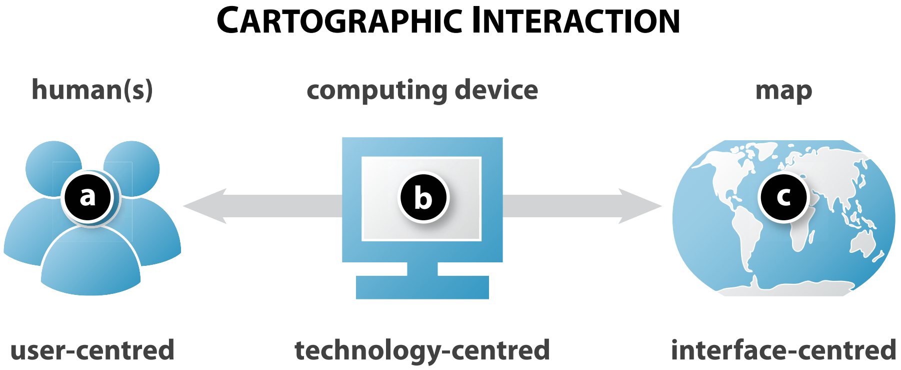

Figure 3: Components of digital cartographic interaction. Cartographic interaction is defined as the dialog between a human (a) and a map (c) mediated through a computing device (b). Figure reproduced from Roth [238].

The schematic in Figure 3 identifies the components of a cartographic interaction, but does not necessarily explicate how a cartographic interaction is initialized and completed. Norman's [200] *stages of action model* provides insight into the process of cartographic interaction, segmenting the interaction into seven observable stages: (1) forming the goal (i.e., an open-ended task, described as a *goal*), (2) forming the intention (determining a closed-ended task, described as an *objective*, that works towards the open-ended goal), (3) specifying an action (identifying a system function, described as an *operator*, that supports the objective), (4) executing the action (employing the operator through an input device), (5) perceiving the state of the system (seeing the result through a display device), (6) interpreting the state of the system (evaluating the meaning of the change in the display), and (7) evaluating the outcome (comparing this meaning to the original open-ended goal to determine if the goal is accomplished). Figure 4 shows Norman's stages of action model in context with the Figure 3 definition of cartographic interaction. Additional annotations in Figure 4 are explained in subsequent sections while the topics of objectives, operators, and operands are treated in more detail under the *how?* question.

Completing each of these stages is essential for the cartographic interaction to succeed (assuming the map and mapped information were useful for completing the goal in the first place), with failures in reaching a given stage resulting in an interruption, or gulf, between

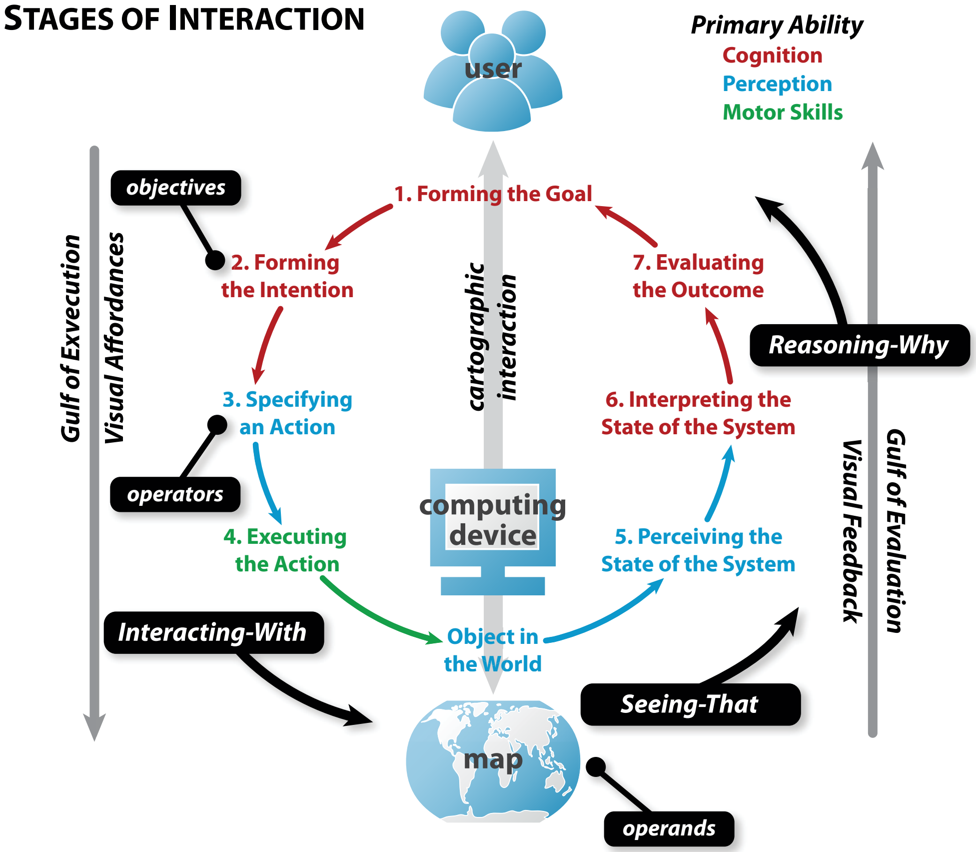

Figure 4: Stages of interaction. Norman's [200] stages of action model provides insight into how a single cartographic interaction exchange is performed. Superimposed in the Figure 4 illustration are the Figure 3 definition of cartographic interaction, after Roth [238], and the Figure 8 stages of pattern-seeking, after MacEachren and Ganter [168]. By relating Norman's stages of action model and MacEachren and Ganter's pattern-seeking model, it is possible to determine if a given stage of action primarily emphasizes cognition (red), perception (blue), or motor skills (green), informing the design scientific experiments accordingly. Finally, extant taxonomies of interaction primitives generally align with one of three stages of interaction: (1) stage #2 (objective primitives), (2) stage #3 (operator primitives), and (3) the map (operand primitives). Figure reproduced and annotated from Roth [238].

user and digital map. The *gulf of execution* describes the disconnect between the user's objectives and the provided cartographic interaction operators (i.e., problems in stages #1–4) and the *gulf of evaluation* describes the disconnect between what the user expected to accomplish through the cartographic interaction and the interface's representation of the result of the cartographic interaction (i.e., problems in stages #5–7). While Norman's [200] stages of action model describes how humans interact with any object in the world—analog or digital—the framework has been informative for understanding digital interaction generally [83, 215] and cartographic interactions specifically [238].

The stages of action model allows for distinction between the overall cartographic interaction, defined above, and the individual *cartographic interface*, or the set of digital tools through which the cartographic interaction occurs [106, 198]. Cartographic interfaces include one-off interactive maps (e.g., a web map found on NYTimes.com) and sophisticated map-based systems (e.g., Esri's ArcMap), as both provide cartographic interaction. Cartographic interactions and cartographic interfaces are inextricably related; digital cartographic interaction cannot occur without implementing some sort of cartographic interface, and the utility and usability of the cartographic interface is determined by the kind and quality of cartographic interactions provided through it. Yet, a science of cartographic interaction must begin with consideration of the overall *experience* of cartographic interaction and not immediately focus upon the *implementation* and *use* of cartographic interfaces supporting these interactions [13, 238]. However, most existing scientific research on interactivity within cartography report on individual cartographic interfaces and not the overall cartographic interaction.

Some scholars place a limit on the time it takes for the cartographic interface to respond to the user input in order for it to be considered "interactive," an issue related to Norman's [200] gulf of evaluation. Three limits on response immediacy are recognized in human-computer interaction: (1) 0.1 second for the user to feel as though the system is responding immediately, (2) 1.0 second to avoid interrupting the user's thinking process, and (3) 10 seconds before the user's attention will be diverted to other tasks [185, 198]. According to their keystroke-level model, Card et al. [31, 32] recommend that the optimal amount of time to complete an interaction is approximately 0.40 seconds for a keyboard press, approximately 1.16 seconds for a coarse mouse movement, and 0.38 seconds for a fine, honing mouse movement. Delays beyond these optimal levels affect user productivity [119]. However, immediate response is difficult in the context of voluminous geographic datasets and complex, vector-based cartographic representations common in the information age (or more appropriately, the "age of big data"). Recommended response time for cartographic interactions ranges between one and two seconds [285], although Haklay and Li [104] note that, "Almost no [geospatial] application is truly interactive and provides a responsive application to the user within two seconds of an operation." System response is reviewed further under the *where?* question.

Many questions on the fundamental nature of cartographic interaction remain. For instance, the radial categorization shown in Figure 1 includes desktop mapping and GIS software. Does the distinction between interactive maps and mapping systems impact cartographic interaction design and use guidelines? Figure 1 also includes geoweb technologies, such as web mapping services (e.g., Google Maps, MapQuest) and map mash-ups that combine geographic information feeds and services through application programming interfaces (APIs) [92, 180, 184, 244]. Figure 1 even includes tools that help users create interactive map mash-ups with these web mapping services, such as the neogeography service provided by GeoCommons [277]. Are these interactive maps? What about applications that coordinate interaction across multiple information views, the map being only one of them [108, 109, 221]? Does simply calling an application an "interactive map" change the way it is understood and used, as with the positive influence of using the term "map" instead of "diagram" [138, 157]? Does the existential question of "what is an interactive map?" even matter [52, 281]? Further understanding also is needed about the influence of analog cartographic interactions in the design of digital cartographic interfaces [223, 224]. To what degree can analog interactions inform the design of digital interactions and to what degree should designers explore new classes of cartographic interactions that have no analog or physical parallel [33]? Finally, research is needed to determine which spatial metaphors can be applied to interactive representations of non-spatial information and vice versa [49, 78, 79, 121, 261]. Are there considerations for user experience (UX) design unique to cartography? These questions concerning the *what?* of cartographic interaction require additional scientific research.

3 Why provide cartographic interaction?

Once defining and scoping cartographic interaction (i.e., the *what?*), it is then possible to consider the purpose of such cartographic interaction, or the value it provides (i.e., the *why?*, Table 1). Traditionally, a map can be thought of as an abstracted externalization of the mapmaker's knowledge about the mapped phenomenon [160, 272]. Beginning with analog mapping, the map is a closed artifact of the mapmaker's interpretation of the mapped phenomenon that can be used as a vehicle to send an intended message to the map user, a perspective of cartography encapsulated in the communication model [19, 144, 230, 231]. We know today that communication of a message from mapmaker to map user cannot be objective, and rarely tries to be. The mapmaker's knowledge of the mapped phenomenon is partial and the mapmaker can embed multiple layers of meaning within the map. Similarly, the map user applies his or her unique set of experiences, perspectives, and skills to extract different meanings from the cartographic representation [190, 293]. Whether successful or not, the goal of this communication process is the transfer of a *known* set of geographic insights from mapmaker to map user.

