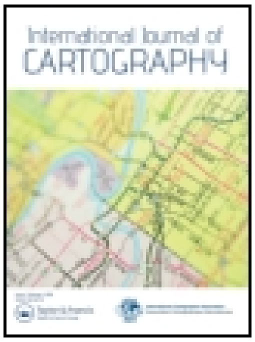

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User studies in cartography: opportunities for empirical research on interactive maps and visualizations

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ABSTRACT
The possibility of digital interactivity requires us to reenvision the map *reader* as the map *user*, and to address the perceptual, cognitive, cultural, and practical considerations that influence the user's experience with interactive maps and visualizations. In this article, we present an agenda for empirical research on this user and the interactive designs he or she employs. The research agenda is a result of a multi-stage discussion among international scholars facilitated by the International Cartographic Association that included an early round of position papers and two subsequent workshops to narrow into pressing themes and important research opportunities. The focus of our discussion is epistemological and reflects the wide interdisciplinary influences on user studies in cartography. The opportunities are presented as imperatives that cross basic research and user-centered design studies, and identify practical impediments to empirical research, emerging interdisciplinary recommendations to improve user studies, and key research needs specific to the study of interactive maps and visualizations.

RÉSUMÉ
La possibilité de l'interactivité numérique nous pousse à revoir le lecteur de cartes comme un utilisateur de cartes et à traiter les considérations perceptuelles, cognitives, culturelles et pratiques qui influencent l'expérience d'un utilisateur de cartes et de visualisations interactives. Dans cet article nous présentons un agenda de recherche empirique sur cet utilisateur et sur les conceptions interactives qu'il ou elle réalise. L'agenda de recherche proposé est le résultat d'une discussion en plusieurs étapes menée par des spécialistes internationaux, facilitée par l'association cartographique internationale selon un processus comprenant un premier ensemble de papiers de positions, suivi

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de deux ateliers dont les objectifs étaient de se concentrer autour de thèmes prioritaires et d'opportunités de recherche majeures. L'objet de la discussion était épistémologique et reflète les larges influences interdisciplinaires des études portant sur les utilisateurs en cartographie. Les opportunités sont présentées comme des impératifs qui associent les recherches fondamentales aux études de conception centrées utilisateurs. Elles permettent d'identifier les obstacles pratiques aux recherches empiriques, les recommandations interdisciplinaires émergeantes pour améliorer les études des utilisateurs et les besoins de recherche prioritaires spécifiques à l'étude des cartes et visualisations interactives.

1. Introduction: whither user studies in cartography?

The possibility of digital interactivity – the topic of this special issue – has fundamentally changed how maps are designed and used. While paper maps and static digital maps remain essential to cartographic research and practice, providing interactivity means that the map *reader* is no longer passive in the creation of the representation. Instead, the map is an interface to potentially boundless amounts of geographic information, and the map *user* is empowered to create a representation that best supports his or her use context (Muehlenhaus, 2013). The designer and user must meet at the interface to ensure a positive experience (Roth, 2013b). Efforts to understand and explain cartographic interaction date to at least the 1960s (Engelbart & English, 1968; Pivar, Fredkin, & Stommel, 1963), and the topic of interactivity was a recurring theme across the prior research agenda on geographic visualization organized by the International Cartographic Association (ICA) (e.g. Cartwright et al., 2001; Fairbairn, Andrienko, Andrienko, Buziek, & Dykes, 2001; Gahegan, Wachowicz, Harrower, & Rhyne, 2001; MacEachren & Kraak, 2001; Slocum et al., 2001). However, as interactive maps become pervasive in society, we as a scholarly and professional community still have many more questions than answers:

What makes an interactive map or visualization work? Interactive mapping services like Apple Maps, Google Maps, and OpenStreetMap are used by millions of people every day – a testament to their high level of usability and utility for achieving specific user goals. We can contrast their spectacular success with many of the interactive maps and visualizations reported in the scientific literature that languish on the servers of research institutions. Accordingly, a number of scholars have flagged the problem of low uptake of interactive mapping and visualization systems among target users (Andrienko & Andrienko, 2006; Lloyd, Dykes, & Radburn, 2007). Furthermore, tools and technology that have seen popular uptake make use of a small range of the interactive functionality available for maps and visualizations (see Roth, Donohue, Sack, Wallace, & Buckingham, 2014, for a survey). These problems persist despite the now numerous recommendations in cartography to follow a 'user-centered' approach to the development and evaluation of interactive maps and visualizations (e.g. Cartwright et al., 2001; Fuhrmann & Pike, 2005; Kveladze, Kraak, & Elzakker, 2013; Lloyd & Dykes, 2011; MacEachren & Kraak, 2001; Robinson, Chen, Lengerich, Meyer, & MacEachren, 2005; Roth, Ross, & MacEachren, 2015).

How do we know an interactive map or visualization works? As with cartography, there is increasing emphasis on user-centered evaluation in the related fields of information visualization and scientific visualization as the essential mechanism for determining whether an interactive design 'works' (e.g. Barkhuus & Rode, 2007; Borkin et al., 2011; Isenberg, Isenberg, Chen, Sedlmair, & Möller, 2013; Lam, Bertini, Isenberg, Plaisant, & Carpendale, 2012). But, which empirical methods should we use, and at what times during design? Greenberg and Buxton (2008) suggest that the wrong methods applied at the wrong time in a tool's development actually can be harmful to the design of the tool. In particular, they note that focusing on usability issues too early in the development of a tool might lead to 'getting the design right' at the expense of 'getting the right design' (Greenberg & Buxton, 2008, p. 115). By extension, too much attention to evaluating usability (rather than utility) may lead to low uptake among potential users (Landauer, 1995). If a tool is sufficiently useful, it will be used despite usability issues and user evaluations of these issues.

What are the roles of user studies for basic research and professional practice in cartography? Besides evaluations for usability engineering, user studies on perception and cognition deliver valuable insights into the design and use of interactive maps and visualizations (Montello, 2002; Virrantaus, Fairbairn, & Kraak, 2009). For basic research in cartography, empirical studies often are quantitative and controlled to investigate the influence of specific design and user factors on map use outcomes. However, few empirically-derived guidelines or time-tested best practices exist for the design and use of interactive maps and visualizations (Roth, 2013b), and even fewer recommendations exist for adapting empirical methods to the interactive context. We need to clarify the role of user studies for interactive cartography and visualization, and do so in a manner that is aware of their historical influences and broader politics so as to hybridize alternative epistemologies (Kwan, 2004; Ricker, Daniel, & Hedley, 2014).

In this article, we present a research agenda for user studies on interactive maps and visualizations. Because our focus is epistemological and not ontological, we take a wide definition of interactivity (e.g. slippy web maps, GIS software, mobile map apps, coordinated multiview visualizations, and neocartographic tools) to identify crosscutting opportunities for methodological contributions to interactive cartography (Table 1). The research agenda is a result of a multi-stage discussion among international scholars facilitated by

Table 1. Opportunities for empirical research on the design and use of interactive maps and visualizations.

Basic research on interactive maps and visualizations	
1.	Expand qualitative and mixed-method research to confirm and enrich quantitative research in cartography
2.	Improve consistency and detail in the reporting of method designs
3.	Promote purposeful sampling of study participants and limit convenience sampling
4.	Adopt new approaches to treat interactive, online, and mobile maps and visualizations as unique study materials
5.	Define and assess high-level, insight-based tasks to complement benchmark tasks in user studies
6.	Complement laboratory and online studies with field studies
Adapting methods for UCD studies	
7.	Establish gold standards for administering and assessing UCD studies on interactive maps and visualizations
8.	Streamline and contextualize the UCD process for interactive cartography and visualization
9.	Promote comprehensive UCD case studies
10.	Leverage UCD studies for participatory action research
11.	Conduct user-centered studies on the political economy of interactive cartography and visualization
Additional empirical needs in interactive cartography and visualization	
12.	Articulate dimensions of interface complexity in user studies
13.	Develop strategies to compare static and interactive maps
14.	Investigate the value of interactivity in new map use cases
15.	Evaluate non-cartographic and neocartographic interfaces supporting map design and production
16.	Evaluate mobile interactions
17.	Develop and integrate design guidelines for interaction and representation in cartography