Maps need not be closed artifacts of a mapmaker's knowledge. The framework of *distributed cognition* proposes that externalizations, with maps being a visual form of such, can act as an extension of cognition [124, 129]. Visual externalizations allow individuals to offload thinking onto information graphics, using perceptual (seeing-that), cognitive (reasoning-why), and motor (interacting-with) processes to reintegrate the external knowledge into existing internal schema [168]. Additional details on this process are provided during review of the *who?* question below. Here, the map is not just an external representation of internalized knowledge, but a complement to it in the overall act of knowledge construction [250]. In this respect, the externalization serves as a memory aid for declarative, procedural, and configurational knowledge [39, 46], as well as a *visual isomorph* (i.e., a representation of equivalent information in a different visual structure) for examining the problem from a different, perhaps more informative perspective [107]. In other words, maps literally allow people to *think visually* to the end of generating new, previously *unknown* insight [12].

DiBiase [59] compares visual thinking and visual communication, as related to the mission of science, in his often reproduced *swoopy diagram* (Figure 5). Drawing from Tukey's [275,276] research on exploratory data analysis (EDA), four stages of science are identified: (1) *exploration* (examining the information from multiple perspectives to identify research questions and to generate research hypotheses); (2) *confirmation* (formally testing hypotheses to answer research questions, the goal of most statistics prior to Tukey's work); (3) *synthesis* (integrating insights generated from multiple iterations of the exploration and confirmation stages to triangulate a final solution to the research questions; this stage was an addition of DiBiase's to EDA); and (4) *presentation* (communicating the uncovered solution to a wider audience). One interpretation of the "swoop" in the diagram is the number of unique cartographic representations needed at each stage, ranging from an infinite number at the exploration stage (i.e., visual thinking) to a single representation during presentation (i.e., visual communication). MacEachren [156] made use of the swoopy diagram, and the notion of visual thinking, in his *cartography cube* framework (Figure 6), which summarizes all possible map uses according to three axes: (1) revealing unknown insights versus presenting known ones, (2) private map use versus public map use, and (3) high versus low human-map interaction (updates to the framework are provided in [167,169,170]). Through the center of the cube runs the swoopy schematic, illustrating the change from visual thinking (i.e., infinite possible views) to visual communication (i.e., one optimal view). The bottom, forward-most corner (revealing unknowns, private map use, and high human-map interaction) of cartography cube has come to represent the cartographic subfield of *geovisualization* (Figure 2e).

Importantly, the cartography cube framework prescribes the way in which visual thinking is best supported: through high levels of human-map interaction. Map-enabled visual thinking begins with the cartographic representation (i.e., what is seen), and static maps have and likely always will be an important component of visual thinking. However, numerous scholars agreed during the digital revolution that digital cartographic interaction was the only way forward for generating the multitude of map views needed to support exploratory visual thinking [5, 62, 68, 118, 153, 168, 188, 278]. As MacEachren and Monmonier [171] wrote, the digital environment "allows visual thinking/map interaction to proceed in real time with cartographic displays presented as quickly as an analyst can think of the need for them." Such exploration of numerous, user-defined, and ephemeral cartographic representations reveals anomalies, patterns, and trends in the dataset that were previously unknown, leading to the generation of *geographic insights*, or any new understanding (hypotheses, ideas, explanations, conclusions, etc.), about the true nature of the studied geographic phenomenon or process [81]. As Roberts [221] stated, the basic premise of visual thinking is that "insight is formed through interaction." It is this promise of visual thinking in a digital age that requires the establishment a science of cartographic interaction.

Many questions remain concerning *why?* cartographic interaction should be provided to support the generation of new insights during exploration. The topic of insight generation has received a great amount of attention from the discipline of cognitive science [267]. However, there has been limited research on the generation of geographic insight using cartographic interaction, which has resulted in few empirically derived interaction strategies or interface design guidelines for facilitating the generation of new geographic insight. Several useful structures for understanding the nature of insight come from the field of *visual analytics*, defined as the use of visual interfaces to computational methods in support

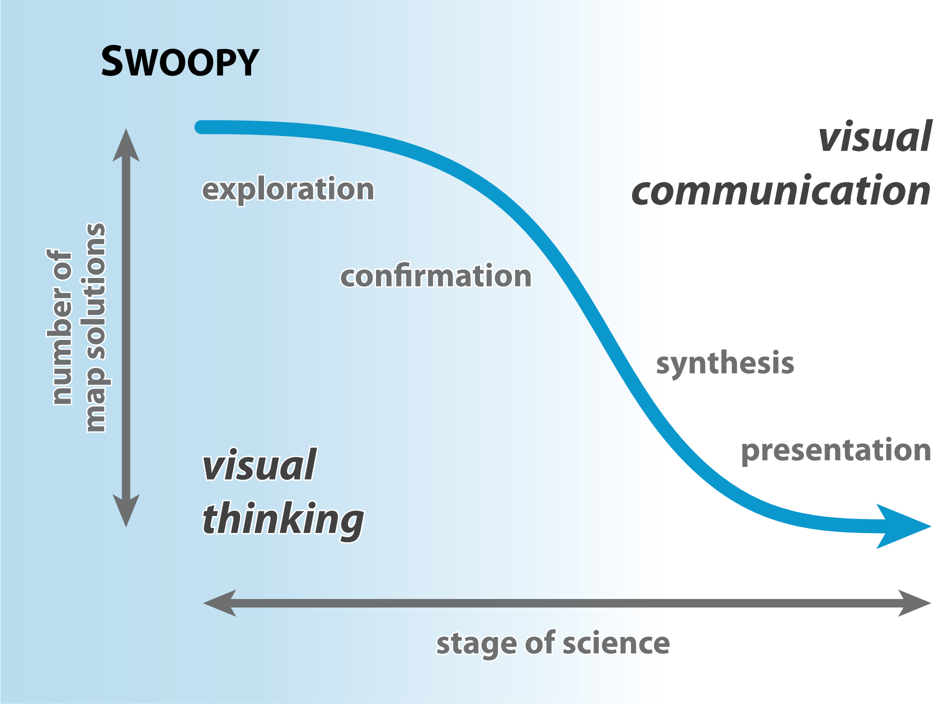

Figure 5: The swoopy diagram. In the early, exploratory stage of science, scientists require numerous different map solutions to promote visual thinking and prompt new research hypotheses. It is not until the later, presentation stage that a single, optimal solution is needed for visual communication. Figure redrawn, reinterpreted, and annotated from DiBiase [59].

of visually-enabled human reasoning [270, 271]. Prompted by Saraiya et al.'s [249] empirical study, North [202] describes insight as varying across five measurable characteristics: (1) complex (insights involve investigating a voluminous dataset in subtle and integrative ways), (2) deep (insights require time and evidence accumulation to be robust), (3) qualitative (insights often are inexact and uncertain), (4) unexpected (insights are considered more valuable when they reveal the unknown), and (5) relevant (insights are couched within the domain of analysis and may not generalize to other domains). In a reaction to the North essay, Chang et al. [36] offer a distinction of insight at a higher conceptual level. They distinguish between insight as small bits of knowledge that build upon existing knowledge (e.g., the insights transmitted through visual communication from mapmaker to map user) and insight as spontaneous new cognitive structures, which explain patterns in new and existing bits of knowledge. The authors describe the difference as *knowledge-based insight* and *spontaneous insight* respectively. Chang et al. argue that the successful application of visual analytics (and so perhaps cartographic interaction as well) must support generation of both types of insights. Research is needed to understand if and how cartographic interaction can promote both knowledge-based and spontaneous insights about geographic phenomena, as well as if and how cartographic interaction can improve the complexity, depth, quality, novelty (unexpectedness), and relevance of geographic insights.

It is quite likely that cartographic interaction, and the visual thinking it supports, has value beyond the exploratory stage of science. Dix and Ellis [60] even go as far as to say that "virtually any existing static representation can be made more powerful by adding interactivity," although evidence suggests this may not always be true, as described under the *when?* question. Returning to the swoopy diagram (Figure 5), subsequent scholars have suggested the utility of cartographic interaction for confirming empirical and model-based analyses [11, 101, 175], for synthesizing analytical results into coherent arguments [223,225,247], and for presenting results to academic and public communities [69,166,240]. The goal of presentation is related to the extent of *interactive cartography* outlined in Figure 2d and includes interactive maps focused on visual storytelling, such as digital atlases, interactive news maps, and a large proportion of map mash-ups. In these situations, does the purpose of cartographic interaction remain visual thinking and insight generation, or does cartographic interaction provide something entirely different? Are the activities of visual thinking and visual communication actually diametrically opposed? Does cartographic interaction equally support the goals of exploration, confirmation, synthesis, and presentation? Does variation in the user goal impact cartographic interaction design and use guidelines? Additional questions arise when considering cartographic interaction for purposes other than support of the mission of science, as many cartographic interaction techniques developed to enable science now are applied commonly to support practical goals in a variety of domains. For example, applications of *geovisual analytics* (the subset of visual analytics focused on geographic information, Figure 2f) is concerned with the process of *sensemaking*, or the collection, exploration, evaluation, and presentation of evidence in order to make an informed decision about the proper course of action [4,197]. Does cartographic interaction serve a different purpose when implemented in such sensemaking tools or other spatial decision support systems? Does an emphasis on practical decision-making over scientific investigation impact cartographic interaction design and use guidelines? Finally, does cartographic interaction support efforts in *critical cartography* (Figure 2c) and how does critical cartography inform what we should and should not be doing with cartographic interfaces, whether employed for interactive cartography, geovisualization, or geovisual analytics [51,74,76,252,292,300]?

A final issue regarding the *why?* question of cartographic interaction deals with a fundamental cartographic concern: the uncertainties that are inherent to all geographic information and therefore the cartographic representations of these information [50, 172]. The process of externalizing geographic knowledge into a single cartographic representation for the purpose of visual communication necessarily requires the mapmaker to abstract their mental model of reality, which itself is already an abstraction of reality. In completing this process, the mapmaker omits information from the page that may be needed for a comprehensive understanding of the geographic phenomenon or process for the sake of clarity. This is the *cartographic problematic*: when abstracting reality (and one's knowledge of reality) to make a cartographic representation understandable and useful, uncertainty is introduced into the cartographic representation [211, 235]. One potential way to overcome the cartographic problematic—and perhaps even to operationalize the numerous uncertainties inherent to cartographic representations for informed decision making—is through cartographic interaction [126, 204]. Such an application of cartographic interaction relates to emerging research on *multiscale mapping*, or the provision of integrated cartographic representations at many-to-all map scales [23, 239]. In the context of multiscale mapping, cartographic interaction is employed to change the map scale and associated

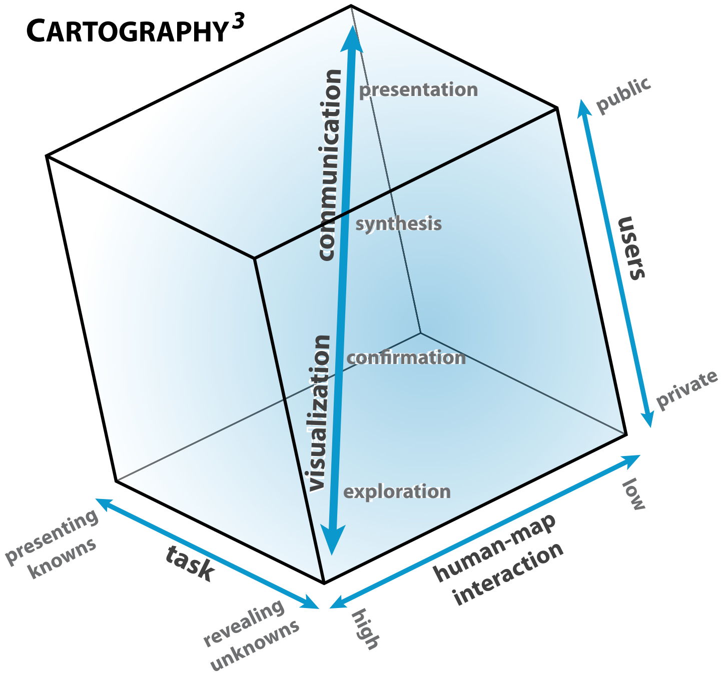

Figure 6: Cartography cube. Visual thinking is best supported through high levels of human-map interaction. Figure redrawn from MacEachren [156].

level of information detail, effectively overcoming the cartographic problematic. Such application of cartographic interaction differs from the aforementioned goal of exploration, with the purpose of revealing unknown insights about the geographic phenomenon. It is possible that interactive, multiscale mapping is changing the relationship of abstraction and cartographic representation altogether, thus resolving the cartographic problematic.

4 When should cartographic interaction be provided?

The above discussion indicates that cartographic interaction adds value for exploratory geovisualization, and perhaps beyond. However, this does not mean that every map, or even most maps, should be interactive. Going a step further, it is necessary to examine the times that cartographic interaction positively supports work, and therefore should be provided (i.e., the *when?*, Table 1). The cartography cube schematic (Figure 6) represents cartographic interaction as a continuum from low to high, with higher levels deemed necessary for geovisualization [156]. This perspective on cartographic interaction has led to the development of many geovisualization *toolkits* that allow users to combine a variety of cartographic representations and cartographic interactions [20, 38, 68, 80, 109, 133, 269, 286]. Such a toolkit may even suggest possible interactions to the users [205], demonstrating the mutual agency of the map and human. While an extensible, component-based approach to cartographic interface development is valuable because it allows for the integration of novel interaction techniques as they are conceived, this approach also implicitly subscribes to the notion that more functionality is better. Following this logic, the answer to the question of *when?* may be "always!"

While it is likely that increasing the level of interactivity improves the utility of a broadly-purposed application, there is growing evidence that interaction may act to inhibit the completion of some tasks. This is true not only of the number of interaction operators implemented in a system, but also of the degrees of freedom available for performing each interaction operator. The term *interface complexity* describes the combination of the number of cartographic interaction operators implemented in a cartographic interface (i.e., *scope*) and the precision (i.e., *freedom*) in performing each provided operator [115]. Complex interfaces allow users to perform alternative sequences of cartographic interaction operators to complete the same task, a concept described as *interface flexibility* [48, 240]. Much of the early research on complexity and flexibility was motivated by the *productivity paradox*, a critique on the immense investment in computing technology in the workplace during the early stages of the digital revolution, because, at the time, the investment had led to only marginal increases in worker productivity [105, 150]. As a result, researchers and developers began to investigate the ways in which flexible interaction could be constrained in order to optimize interaction workflows (i.e., to permit only a small set of possible interaction strategies) and to increase productivity. This design philosophy became known as *Taylorism* after its early proponent in mechanical engineering, Frederick Winslow Taylor [141], and, when applied to the design of digital interfaces, forces all users to perform the same, "best" interaction strategy in order to achieve an objective [2]. There are at least four empirical studies relevant to cartography that indicate a need for increased *interface constraint*, or a reduction to the number of cartographic interaction operators and/or the degree of freedom in performing these operators.

Davies [55] describes a participant observation study first reported by Davies and Medyckyj-Scott [57] in which GIS analysts working in a range of application domains were videotaped while completing their daily work. A coding scheme was developed for qualitative data analysis using Whitefield et al.'s [291] distinction between work and enabling actions. *Work (inter)actions* include those interactions that accomplish the desired goal, while *enabling (inter)actions* include those interactions required to prepare for, or clean up from, work actions. From a productivity perspective, it can be assumed that enabling interactions should be eliminated where possible and that interaction strategies consisting primarily of work interactions should be promoted. Davies found that no participant spent more than 30% of their time on actual work interactions with the GIS, with most participants spending approximately 10-20% of their time performing work interactions.

Keehner et al. [139] describe a series of controlled experiments requiring participants to draw the shape of a cross section produced by splitting a three-dimensional shape with a two-dimensional plane. Completion of the task was facilitated by navigating to the optimal visual isomorph, which was the viewpoint showing the intersecting plane at nadir. Advantages of interactivity that were found in an initial experiment were no longer found in a follow-up *yolked* experiment in which the "non-interactive" experimental group of participants was shown non-interactive video recordings of the interactions from the "interactive" experimental group. The experimental findings suggest that interaction is only helpful when it leads to presentation of task-critical information (i.e., the optimal visual isomorph), leading the authors to make their titular declaration that "What matters is what you see, not whether you interact."

Jones et al. [136] describe an informal, discount workshop evaluation in which a small team of targeted end users of a suburban profiling application were videotaped during an initial session with the system. The cartographic interface was informed by Buxton's [28] "less-is-more approach" to interface design, with the authors arguing for the application of Philbruck's [210] *simplicity principle* (i.e., design parsimony or an economy of design) for cartographic interaction as well as cartographic representation. The less-is-more approach was considered successful, as the video recording revealed that participants were "on task" (i.e., discussing map patterns) for 71% of the time, a sharp contrast to the Davies [55] study (although Jones et al. did not explicitly code for work versus enabling interactions).

Recently, Dou et al. [63] examined the importance of interaction constraint in a spatial problem solving experiment using the number scramble card game, in which two players alternate in drawing from a set of nine cards marked ace (i.e., one) through nine, with the goal of obtaining three cards that add up to fifteen. The number scramble problem is simplified greatly once identifying the optimal visual isomorph, a three-by-three spatial arrangement of the numbers called the *magic square* (Figure 7). The experimental groups' performance on the task varied according to the materials they were provided for strategizing prior to the game, with materials varying in the constraint they imposed in suggesting the magic square solution. Interaction constraint had a significant positive impact on the likelihood of identifying the optimal visual isomorph and on performance in the number scramble game. However, constraint on interaction impeded response time (i.e., it took longer for participants in the most constrained groupings to respond), a finding that surprised the authors. These results led the authors to conclude that "complete freedom of interaction may make problem-solving more difficult."

This set of studies indicates that provision of increased levels of cartographic interaction does not always add value to the cartographic representation, requiring further research aimed at delineating map use scenarios that are better supported by static maps from those requiring increased cartographic interface complexity. The above set of studies appears to be particularly relevant for interactive cartography and its emphasis on presentation over exploration. However, there may be situations within interactive cartography when the provision of interaction is justified. For instance, cartographic interaction can allow the user to customize the communicated message to his or her particular context and interests (see the discussion on adaptive cartography under the *who?* question). Further, cartographic interaction may allow the user to overcome the cartographic problematic—as introduced in the above review of the *why?* question—allowing for communication of additional details once the overview is first understood. Finally, digital cartographic interaction arguably empowers the user in a manner different than the use of analog maps, giving the user a sense of control over the experience and thus increasing his or her motivation to study the map (see the review of the *who?* question for more details). More research is needed regarding if and how cartographic interaction supports the goal of presentation, particularly given the growing popularity of web map mash-ups that support a basic set of interaction operators (i.e., the *slippy* map).

Recommendations for increased interface constraint must be questioned in the context of exploratory geovisualization, as such toolkits are designed to support tasks that are loosely-defined, open-ended, and highly iterative. It is not possible to define one, optimal interaction strategy that generates one, optimal visual isomorph, as the goal of geovisualization is to complete analytical work that never before has been done (i.e., to reveal previously unknown insights). What, then, does "task-critical information" mean in the context

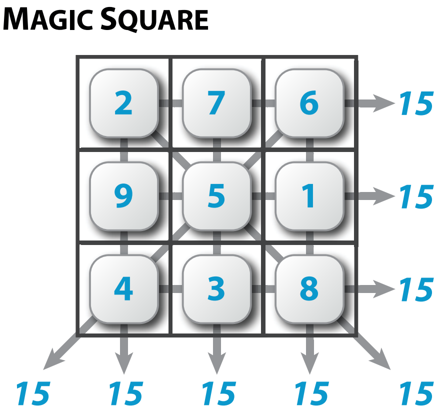

Figure 7: The magic square visual iomorph. The magic square is an optimal visual isomorph for solving the number scramble game. Once a tile has been selected, the magic square prescribes which other tiles can be taken to produce a sum of 15. Figure redrawn from Dou et al. [63].

of exploratory geovisualization? Can such task-critical information only be identified after exploration has been completed, or can the toolkit suggest potentially important information during exploration? Is the delineation between work and enabling interactions—and therefore the concept of productivity generally—even relevant when considering exploratory geovisualization? Do enabling operators act to improve the experience of cartographic interaction, if not the productivity with the cartographic interface? Further, are the concepts of work and productivity even relevant in the context of interactive cartography, with the presentation of interactive maps often for the purpose of entertainment? Finally, at what point does increased constraint or increased flexibility stifle visual thinking? To respond to Keehner et al. [139], while it definitely matters what you see, it might be that you do not know what you need to see until you begin to interact, at least in the context of exploratory geovisualization. Thus, the appropriate question for geovisualization likely is *how much?* rather than *when*?

5 Who should be provided cartographic interaction?

Individual users vary greatly in the cartographic interaction strategies they apply to complete a given task [177]. The review of the *when?* question attributes this variation primarily to the cartographic interface component of the interaction conversation. Under this *interface-centered perspective* (Figure 3c), the primary way to improve the cartographic interaction is to reduce the interface complexity, thus preventing suboptimal interaction strategies. However, even when interaction is constrained considerably, a large amount of difference still is observed in cartographic interaction strategies across users [55, 139]. It is possible that much of this variation in performance instead can be explained by individual user differences [263]. Thus, it is important to investigate the types of users provided cartographic interaction and the way in which differences across users impacts interaction strategies and interface designs (i.e., the *who?*, Table 1).

Understanding the characteristics of the targeted set of end users falls in line with a *user-centered perspective* of cartographic interaction (Figure 3a), which attempts to improve cartographic interaction by designing for anticipated user differences, rather than forcing all users to complete the same interaction strategy. Accounting for the variation across users during cartographic interface design and development aligns with the concept of *universal usability*, or the provision of flexible interfaces that work for a diverse range of users [34,214, 240]. Therefore, the degree to which the provided cartographic interface can be constrained is a function of how well the user tasks can be defined and how homogeneous the user group is expected to be. Knowledge of both conditions can be acquired through early and active input from targeted end users, a process often referred to as *user-centered design* [200]. User-centered design is becoming increasingly popular in cartography [21, 27, 85, 86, 105, 106, 123, 228, 245, 262, 273]. Rather than repeat these efforts to transition the tenets of user-centered design to cartography, the following review of the *who?* question identifies three user characteristics that impact the quality of cartographic interactions and thus need to be considered during user-centered design: ability, expertise, and motivation.