the ICA that included an early round of position papers and two subsequent workshops to identify pressing themes and important research opportunities (Griffin, Robinson, & Roth, 2017). The set of opportunities include practical impediments to empirical research, emerging interdisciplinary recommendations to improve user studies, and key research needs specific to the study of interactive maps and visualizations. While our focus is on user studies investigating interactivity, many of the opportunities we present also apply to paper maps and static digital products, therefore addressing cartography as a whole.

We develop the research agenda in four sections. We start by reviewing interdisciplinary influences on empirical cartographic research as a way to expose what is 'special' about user studies of interactive maps and visualizations. We then identify epistemological opportunities related to basic scholarly research in interactive cartography and visualization. We subsequently discuss the adaptation of user studies for professional practice, outlining opportunities for user-centered design (UCD) studies. These sections build into treatment of research opportunities specific to the study of interactivity in cartography and visualization. We conclude by summarizing our proposed research agenda and presenting opportunities for concrete deliverables to support user studies in cartography.

2. Looking back to interdisciplinary influences on cartographic methods

Cartography has never been 'monodisciplinary'. For instance, cartographic design draws from the very different areas of applied mathematics (computer-assisted projections, simplification algorithms, vector and raster math, etc.; Tobler, 1976) and graphic design (clarity and legibility in symbolization, labeling, etc., to encode a message; Robinson & Petchenik, 1975). Furthermore, the topics approached by and methods used in cartographic research always have been calibrated to the evolution of the underlying technology available to make maps (Monmonier, 1985). This remains true today as cartography welcomes a new generation of tools and technologies that support the design and use of interactive, online, and mobile maps and visualizations (Roth et al., 2014). Arguably, the range and depth of influences on cartography from other disciplines has only increased as mapping technology has changed. Here we outline four interdisciplinary influences on the ways that user studies are designed in cartography, both to chart cartography's diverse epistemological origins and to question how interactive maps and visualizations are a unique subject of study and thus require unique methods.

Psychology

The past 75 years of empirical research in cartography have been heavily influenced by *psychology* (MacEachren, 1995; Robinson, 1952). Historically, cartography has intersected with psychology in two ways: we contribute insight on visuo-spatial perception and cognition to psychology, and we employ theoretical frameworks and controlled experimental methods developed in psychology to study maps (Montello, 2002; Olson, 1979). Regarding the former, there is a growing body of cartographic research reported in the psychology literature on spatial concepts (e.g. Liben & Downs, 1993; Wiener, Hölscher, Büchner, & Konieczny, 2012) and spatial abilities (e.g. Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). We also adopt concepts from psychological studies, for example, how visual attention directs map reading

(Carrasco, 2011) and leads to errors in map interpretation (Fish, Goldsberry, & Battersby, 2011), or how individual and group differences in visual and spatial abilities might affect map-use performance (McGuinness, 1994). Furthermore, the cartographic research thrust of geovisual analytics has renewed interest in user studies informed by psychology and the related areas of cognitive science and neuroscience (Andrienko et al., 2007; Thomas et al., 2005). For instance, the framework of distributed cognition, or the role of external artifacts as part of reasoning (Hollan, Hutchins, & Kirsh, 2000), has generated new ideas for the design of interactive maps and visualizations that support visual cognition (Liu & Stasko, 2010; MacEachren, 2015; Pohl, Smuc, & Mayr, 2012). Additionally, promising avenues of research include psychology-driven approaches to multimodal interaction and motor skills as applied to immersive visualizations (Çöltekin, Lokka, & Zahner, 2016; Edsall & Larson, 2009; MacEachren et al., 2005), augmented reality (Schmalstieg & Reitmayr, 2007), and holograms (Fuhrmann, Holzbach, & Black, 2015), as well as the use of these tools to simulate a real-world setting in psychology-driven experiments on spatial cognition and mobile map design (Lokka & Çöltekin, 2016; Loomis, Blascovich, & Beall, 1999).

However, there are several issues with directly transferring psychology concepts and techniques to cartography. In most psychological studies on spatial concepts, the visual stimuli are greatly simplified (e.g. restricted to a single map symbol design) to obtain maximum experimental control for establishing cause–effect relationships. However, user studies in cartography often require evaluation of complete, realistic map designs to improve ecological validity, possibly compromising the experimental control required in psychology (Montello & Sutton, 2013). Furthermore, psychology studies on perception and cognition offer limited insight into how maps become imbued with meaning, or become cultural artifacts with contested meanings. While new psychology-based approaches to studying affect and emotion will help us understand how maps make us feel (Fabrikant, Christophe, Papestefanou, & Maggi, 2013; Griffin & McQuoid, 2012), alternative approaches from art, historical cartography, linguistics, and social theory, among others, are needed to fully enrich discussion on how maps become meaningful.

Geography

A second, important influence is our disciplinary relationship with the phenomena and processes we map: *geography*. Bridging earth science, social science, information science, and the humanities, geography employs a wide range of methods, including both quantitative (i.e. controlled experiments, field site studies) and qualitative methods (e.g. observation, interviews, focus groups) (Suchan & Brewer, 2000). Maps and mapping techniques are tools that facilitate and present geographic research. In this way, cartography is nested within the geographic disciplinary tradition, a relationship that was explicit in the initial use of high human-map interactivity to support 'geographic' and not 'cartographic' visualization (MacEachren, 1994). Maps also can be the object of geographic inquiry, enabling their critical deconstruction to expose the specific interests, power relationships, and social implications behind the map and overarching mapping practice (Harley, 1989). Here, maps are secondary sources, or sites of power in their own right, supporting discourse analysis and informing empirical study of the political economy of cartography (Crampton, 2010).

As with other disciplinary influences, the footprint of geographic epistemologies in cartography only has grown with the possibility of interactive and online maps – a collection of information, maps, and technologies collectively described as the *GeoWeb* (Crampton, 2009; Haklay, Singleton, & Parker, 2008). Hybridized geographic/cartographic approaches have been vital in framing and theorizing the societal challenges related to emerging map practices and technologies (Leszczynski & Wilson, 2013; Ricker et al., 2014). Furthermore, critical geographic perspectives have identified historical limitations of user studies in cartography and are also shaping new ways for conducting such research (D'Ignazio & Klein, 2016; Elwood, 2010; Sheppard, 2005), including the UCD studies discussed below (Sack, 2013). Opportunities for hybridization continue to present themselves as geography and cartography further converge at the site of the mobile map.

Human–computer interaction and usability engineering

More recent influences on user studies in interactive cartography include the related areas of *human–computer interaction* (HCI) and *usability engineering* (UE) (Shneiderman & Plaisant, 2010). Scientists working in HCI have produced a range of technology-driven research on interaction design that is broadly applicable to the cartographic context (e.g. Card, English, & Burr, 1978; MacKenzie, 1992). Furthermore, cartographers have borrowed empirical methods commonly used in HCI – such as interaction logging, task analyses, and think aloud studies (e.g. Davies, 1998; Griffin, 2004; Harrower & Sheesley, 2005; Ooms et al., 2015) – to supplement psychology- and geography-based approaches when digital interactivity is provided. Scholars in HCI increasingly are turning their attention to interactive maps (e.g. Hecht et al., 2013; Rädle, Jetter, Butscher, & Reiterer, 2013; Schöning et al., 2008), again pointing to an increased mutual influence as maps become interactive and move online or to mobile devices.