The primary map user characteristic of concern during the aforementioned Robinson-era of cartography was *ability*, emphasizing the perceptual and cognitive limits of the average map user. It might be argued that the possibility of cartographic interaction reduces the need for perceptual and cognitive research on map use, as the cartographic representation is no longer a one-shot chance at delivering an intended message. It allows users to (inter)act like themselves, rather than to conform to the average user. There is a growing body of research and development falling under the heading of *adaptive cartography* that is concerned with allowing users to customize the mapping system according to their abilities and preferences, in addition to allowing the computing device to customize the system according to changes in the mapping context [84, 132, 145, 217, 218, 299]. Despite the potential of adaptive cartography, it is likely that the introduction of cartographic interaction poses new challenges in designing for human ability, perhaps with a greater emphasis on cognition than in the past given the focus on visual thinking [163]. Further, cartographic interaction also requires consideration of motor skills to make use of keying or pointing input devices (see the review of the *where?* question) [13]. *Fitt's law* [82], a predictive model of the time it takes the average user to point to a screen object, provides initial insight about how the design of cartographic interfaces may be influenced by knowledge about motor skills.

MacEachren and Ganter [168] provide an overarching, guiding framework for investigating the relationship between user ability and cartographic representation, integrating perception, cognition, and motor skills. The authors propose a *pattern-matching model* of visual thinking (Figure 8), later clarified by MacEachren [157] under the heading of feature-identification. The model includes two main stages: a blended perceptual-cognitive stage of *seeing-that*, or recognizing previously known patterns and noticing unexpected ones, and a cognitive stage of *reasoning-why*, or evaluating the viewed patterns and integrating them into existing knowledge schema. Importantly, seeing-that and reasoning-why are mediated by a stage of action, or *interacting-with*, which is conducted mentally when given a single, static cartographic representation. As described above, this mental action can be offloaded onto the cartographic representation through cartographic interaction [250], making visual thinking a highly iterative process composed of seeing the cartographic representation (perception), interacting with the cartographic representation to change it (motor skills), and thinking about the newly created cartographic representation (cognition). Importantly, MacEachren and Ganter's pattern-seeking model can be superimposed upon Norman's [200] stages of action model, providing insight into the kind of scientific experiment required given the stage of interaction under investigation (Figure 4). However, research into the impact of user ability on cartographic interaction remains in its infancy, with few studies including pre-tests to measure individual abilities and therefore stratifying results across differences in these abilities. Further, there is limited research proposing successful strategies to account for variation in user abilities during cartographic interaction design.

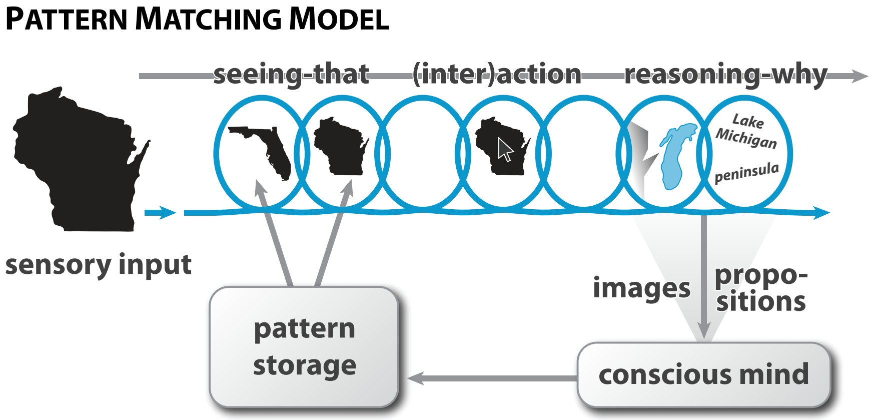

Figure 8: A pattern-matching model for visual thinking. The pattern matching model considers visual thinking as a process in which sensory input iteratively is compared against and integrated with existing knowledge schema. The model identifies three user abilities important to visual thinking: perception (sensory input and seeing-that), motor skills (interacting-with), and cognition (reasoning-why). Figure modified from MacEachren and Ganter [168].

One aspect of user ability receiving considerable attention in the broader GIScience literature is spatial thinking, defined as the skills needed to think geographically [93]. Spatial thinking, while primarily an aspect of cognition, also is related to physical (e.g., equilibrium and balance) and perceptual abilities (e.g., depth perception). It currently is unclear how differences in spatial thinking abilities impact cartographic interaction strategies and cartographic interface designs. On one hand, spatially able users are more likely to make use of cartographic interface designs based upon metaphors of analog interactions [56]. On the other hand, users with less developed spatial thinking abilities are less likely to be able to hold complex spatial concepts in their head, and therefore may be more dependent upon externalizing their spatial thinking through cartographic interaction [64]. Further, spatially less able users may get lost more easily when navigating an interactive map, requiring additional orientation cues in the cartographic representation and additional map browsing interactions to navigate the representation [116,282]. Spatial thinking, like many aspects of perception, cognition, and motor skills, also may be dependent upon other user characteristics, such as age [17,120,176], gender [193,253,254], and possibly culture [42]. Inclusion of spatial ability tests [122] as part of experimental design may allow for understanding the impact of spatial thinking on cartographic interaction strategies and cartographic interface designs; which spatial ability tests are best suited in the context of cartographic interaction remains an open question.

A second influential user trait on cartographic interaction is *expertise*, which emphasizes the importance of learned knowledge and skills to enhance and extend one's innate abilities. The characteristic of user expertise is implicit to the cartography cube framework (Figure 6). The "user" dimension of cartography was relabeled subsequently as public versus specialist by MacEachren et al. [167], with a recommendation that specialists (i.e., experts) be provided with a higher level of cartographic interaction. Expertise is a multifaceted concept and is best conceptualized as a set of continua that vary from novice to expert, rather than a single binary with two discrete states. Definitions of expertise in the context of cartographic representation include the amount of formal education or training on making and/or using maps [77], the amount of professional experience one has making and/or using maps [125,143], and the self-reported degree of familiarity with maps generally [1]. Further, there are various kinds of expertise that may be relevant to cartographic interaction, including general map reading, use of computing devices and other digital technologies, and knowledge of important domain concepts or analytical methods [234, 236].

McGuinness and colleagues [181, 182] completed important early work on the impact of expertise on cartographic interaction in a think aloud study using ArcInfo that included an "expert" and a "novice" experimental group. Drawing from work on expertise in cognitive science [37, 72, 151], the authors expected experts to demonstrate superior pattern-matching ability (Figure 8). In other words, the authors proposed that the abilities needed for visual thinking are less innate than learned, with a direct dependency on user expertise. Interestingly, experts did not exhibit significant in the quantitative interaction metrics collected during the experiment, such as time to complete tasks or number of maps plotted. However, analysis of the verbal externalizations revealed that the experts were engaging with the system at a higher level, resulting in generation of a deeper and more complex set of insights from the system. It would be interesting to see if similar results would be attained with expert and novice users today, as both groups are now more familiar with digitally-native interaction. Yet, subsequent research examining the impact of expertise on cartographic interaction is limited [99], with the few reported studies on expertise designed to improve usage of a single cartographic interface [114, 142, 264]. Therefore, many of the research questions identified by McGuinness [181] remain open:

> Why is expertise important? It may seem an obvious prediction to make that experts are likely to be better than novices at a given task—they know more. But does this difference always affect performance? If not, when does it? When experts view or interact with a single display or a sequence of displays, do they extract the same information as novices do? Do they follow the same solution steps as novices or less experienced people? In terms of cognitive organization, we can ask whether the experts' mental representation of the task and their solution processes are similar to those of novices. Additional questions center on the development and training of expertise. How is expertise acquired? Through what stages does it proceed? How does education and training impact on its development? Can support aids and tools affect how expertise is exercised?

There is a growing body of research in cartography seeking to bridge the expert-novice divide through cartographic interfaces. One solution is provision of a *multi-layered interface* [137, 191] exhibiting a *cascading information-to-interface ratio* in which each increased level supplies the user with additional interface complexity without changing the underlying information complexity [115, 240]. A common example is inclusion of a "regular" versus "expert" mode within an application. An alternative strategy for bridging the expert-novice divide is to provide users with process-oriented training or help materials, essentially improving the cartographic interaction by improving the user's knowledge of interactive maps or domain concepts [229,242]. A third solution is development of an *intelligent visualization*, or an expert system that leverages the cartographic and domain knowledge that otherwise may be available only as training and help materials in order to present context-appropriate representation and interaction solutions [5,6]. A final solution for spanning the expert-novice divide is provision of a *map brewer*, or a cartographic design support system that recommends a subset of appropriate representation (or possibly interaction) design solutions based upon expert knowledge, allowing the user then to select their preferred choice from the subset [22, 112, 241, 251, 256, 268]. Intelligent visualizations and map brewers are particularly useful in the context of the democratization of cartography [232, 295] and neogeography [277], as the map user is also the mapmaker and may not have the necessary expertise to make informative mash-ups that appropriately combine cartographic representations and cartographic interactions, even if he or she has an understanding of the mapped information. Future research is needed to examine the relative effectiveness of these strategies to improve or account for user expertise.

A third user characteristic requiring consideration is *motivation*, or the desire one has to use the cartographic interface either out of necessity (i.e., to complete a work task) or out of interest (e.g., curiosity, entertainment, popularity, recommendation) [97]. Motivation differs from expertise in that users with low levels of motivation are not necessarily incapable of using a complex cartographic interface, they simply do not wish to do so. Motivation, when high, is a user characteristic that plays to the advantage of cartographic interface designers and developers, as it inspires users to overcome barriers to using a system [240]. While user preference and satisfaction do not always result in effective and efficient interactions, there is growing evidence that users are more likely to be successful with interfaces that they like and thus want to use [201]. User motivation therefore should be cultivated whenever possible to promote both initial use (e.g., offering incentives, demonstrating utility through real world examples) and continued use of a cartographic interface (e.g., rewarding positive interaction strategies, offering easy ways to correct mistakes) [199]. In contrast, low levels of user motivation work against cartographic interface designers and developers, as individuals with no need or no interest in using a cartographic interface are unlikely to take the time to learn complex interfaces, even if they easily can do so because of past experience or training. Therefore, successful cartographic interaction may be contingent upon the relationship between interface complexity and user motivation, not user expertise (Figure 9) [117,240]. User motivation has important implications not just for the design of cartographic interfaces, but also the scientific investigation of cartographic interaction, as the promotion of motivation may act to improve the ecological validity of experimental results [237].

Finally, the prior review of the *who?* question assumes that the user is working alone, but how does the nature of cartographic interaction change when multiple users are interacting with the system? There is a growing body of work within cartography, falling under

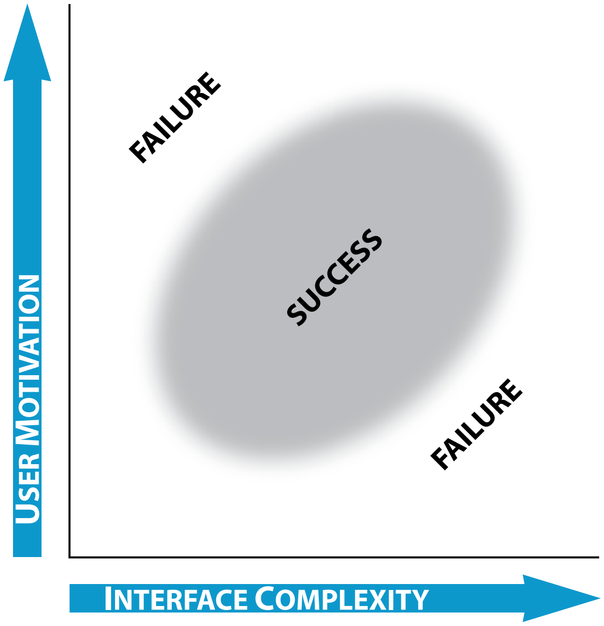

Figure 9: Interface complexity versus user motivation. The success of cartographic interaction is contingent upon the relationship between interface complexity and user motivation. Figure modified from Roth and Harrower [240].

the subfield of *geocollaboration*, that is focused upon the design and use of cartographic interfaces that support group activities [154, 158, 162]. This subfield draws upon relevant research from the field of computer supported cooperative work (CSCW), adopting two basic distinctions to inform the design of collaborative tools: (1) same-time (synchronous) versus different-time (asynchronous) collaboration and (2) same-place (face-to-face) versus different-place (distributed) collaboration [73]. Each time-place combination is likely to require unique cartographic interface solutions [103]. Further, there are three ways in which a map can support group work: (1) the use of the cartographic representation as the object of collaboration, (2) the use of the cartographic representation to support dialogue, and (3) the use of cartographic representation to support coordinated activity [160]. Does the purpose of the cartographic interaction change according to these different collaborative map uses? The possibility of geocollaborative interaction calls into question the underlying assumption of the swoopy diagram (Figure 5) and cartography cube (Figure 6) frameworks that visual thinking is a private activity. In particular, how can cartographic interaction promote visual thinking among a group of users to the end of better supporting discussion, deliberation, and consensus building [219, 220, 260]? Further, research on geocollaboration is related to the possibility of *role-based interaction*, or interface customization based on the user's duties on the collaborative team [46, 47, 283]. Does the potential for role-based cartographic interaction suggests the need to compensate for variation not only in user ability, expertise, and motivation, but also user responsibilities?

6 Where should cartographic interaction be provided?

The previous pair of sections accentuate that cartographic interaction is bounded by the cartographic interface providing the interaction and the map user performing the interaction. Emphasis on one component over the other is referred to as an interface-centered perspective (Figure 3c) versus a user-centered perspective (Figure 3a) of cartographic interaction respectively. There is a third component necessary to consider: the computing device through which cartographic interaction is provided and the limitations or constraints on cartographic interaction imposed by the device (i.e., the *where?*, Table 1). Emphasis on the computing device supporting the cartographic interaction is described as a *technology-centered perspective* (Figure 3b). There are three primary categories of technological considerations regarding cartographic interaction, each relating to different intersections in the cartographic interaction conversation (Figure 10): (1) input capabilities, (2) bandwidth size and processing power (together impacting system response time), and (3) display capabilities.

Input devices are the computing technology that allows the user to "speak" to the map (Figure 10a). Most personal computers support two kinds of input devices: keying (for the entry of long text strings) and pointing (for point-and-click direct manipulation operations). Although keying is a basic low-level interaction, most of the interaction research regarding information visualization and visual analytics emphasizes the implementation of pointing devices for manipulation of graphical user interface widgets or the visual representation itself. Traditional point devices include directional pads, joysticks, mice, touchpads, touch points, and trackballs, among others [259]. While past research has indicated that the mouse generally outperforms other pointing devices for two-dimensional representations [186], more recent research has shown that alternatives such as joysticks and gamepad controllers may be viable alternatives for virtual globes, digital block diagrams, and even two-dimensional representations [287]. Touch screens and multitouch screens are an intriguing pointing solution for cartographic interaction, as they unite the input with the display to produce a more congruent metaphor to real-world interaction [290]. Touch and multitouch screens are particularly useful for handheld mobile devices, where an external pointing device is impractical, and geocollaborative work, where many people need to be interacting with the same cartographic representation at once. However, they lack the ability to implement a highlighting mode when probing, a common solution for coordinated, multiview visualization [227]. Additional research is needed to determine the degree to which cartographic interaction is impacted by variation in these devices, as well as to determine if keying and pointing input devices are better purposed for different kinds of cartographic interactions. Finally, research also has been completed on multimodal interfaces—a possible third kind or hybrid kind of input device—that allow text entry and selection through voice commands, device-less gesturing, and eye-tracking [29, 164, 165, 255]. While multimodal interfaces hold much promise given the natural interaction metaphor, they suffer from the Midas touch problem, in which the cartographic interface attempts to assign meaning to verbalizations or gestures that are meaningless [131]. Possible interface design alternatives for combating the Midas touch problem have been offered in more recent research [35, 130].

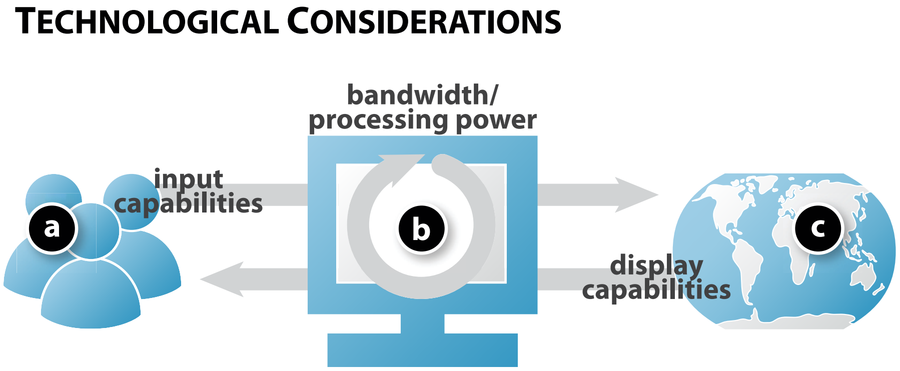

Figure 10: Technology considerations. Issues regarding a technology-centered perspective of cartographic interaction include device's input capabilities (a), bandwidth size/processing power (b), and display capabilities (c), each of which relate to a different component in the cartographic interaction conversation.

Bandwidth and processing are considered together because they determine the speed at which interaction occurs (Figure 10b). As reviewed under the *what?* question, the response time of an interactive system is essential to the experience of the cartographic interaction [185, 198], with instantaneous interactions needed to support fluid visual thinking [171]. Gahegan [87] refers to this as the "need for speed" and notes that delays in cartographic interaction can be caused by lags in processing the geographic information calculations and serving the updated cartographic representations. Although interaction response time generally improves as bandwidth and processing capabilities improve, advances in disk storage space are outpacing those in bandwidth and processing by an order of magnitude [259], resulting in a possible "catch-22" in which the state-of-art in bandwidth/processing always struggles to handle the largest available geographic information sets. This often is true in the context of *volunteered geographic information*, or the collection and maintenance of geographic information by citizens that are not acting in their professional capacity [75, 95, 96, 173, 301]. Thus, new strategies are needed to scale existing cartographic interactions to increasingly voluminous geographic information sets, volunteered or otherwise [4, 271]. The emergence of spatially-explicit parallel processing and cloud computing appear to be one solution for overcoming this "catch-22" in the age of big data [127, 128, 296]. The efficient processing, web delivery, and representation of voluminous and crowdsourced geographic information through cartographic interfaces remains a key research topic spanning all areas of cartography.

The final technological concern for cartographic interaction is the display capability, the computing technology that allows the map to "speak" to the user (Figure 10c). The visual display enables cartographic interaction by providing affordances and feedback [200]. *Visual affordances* are graphic signals to the user about how to interact with the interface, and are essential for specifying and executing an action (Figure 4, stages #3 and #4). In contrast, *visual feedback* describes graphic signals (including updates to the map itself) to the user about what happened as a result of the interaction, and is essential for perceiving and interpreting the state of the system (Figure 4, stages #5 and #6). Harrower et al. [113] identified three display characteristics that vary from screen to screen and that therefore affect cartographic representations and interactions: (1) screen resolution, (2) screen size, and (3) color depth. Characteristics that can be added to this listing include: (4) luminance capability, (5) refresh rate, (6) expected viewing distance, (7) display continuity (in the case of multiple screens linked together in display walls), (8) lighting conditions, and (9) portability [259]. All of these characteristics influence the amount and type of affordances and feedback provided to support cartographic interaction. It should be noted that multimodal interfaces may provide affordances and feedback through channels other than vision, such as sound [147] and haptics [98].

Designers and developers working professionally in interactive cartography and geovisualization necessarily spend a majority of their time engaging with the technological component of cartographic interaction (Figure 3b), with less time available for understanding user characteristics and needs (Figure 3a) or conceptualizing the user interface (Figure 3c). The focus on technology is appropriate from an applied perspective, as practitioners need to engage closely with the technology *de jour* to develop customized mapping solutions that provide the requisite set of cartographic interactions. A technology-centered view is less appropriate when considering the science of cartographic interaction, as it often leads to a scholastic *cul-de-sac* by which scholarly contributions exhibit an abbreviated shelf-life and offer little opportunity for extension. Technology is certain to evolve, and the ultimate objective of scientific cartographers is to establish theories and frameworks that are broadly applicable across technologies and that remain useful even after a set of technologies fades from use [187, 203, 206].

That said, major advances in technology do influence, or even inspire, new research lines within cartography. Two recent examples are the emergence of *mobile mapping*, or the provision of cartographic interfaces first on PDAs and wearable computers and now on smart phones and handheld tablets [44, 45, 195], and *location-based services*, or cartographic interfaces that leverage GPS technology to update the map with information tailored to the user's current location [88, 90, 134, 216]. Mapping on mobile devices presents a situation in which cartographic interaction is provided under extreme input, processing, and display constraints, requiring a rethinking of design conventions derived from desktop- or browser-based cartographic interfaces [26]. Can emerging research on responsive web design be used to customize representations and interactions for optimal mobile and desktop experiences? Further, the pervasiveness of mobile mapping and location-based services leads to new questions of cartographic ethics, particularly those surrounding privacy [292]. Despite these new technological opportunities and ethical concerns, the principles of cartographic interaction should persist, even if the cartographic interface solutions providing these interactions vary across technologies.