While HCI focuses on basic science in *user interface* (UI) design, UE employs user studies to evaluate and improve a single interface. Core UE tenets have influenced user studies on interactive cartography in several important ways. First, UE provides a set of basic metrics for evaluating the usability of an interactive application, mapping or otherwise, such as learnability, memorability, efficiency, error frequency, error severity, and satisfaction (Rubin & Chisnell, 2008), although an exact articulation of each metric for interactive cartography has not yet been developed. Second, UE encourages the completion of user studies, but in a rapid, discount manner that involves only a small number of participants (Nielsen, 1993). While the recommendation of discount user evaluations means that cartographers must know how to collect information from users, it also complicates the expectations of user studies in cartography directed to academic research versus professional practice. Finally, UE prescribes an iterative *UCD process*, making the user a formal part of the design workflow (Nielsen, 1992). Interestingly, while UE concepts have had a large impact in cartographic research, several studies have noted minimal transition of UE concepts into cartographic practice (e.g. Nivala, Sarjakoski, & Sarjakoski, 2007; Roth, 2015), despite other studies suggesting that uptake fails when users are not integrated into the design process (e.g. Mendonça & Delazari, 2014; Rogers et al., 2007).

Information visualization and scientific visualization

Differences in user study practices across psychology, HCI, and UE also are a topic of conversation in other disciplines that deal with visualization. For example, many user studies in the *information visualization* community use visual stimuli that are necessarily more complex than those in psychology (Munzner, 2016). Information visualization, like HCI and UE, is largely driven by computer science and views maps as one of many, largely equivalent visualization types (Heer, Bostock, & Ogievetsky, 2010; Shneiderman, 1996). We also observe parallels in the application of HCI/UE approaches in domains such as astronomy, chemistry, and medicine, where interactive maps and visualizations are classified as *scientific visualization* (Brodlie et al., 1992).

Importantly, scholars in information visualization and scientific visualization now make a fundamental distinction in user research between basic science, or controlled research informed by psychology, and visualization evaluations informed by UE (Plaisant, 2004). The latter usability evaluations increasingly are referred to as *design studies* in which an interactive visualization is created to meet a real-world problem domain, and then evaluated to determine its effectiveness and efficiency in meeting this use and user context (Munzner, 2009; Munzner, 2014). While traditional controlled experiments informed by psychology seek *generalizable* and *reproducible* insights serving as overarching guidance, the design studies informed by HCI and UE instead seek *transferrable* and *contextual* insights that may be useful in similar use and user scenarios (Sedlmair, Meyer, & Munzner, 2012). Slocum et al. (2001) made a similar distinction in their ICA research agenda article, and, not surprisingly, user studies since reported in the cartographic literature exhibit a bifurcation between hypothesis-driven laboratory experiments imposing great control over the map design and use contexts versus design studies that follow a user-centered process to evaluate a single interactive application in context.

3. Reenvisioning basic research on interactive maps and visualizations

The interdisciplinary influences on user studies in cartography are broad and growing, as reviewed in the prior section. In this section, we reenvision key themes from these historical and contemporary influences to identify opportunities for empirical research on interactive maps and visualizations, primarily addressing the trajectory of basic research in cartography. We begin by reaffirming the need for qualitative and mixed-methods research, and then list methodological opportunities as they loosely align with three aspects of method design: the participants, the materials, and the procedure. While our focus in this section is on interactive maps and visualizations, the recommendations largely extend to static representations as well.