7 How should cartographic interaction be provided?

The five Ws of cartographic interaction outlined in the prior sections provide the context for designing or using an interactive map, map-based system, or map mash-up. After reviewing these considerations, it is possible to treat the cartographic interaction process itself, which includes the fundamental cartographic interaction primitives that are combined into broader interaction strategies and the design of cartographic interfaces that support these strategies by implementing the primitives (i.e., the *how?* question, Table 1). The *how?* question regarding the science of cartographic representation (Figure 2: green) was enlightened by the identification and articulation of the *visual variables*, or the fundamental dimensions across which a representation can be varied to convey information [16,30,155,194]. The visual variable framework allowed for development of a *syntactics* of cartographic representation, and all information graphics generally, prescribing feasible visual variable solutions based on the level of measurement of the encoded information [157]. Similar identification of a taxonomy of *interaction primitives*, or the fundamental units of an interaction that constitute an interaction exchange, is considered the "grand challenge" of a science of interaction broadly [271], and an important research topic for the science of cartographic interaction specifically [34,159].

There are an astounding number of efforts to identify and articulate the basic interaction primitives offered both in cartography and the related fields of human-computer interaction, information visualization, and visual analytics. In past work, Roth [238] found that extant taxonomies generally follow one of three approaches, with each approach aligning with a different stage of interaction (Figure 4): (1) an objective-based approach, (2) an operator-based approach, and (3) an operand-based approach. Each is summarized briefly below:

1. *Objective-based approaches* compartmentalize interaction according to different kinds of closed-ended user tasks, with taxonomies of objective primitives aligning with Norman's [200] forming the intention (Figure 4, stage #2) stage of action [3,8,18,53,174,288,289,297,298]. The most commonly included objective primitives are *identify* and *compare*, with more complex taxonomies typically discriminating within this pair of objective primitives [238].
2. *Operator-based approaches* compartmentalize interaction according to different kinds of generic interface tools provided in support of user objectives, with taxonomies of operator primitives aligning with Norman's [200] specifying the action (Figure 4, stage #3) stage of action [14,15,25,43,60,68,70,140,174,178,257,258,279,284]. The most commonly included operator primitives are *brushing*, *focusing*, and *linking*, although the definitions provided for these operator primitives vary across taxonomies [238]. Additional operator primitives generally fall into one of three categories: (1) those that change the map symbolization in some way, (2) those that change the user's viewpoint of the map, and (3) enabling operators. The exact set of operator primitives and the terminology used to describe these primitives vary widely across taxonomies.
3. *Operand-based approaches* compartmentalize interaction according to characteristics of the recipient of the interaction operator, with taxonomies of operand primitives aligning with what Norman [200] described as the "real world" or what is described in Figure 4 as "the map." Roth [238] found that operand primitive taxonomies focus either on the type of information that is being represented in the map [7,8,140,209,258,288] or the state in the information pipeline from data to display [40,41,43,102,284]. It is type-centric operand-based taxonomies that treat cartographic animation and time-series small multiples, as they expose differences in interaction within the *space*, *time*, and *attribute* operand primitives [7,8,209].

The fundamental interaction primitives are important for the science of cartographic interaction (like the visual variables for the science of cartographic representation) as they both inform experimental design and allow for synthesis of research insights into a single corpus. Such investigation also is important practically for identifying the appropriate amount of interface constraint (reviewed under the *when?* question), as it is essential to have an understanding of the complete cartographic interaction design space before knowing how best to select from that space to constrain interaction [21]. Cartographic interaction experiments therefore offer the potential of deriving a syntactics of cartographic interaction primitives, allowing for prescription of the design and use of cartographic interfaces [9, 71, 161, 223, 224, 237]. Much work remains in developing a formal syntactics of cartographic interaction primitives that directly informs cartographic interaction design and use. Is there a composite taxonomy of objective, operator, and operand primitives that can be established from the plethora of offerings summarized in Roth [238]? Can a composite taxonomy of interaction primitives be generated at each of the seven stages of interaction? Can the composite taxonomy be operationalized through cartographic interaction experiments to identify prototypically successful operator primitive strategies for a particular pairing of objective and operand primitives? Can the spatial component of interaction primitives that are explicitly cartographic be leveraged in some way to improve the interaction strategy [10,66,67,280]? Do users fall into one of several interaction strategy profiles, allowing for the design of adaptive cartographic interfaces that automatically refine the system once the interaction profile is identified? Are all cartographic interactions contingent on the broader interaction context (i.e., the five Ws of interaction)? Empirical investigation of cartographic interaction primitives is a promising way forward for answering these questions regarding the *how?* of cartographic interaction.

While the cartographic interaction primitives—and a potential for a syntactics therein—are important from a scientific and practical perspective, much of the contemporary research on cartographic interaction focuses on the design and development of a single cartographic interface. Emphasis on interfaces before interactions was cautioned under review of the *what?* question above [13]. However, insights into the development of cartographic interfaces remains important to the overall success of the cartographic interaction. Although variation in terminology varies across scholars, a cartographic interface generally exhibits three distinct characteristics that altogether define how it can be used, the actions it performs, and its general look and feel: (1) the cartographic interaction it supports (i.e., the combined objectives, operators, and operands, as described above); (2) its *interface style*, or the way in which user input is submitted to the software to perform the interaction operator [259]; and (3) its *interface design*, or the graphics, sounds, haptics, etc., that constitute the interface widget and its feedback mechanism [48].

The distinction among cartographic interaction, interface style, and interface design is related to two frameworks within geovisualization concerning "levels" of cartographic interface design (Figure 11). Lindholm and Sarjakoski [152] make the distinction among three "user interface levels": (1) the *conceptual level* (the goals of the cartographic interaction, the users included in the interaction conversation, the operands that are represented and manipulated, and the interaction metaphor used); (2) the *functional level* (the interaction operators provided by the cartographic interface and the interface styles used to implement the operators); and (3) the *appearance level* (the perceptible aspects of the cartographic interface that are presented to the user). Similarly, Howard and MacEachren [126] make the distinction among three "levels of analysis for geovisualization interface design": (1) the *conceptual* *level* (as defined by Lindholm and Sarjakoski); (2) the *operation level* (the operators provided in the cartographic interface to match the conceptual level goals and the operands that are represented and manipulated); and (3) the *implementation level* (the interface style and interface design together).

Designers and developers should consider the cartographic interaction, the interface style, and the interface design in sequence when conceptualizing and prototyping a cartographic interface. At the most abstract level is the cartographic interaction that the interface will support. This includes overarching consideration of the users, the technology, and the map itself (Figure 3). Specifically, it includes enumeration of the anticipated user goals and objectives, the associated operators that will be included in the cartographic interface to support these objectives, and the operands on which the operators will be applied. These use and user characteristics should be identified in the initial, needs assessment stage of a user-centered design approach [228]. Arguably, many cartographic interface failures are a result of improper consideration of the cartographic interaction characteristic, resulting in a cartographic interface that looks great and works well, but does not support the objectives of the intended end users [24].

Once parameters of the cartographic interaction are determined, an appropriate interface style is selected for each operator primitive. Operators rely upon one of five interface styles: (1) direct manipulation, (2) menu selection, (3) form fill-in, (4) command language, and (5) natural language [259]. *Direct manipulation* interfaces make use of pointing devices or gesturing to probe, drag, and adjust the graphics constituting an interface design. The "directness" of this interface form varies with regard to interfaces providing cartographic interaction: (1a) direct manipulation of the map features themselves (Figure 12a), (1b) direction manipulation of the map as a whole (Figure 12b), (1c) direct manipulation of a map legend that doubles as an interface widget (Figure 12c), (1d) direct manipulation of information elements in a second isomorphic view, producing coordinated highlighting of associated map features (Figure 12d), and (1e) direct manipulation of an interface widget that is not part of the map, but evokes changes to the cartographic representation (Figure 12e). Increasing the system dependence on highly direct interface styles has the advantage of increasing the information-to-interface ratio, considered an overarching positive by Harrower and Sheesley [115]. However, these methods often lack sufficient visual affordances to make them self-evident, meaning that novice users may be unaware that the functionality exists. Roth and Harrower [240] therefore recommend implementing the same cartographic operator using multiple interface styles, an approach that falls in line with the concept of interface flexibility reviewed under the *when?* question. A slightly less direct interface style is *menu selection*, allowing the user to select one or several items from a presented list (Figure 12f). The menu itself acts as a visual affordance, apprising users of all possible operator parameters.

Indirect methods make use of keying devices or voice recognition. The *form fill-in* interface style is less constrained than menu selection (Figure 12g), allowing the user to key in a set of characters that indicates the desired parameters for a single interaction, while the *command language* interface style increases interaction freedom by an additional order of magnitude (Figure 12h), allowing users to specify a series of interactions using a powerful, but more difficult to learn syntax of variables and functions. Finally, the *natural language* interface style mimics verbal communication between two humans, using complex ontologies and syntax rules to disambiguate the user input (Figure 12i). There is a large amount of research in human-computer interaction on relative advantages and disadvantages of

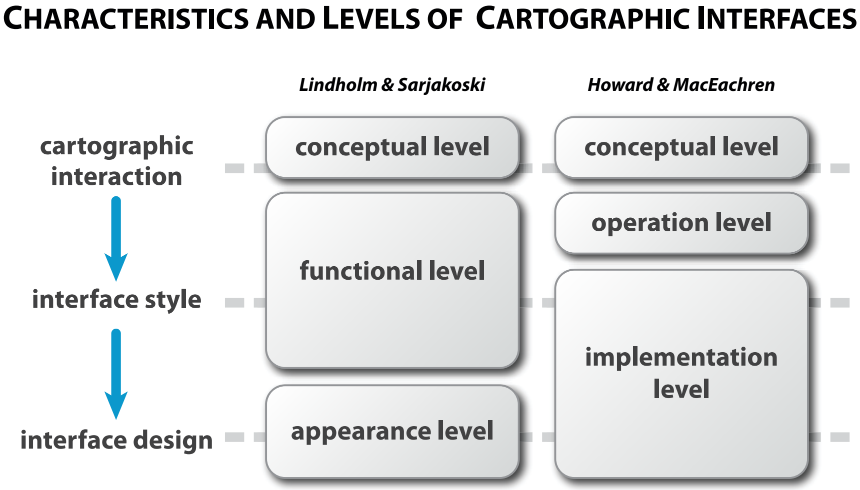

Figure 11: Characteristics and levels of cartographic interfaces. Cartographic interfaces exhibit three fundamental characteristics: (1) the cartographic interaction, (2) the interface style, and (3) the interface design. The Lindholm and Sarjakoski [152] and Howard and MacEachren [126] frameworks defining levels of cartographic interface design can be compared according to which interface characteristics are examined at each level.

the five basic interface styles. Shneiderman and Plaisant [259] provide a summary of these trade-offs in their textbook. However, there is limited research translating this insight to cartographic interaction. For instance, is the cartographic interaction impacted by variation in the provided interface style, both across the five basic interface styles and within the possible cartographic variants of direct manipulation offered in Figure 12. Can interface styles be matched with particular configurations of objective, operator, and operand primitives? Are there additional interface styles that are specific to cartographic interaction? Finally, is direct manipulation more appropriate for cartographic interaction, as suggested in Figure 12, or are there situations in which less direct or fully indirect interface styles are appropriate for cartographic interaction?