Opportunity: expand qualitative and mixed-method research to confirm and enrich quantitative research in cartography

One of the most important steps in setting up a user study is choosing the best method or methods to address the research questions at hand. As introduced above, there is a long tradition of quantitative, psychology-driven research in cartography (Montello, 2002). This research prescribes a hypothesis-driven and highly-controlled approach to user studies to reveal generalizable and reproducible insights about map design and use. However, geographers, cognitive scientists, and usability engineers alike recognize that quantitative methods will not explain everything we need to know about how maps work. Historical critiques from geographers on an exclusively quantitative and positivist approach to user studies in cartography are well-documented (Pickles, 1995), and a range of qualitative and non-empirical alternatives have been suggested since (Kitchin & Tate, 2013). Furthermore, there are a number of qualitative techniques emerging from cognitive science that have direct applicability to the study of interactive maps and visualizations (e.g. Chandrasekharan & Nersessian, 2011; Davies, Goel, & Nersessian, 2009; Harmon & Nersessian, 2008). Finally, qualitative and mixed-method research is now a staple for user studies in interactive cartography – particularly in the requirements analysis stage of UCD studies (e.g. Marsh & Haklay, 2010; Robinson et al., 2005; Roth et al., 2015) – and continued adaptation of social science methods from geography and related fields is a key methodological need.

Continued expansion of qualitative and mixed-method user research presents opportunities for cartography in at least three ways: we can triangulate controlled laboratory research with qualitative field studies to better contextualize map design and use recommendations from quantitative studies (discussed further below), we can integrate core concepts from critical epistemologies (e.g. discourse, reflexivity, intertextuality) into empirical cartographic research to improve qualitative study design and interpretation, and we can open new avenues of research on the emotional, cultural, and political dimensions of cartographic design. However, as the number of interdisciplinary influences and epistemological perspectives in cartography grows, so too does the difficulty of getting one's bearings across available quantitative and qualitative methods. Furthermore, synchronizing the recordings obtained from multiple, different methods remains challenging logistically and analytically (Maggi & Fabrikant, 2014). Thus, work is needed to synthesize the relative advantages of different qualitative and qualitative methods, and to develop recommendations for properly mixing methods across a research project.

Opportunity: improve consistency and detail in the reporting of method designs

The diversity of epistemological perspectives is not detrimental to cartographic scholarship, and is likely a great advantage of the interdisciplinary nature of cartography. However, this diversity does require greater consistency and detail in the reporting of method design (e.g. see Kinkeldey, MacEachren, & Schiewe, 2014; Smith, Retchless, & Klippel, 2016, for efforts to interpret the design of user studies on uncertainty visualization). Furthermore, although the expectations of rigor ultimately may vary across methods, our review of empirical cartographic research reveals a large amount of variation in study design even within a single method. While there are many ways of characterizing study designs across quantitative and qualitative user studies (Forsell & Cooper, 2014), there are at least three basic ingredients for empirical research on interactive maps and visualizations: the *participants* (i.e. users), the *materials* (i.e. the map designs or other study materials), and the *procedure* (e.g. the experimental tasks, laboratory versus field testing). However, many user studies in cartography fail to report details about one or several of these methodological components. Improving reporting consistency presents the opportunity to perform a meta-analysis of user studies on interactive maps and visualizations, both to assess the generalizability of insights from controlled experiments and support the transferability of insights across UCD studies. In addition, there is a parallel methodological opportunity to outline best practices for choosing and parameterizing methods, to the end of improving research design and reporting for interpretation, synthesis, and provenance.

User study participants

Opportunity: promote purposeful sampling of study participants and limit convenience sampling

The first aspect of user study design – participants – greatly impacts the generalizability of study results. Participants should represent the envisioned user of an interactive map or visualization (Rubin & Chisnell, 2008), and accordingly it is important that the sampled participants represent the targeted levels of expertise and motivation for both controlled experiments and UCD studies (Roth, 2013b). Much empirical research in interactive cartography and visualization uses *convenience sampling*, drawing from university students or otherwise easily accessible populations (Harrower, Keller, & Hocking, 1997). While undergraduate students may be appropriate for simplified, psychological studies on visual perception, such convenience sampling can be problematic, as students often fail to represent the wide variety of users an interactive design may support (Carpendale, 2008).