Once the interface style or styles are determined, the interface then can be designed. Cartographic interface design—much like traditional cartographic design focusing on representation—is an open-ended and highly creative process in which designers make *global design decisions* about the interface layout, application navigation, color scheme, fonts, etc., as well as *local design decisions* about the graphics, text phrasing, sounds, etc., of each interface element's visual affordances and feedback [48]. Cartographic interface design overlaps with traditional cartographic design (i.e., cartographic representation design), as the interaction may evoke changes to the overall representation form, the applied layer styling, and individual map symbol states. One example important to cartographic interfaces is the design of a resting versus highlighted symbol state for indicating selected or probed map features, an important topic for geovisualization as it relies on the coordination of user interactions across multiple visual isomorphs. Robinson and colleagues [100, 222, 226, 227] draw from literature on semiotics to describe the complete solution space for visually-enabled, coordinated highlighting across multiple isomorphic views. It is likely that core concepts from semiotics are equally informative for cartographic interaction as they are for cartographic representation, although there has been little reported work to make the connection. For an example applying semiotics to interface design broadly, see de Souza [266].

The topic of interface design in the field of human-computer interaction is discussed in terms of golden rules [259], guidelines [265], or heuristics [199] that inform, but do not prescribe, the look and feel of the interface. There is yet to be a consolidated set of design guidelines specific to cartographic interfaces. Instead, cartographic interface design appears to be gravitating towards the default solutions—both in terms of representation design and interaction design—provided through popular web mapping services. Such reliance on convention, while promoting learnability, often results in a *lorem ipsum map* (after *lorem ipsum* placeholder text), or a situation in which the map content is unrelated to or ungeneralized for the map purpose [240]. Future research is needed regarding the look and feel of cartographic interfaces. Are there broad categories of cartographic interface design techniques, such as the different thematic map types in cartographic representation? Is employment of these design techniques contingent on aspects of the cartographic interaction (i.e., the five Ws)? Are there any broadly applicable golden rules, guidelines, or heuristics that inform cartographic interface design? Can cartographic interface design draw from established design principles in representation, such as Philbruck's aforementioned simplicity principle [210] or Tufte's data-ink maximization [274]. What is the value added by customizing the look and feel of cartographic interfaces? Does this value outweigh the practical cost of customization? Can we learn as much from art as science regarding the aesthetics of cartographic interface design? This final topic regarding the *how?* question is addressed in the subsequent, concluding section.

8 Summary and outlook

This article provides a review of the current state of science regarding cartographic interaction. The content is organized into six key themes, each presented as a fundamental question facing the science of cartographic interaction. The *what?* and the *why?* questions establish the meaning of cartographic interaction and justify its significance to cartography, respectively. The *when?*, *who?*, and *where?* questions examine the three components of cartographic interaction identified in Figure 3 and the perspectives on cartographic interaction therein: (1) the map (an interface-centered perspective), (2) the human (a user-centered perspective), and (3) the computing device (a technology-centered perspective). The *how?* question illuminates the process of cartographic interaction, both in terms of the fundamental interaction primitives and the design of cartographic interfaces implementing these primitives. This review provides a snapshot of our current understanding of cartographic interaction (i.e., what we know). Further, the review reveals that there are many more open questions than conclusive answers regarding the science of cartographic interaction. Table 1 provides a summary of further research questions about cartographic interaction within each of these six fundamental questions (i.e., what we need to know). The Table 1 summary serves as a preliminary research agenda for cartographic interaction, requiring extension and modification as subsequent research is completed.

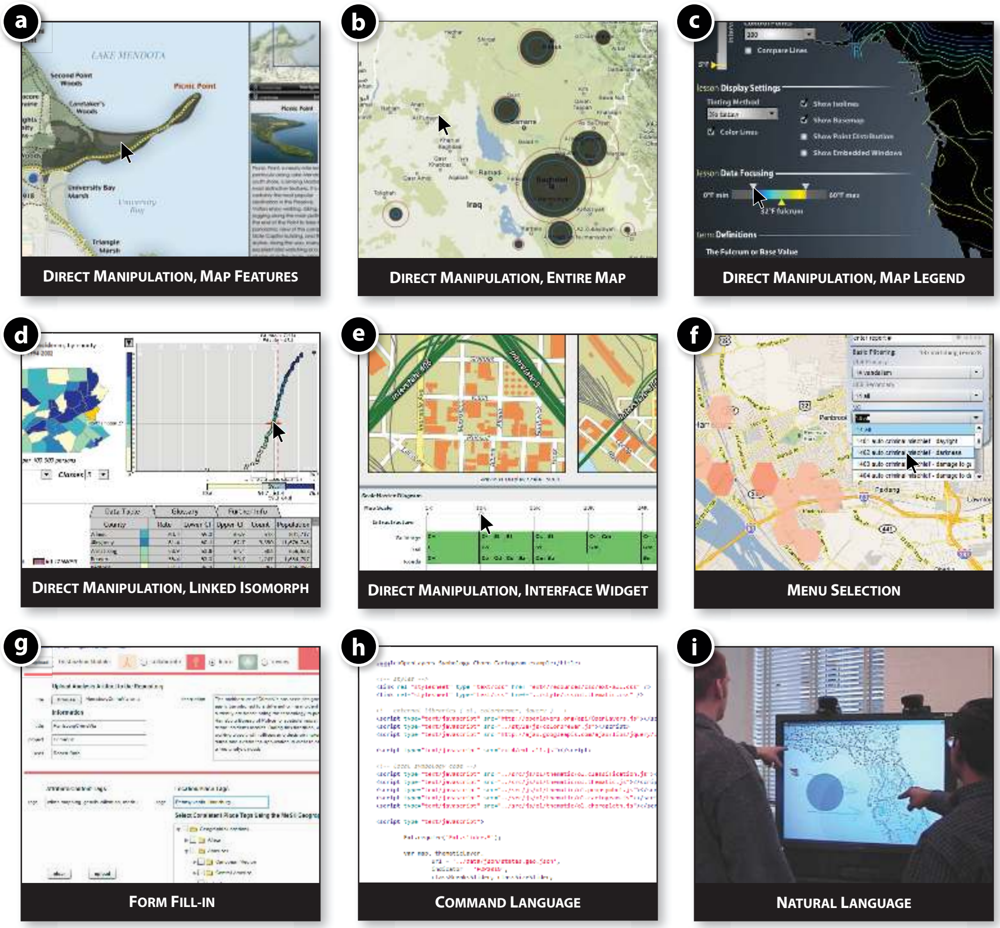

Figure 12: Cartographic interface styles. (a) Direct manipulation of a map feature in the Lakeshore Nature Preserve Interactive Map to retrieve details [246]. (b) Direct manipulation of the basemap in the Basic Ordnance Observational Management System (BOOMsys) to pan to a new location [197]. (c) Direct manipulation of the isoline colour ramp legend to filter the temperature range displayed in Isoline Engine [241],(d) Direct manipulation of a point in the Pennsylvania Cancer Atlas' cumulative frequency plot to retrieve details about the linked county [166,243]. (e) Direct manipulation of an interface widget to zoom to a new map scale in the ScaleMaster.org application [268]. (f) Using a set of hierarchical menus to filter the map by crime type and modus operandi in GeoVISTA CrimeViz [233, 245]. (g) Using a form fill-in interface to edit the metadata of an analysis artefact uploaded to the G-EX Portal [229, 242]. (g) An OpenLayers code library for thematic mapping provided by indiemaps [135]. (h) Using voice recognition natural language and gesture-based pointing in DAVE_G to annotate a map [29, 165].

Theme/Topic	*Definition/Research Questions*
What?	***the meaning of cartographic interaction in the context of cartographic research***
analog vs. digital	Are there differences between analog and digital cartographic interactions? To what degree can analog interactions inform the design of digital interactions?
interaction vs. interface	Is the experience of a cartographic interaction different from the implementation/use of cartographic interfaces? Are there considerations for user experience (UX) design unique to cartography?
stages of interaction	Are there basic components or stages of a cartographic interaction? Are there barriers or gulfs to this interaction exchange that are explicitly cartographic?
response time	Is the experience of a cartographic interaction dependent on a response time threshold? Can this threshold be overcome in the context of GIS and big data?
interactive maps vs. mapping systems	Does cartographic interaction differ in the context of an interactive map versus a map-based system? Does such a distinction impact cartographic interaction design and use guidelines?
map mashups	Does cartographic interaction differ in the context of map mashups or when the mapmaker is also the map user? Does such a distinction impact cartographic interaction design and use guidelines?
Why?	***the purpose of cartographic interaction and the value it provides***
visual thinking	Does cartographic interaction improve visual thinking? Is visual thinking diametrically opposed to visual communication?
geographic insight	Can cartographic interaction promote both knowledge-based and spontaneous geographic insight? How should cartographic interaction be provided to improve the complexity, depth, quality, novelty, and relevance of insights?
stages of science	Does cartographic interaction equally support the goals of exploration, confirmation, synthesis, and presentation? Does variation in the user goal impact cartographic interaction design and use guidelines?
decision making	Can cartographic interaction support and/or improve sensemaking and decision making? Does an emphasis on practical decision-making over scientific investigation impact cartographic interaction design and use guidelines?
research thrusts	Does cartographic interaction impact the research thrusts of geovisualization, interactive cartography, geovisual analytics, and critical cartography differently? Does its value vary across these research thrusts?
cartographic problematic	Is cartographic interaction a solution to the cartographic problematic? Is interactive, multiscale mapping changing the relationship of abstraction and cartographic representation?
When?	***the times that cartographic interaction positively supports work, and therefore should be provided***
static vs. interactive	Should cartographic interaction be provided for all maps? What map use scenarios are better supported by static maps?
interface complexity	What cartographic interaction considerations increase the complexity of a cartographic interface? What map use scenarios are better supported with increased interface complexity?
productivity paradox	Can cartographic interaction support work and improve productivity? Does what you see matter more than how you interact?
flexibility versus constraint	Does cartographic interaction improve with increased flexibility or increased constraint? At what point does increased constraint or increased flexibility stifle visual thinking?
work interactions	Is the meaning of work cartographic interactions dependent on the user's goal and/or context? What does work mean regarding geovisualization, with the goal of open exploration, or interactive cartography, with the presentation of interactive maps often for entertainment?
enabling interactions	Is the meaning of enabling cartographic interactions dependent on the user's goal and/or context? Do enabling interactions actually improve the experience of a cartographic interaction?

Table 1: The six fundamental questions of a science of cartographic interaction and an associated, preliminary research.

Who?	***the types of users provided cartographic interaction and the way in which differences across users impacts interaction strategies and interface designs***
user-centred design	Is variation in user performance with cartographic interfaces explained by individual user differences? Is designing for these user differences superior to enforcing consistent cartographic interaction strategies across users?
user ability	Is cartographic interaction impacted by variation in the user perceptual abilities, cognitive abilities, or motor skills? Are there successful strategies to account for variation in user abilities during cartographic interaction design?
spatial ability	Is cartographic interaction impacted by variation in the spatial thinking abilities of users? Is cartographic interaction more or less important for individuals with poor spatial thinking abilities?
user expertise	Is cartographic interaction impacted by variation in the user education, experience, or familiarity with maps, technology, domain concepts, or analytical methods? Are there successful strategies to improve user expertise or account for variation in user expertise?
user motivation	Is cartographic interaction impacted by variation in the user motivation in the interface? Are there successful strategies to promote user motivation?
adaptive cartography	Can cartographic interaction allow the user to adapt the representation and interface to his or her level of ability, expertise, and motivation? Does adaptability impact the recommended level of interface complexity?
geocollaboration	Does cartographic interaction differ in the context of single user versus multiple user interfaces? Is cartographic interaction impacted by variation in user roles or responsibilities?
Where?	***the computing device through which cartographic interaction is provided and the limitations or constraints on cartographic interaction imposed by the device***
input capabilities	Does cartographic interaction differ across input devices? Are keying and pointing input devices better purposed for different kinds of cartographic interactions?
bandwidth & processing power	Is the cartographic interaction experience impacted by variation in the bandwidth size and processing power? Can improvements in bandwidth/processing power meet increases in information volume, particularly in volunteered geographic information?
display capabilities	Does cartographic interaction differ across display devices? Can affordances and feedback be designed to work across display capabilities and through non-visual channels such as sound and haptics?
mobile mapping	Does cartographic interaction differ in the context of mobile mapping? Can responsive web design be used to customize mobile and desktop cartographic interaction experiences?
location-based services	Does cartographic interaction differ when provided as a location-based service? How is privacy impacted by mobile mapping and location-based services?
How?	***the fundamental cartographic interaction primitives and the design of cartographic interfaces that implement them***
interaction primitives	Are there fundamental units of an interaction that constitute an interaction exchange? Do primitives vary by objective, operator, and operand?
interaction primitive taxonomies	Can a composite taxonomy of objective, operator, and operand primitives be generated from existing offerings? Can a taxonomy of cartographic interaction primitives be generated at each of the seven stages of interaction?
syntactics	Is it possible to prescribe the design and use of a cartographic interface given the use and user context? Are there prototypically successful operator primitive strategies for different pairings of objective and operand primitives?
interface styles	Is cartographic interaction impacted by variation in the provided interface style? Are there interface styles specific to cartographic interaction?
direct manipulation	Is cartographic interaction impacted by variation in the directness of the provided interface style? Is direct manipulation more or less important for cartographic interaction?
interface design	Are there broadly applicable golden rules, guidelines, or heuristics that inform cartographic interface design? Can cartographic interface design draw from established design principles in cartographic representation?

Table 1 (continued): The six fundamental questions of a science of cartographic interaction and an associated, preliminary research.

So how do we to answer the six fundamental questions and approach this preliminary research agenda presented in Table 1? Science is emphasized throughout the review, paralleling broader efforts in information visualization and visual analytics to establish a science of interaction [212, 270]. As an outlook, it is necessary to reflect on additional approaches for generating insight within cartography, both for cartographic representation and cartographic interaction. Figure 13 presents a framework that integrates the diverse topics of study and methods of inquiry that constitute cartography. The Figure 13 framework draws a parallel to Sack's [248] relational framework that is used to characterize the field of geography as one that is intrinsically integrative. The relational framework leverages the concept of place, fundamental to the study of geography, as the central "loom" by which three bodies of knowledge (meaning, nature, and social relations) and three ways of knowing (the scientific, the aesthetic, and the moral) are woven into a single fabric. To use Heideggerian terminology, it characterizes its ontology (the concept of place), its ontics (the topics of meaning, nature, and social relations), and its epistemologies (the scientific, the aesthetic, and the moral).

The Figure 13 framework provides a similar philosophical foundation for cartography, integrating its ontologies, ontics, and epistemologies. The Figure 13 description of cartography pivots upon the map, much like geography pivots upon place. Cartography's *ontology*, or pursuit of the nature of being, is and always will be a question of the map itself. The cartographic ontology is one characterized by existentialism. Considering the radial categories illustrated in Figure 1, the properties that define existence may include degree of abstraction and map scale (for the case of the "analog map") or instead may include web dissemination and cartographic interaction (for the case of the "digital map"). The question "Is this a map?" defines how cartography is researched and practiced, as well as how maps are made and used. Therefore, it is upon the map where the cartographic ontics meet the cartographic epistemologies, where the bodies of cartographic knowledge meet the ways of constructing this knowledge.

Cartography's *ontics* describe the bodies of knowledge to which cartographers actively contribute and from which cartographers draw. The cartographic ontics include both continua in Figure 2, the first being the traditional distinction between mapmaking and map use and the second being the emergent distinction between cartographic representation and cartographic interaction (the latter end of the continuum being the focus of this review). The cartographic ontics clearly overlap, both within each continuum and across them. The overlap occurs at the map itself, as the map must draw from each of these bodies of knowledge to come into existence (Figure 13).

This pair of ontical continua is complemented with several *epistemologies*, or ways of knowing about mapmaking and map use as well as cartographic representation and cartographic interaction. The cartographic epistemologies intersect the cartographic ontics at the map, as it is through the generation and examination of maps that the epistemologies contribute to the ontics (Figure 13). Again, the emphasis of this review is on science, or the way of knowing through reason and empiricism. However, the *artistic* epistemology, or the way of knowing through aesthetics and emotion, remains critical to the discipline and arguably has a longer tradition within cartography. While relevant to all aspects of cartographic interaction, the artistic epistemology appears particularly informative for cartographic interface design, as reviewed under the *how?* question. Finally, the *ethical* epistemology, or way of knowing through equity and probity, is essential for understanding what is appropriate (i.e., what we ought to do), rather than what is functional (science) or beautiful (art).

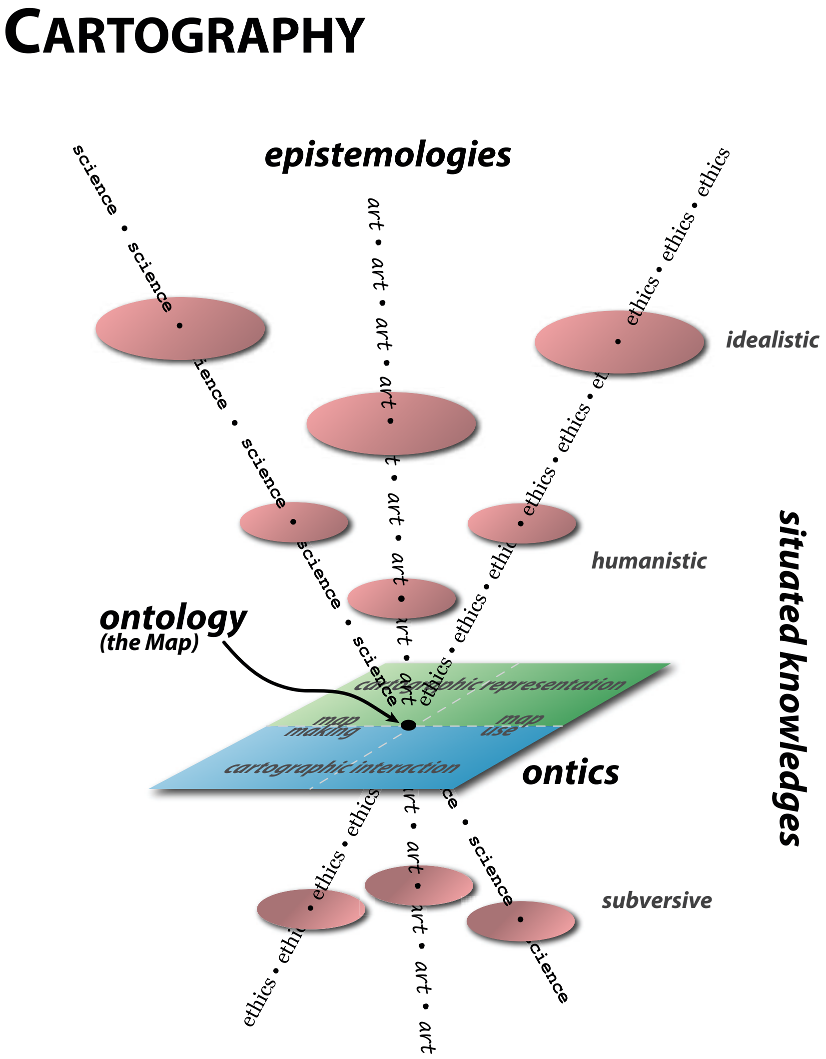

Figure 13: A comprehensive view of cartography. Cartography's ontology centers on the map. Its ontics include two important continua: (1) mapmaking versus map use (a traditional distinction in cartography) and (2) cartographic representation versus cartographic interaction (the latter end of the continuum being the focus of this review). This body of knowledge can be expanded through at least three epistemologies: (1) science, (2) art, and (3) ethics. Within these epistemologies, situated knowledges can be applied at three levels: (1) idealistic, (2) humanistic, and (3) subversive.

Monmonier's [189] argument for breaking from the one-map paradigm—among the first arguments in support of cartographic interaction—is one that is explicitly based on ethics. Further, ethics perhaps are the dominant cartographic epistemology employed for critical cartography, as such critique reveals power relations among mapping forms and practices to the end of ameliorating the deleterious impacts of privileged cartographies [110, 293].

Finally, it is important to remain cognizant of the cartographer himself or herself and the *situated knowledges*, or unique sets of cartographic and non-cartographic experiences, he or she leverages when generating or applying cartographic knowledge. Consideration of situated experiences (i.e., how maps become imbued with meaning) is a primary contribution of semiotics to cartographic representation [16, 157]. These situated knowledges position the cartographer differently with regard to their epistemology, adjusting the orientation of the cartographer in relation to the ontologies and ontics with which he or she is engaging. The *idealist* viewpoint is one that searches for generalized truths. Attempts to define the average map user, and thus produce an optimal map, is one example of such an endeavor. In contrast, the *humanistic* viewpoint is one that considers the unique conditions that contextualize mapmaking and map use as well as cartographic representation and interaction, and therefore is conceptually nearer to the map itself (as illustrated in Figure 13). The application of user-centered design perhaps is one example of a humanistic viewpoint regarding the scientific epistemology, as the emphasis is on design and development of a single cartographic interface to meet a single map use scenario and user group, rather than generating insights that are generalizable across all map uses and map users. Finally, the *subversive* viewpoint is one that is intentionally radical, using approaches and techniques counter to the status quo [54, 213], and therefore is conceptually beneath the surface of the cartographic ontics (as illustrated in Figure 13). Such a viewpoint may be dubious in motive, as with cartography's history of propaganda maps in support of political persuasion [196]. However, the subversion can (and thinking ethically, should) be productive, jarring map users from their preconceptions and allowing for generation of new insights regarding the represented geographic phenomenon [58].

In close, cartography is all of these things. It is a discipline ontologically aligned with the map. It is a discipline whose ontics comprise at least two bodies of knowledge, each defined by a central continuum. It is a discipline constructed by artistic, scientific, and ethical epistemologies. Finally, it is a discipline in which situated knowledges, or individual viewpoints, are influential on the generation and application of these cartographic ontologies, ontics, and epistemologies. The Figure 13 framework, and the research synthesized above, offer one possible way for organizing future research on cartographic interaction specifically, and for integrating these findings with research on cartography broadly.

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