Instead, we need to shift emphasis to *purposeful sampling* in which a participant population is restricted by factors that are meaningful to the study objectives, such as age, gender, demographics, culture, sensory and physical disabilities, expertise, education, or motivation (Slocum et al., 2001). While it is important to collect and report background information on these characteristics to describe the sample, not all of these factors are equally important to all user studies. Therefore, an opportunity exists to better understand user characteristics themselves as they apply to the design of interactive maps and visualizations. Such understanding of participant ability, expertise, and motivation will inform the way in which these maps and visualizations could be transferred to different map use and user situations (Griffin et al., 2017). Therein lies a challenge with purposeful sampling: it is more difficult to recruit a sample size with sufficient statistical power for generalizability (Ellis, 2010). Thus, purposeful sampling must be stressed in qualitative research and UCD studies, while statistical power and biographic information must be reported in conveniently sampled quantitative research in order to contextualize findings within a particular user profile.

User study materials

Opportunity: adopt new approaches to treat interactive, online, and mobile maps and visualizations as unique study materials

Maps are the materials in cartographic research, serving as empirical stimuli in quantitative research and discussion prompts in qualitative research. Technological innovations have fundamentally changed how maps are produced and consumed (Montello, 2009; Virrantaus et al., 2009). We both need to pose new research questions (as addressed in Section 5) and adopt new methodological designs in order to account for maps and visualizations that are highly interactive, delivered on-demand over the web, and responsive across devices (Nivala et al., 2007; Ooms, Andrienko, Andrienko, Maeyer, & Fack, 2012). Furthermore, technological innovations have opened map creation and use to the larger public, creating opportunities to conduct user research through volunteered geographic information (VGI) platforms (e.g. Crampton et al., 2013; MacEachren et al., 2011) or services like Amazon Mechanical Turk (e.g. Heer &

Bostock, 2010; Kosara & Ziemkiewicz, 2010). Future research is needed about the characteristics – and inequalities therein – of this crowdsourced fleet of maps and mappers (Stephens, 2013).

To this end, there is an opportunity to adopt new kinds of experimental apparatus to capture information about new kinds of interactive maps and visualizations. The *apparatus* in user studies serves two purposes: present stimuli to participants and record information about user responses to the stimuli. Once prohibitively expensive, wearable devices such as Oculus Rift or Google Cardboard and eye trackers such as the Eye Tribe Tracker are now feasible options for modest cartography research labs (Ooms et al., 2015). Additionally, as interactive maps and visualizations move to mobile devices, cross platform research is increasingly important in the context of mobile mapping, as information is perceived differently according to the display device (screen size, resolution, color range, etc.) and user environment (Chae & Kim, 2004).

Finally, there is an opportunity to develop new *software* to capture and process data during user studies. New software means that additional performance metrics can be collected during user studies, and that these metrics can be analyzed in near real-time. For example, interaction logging – once a time-consuming endeavor (MacEachren, Boscoe, Haug, & Pickle, 1998) – is now facilitated through services like Google Analytics and Hotjar (Clifton, 2012; Veregin & Wortley, 2014). In particular, there is an opportunity to foster open source software initiatives (e.g. Andrienko & Andrienko, 2013; Ooms et al., 2015) to promote a community around user study research and practice and reduce duplication of effort. Overall, integration of new apparatus and software raises new questions about user studies in cartography, including issues of representativeness, learning effects, fatigue, privacy, and ecological validity.

User study procedures

Opportunity: define and assess high-level, insight-based tasks to complement benchmark tasks in user studies

Finally, we identify two pressing needs regarding study procedure. First, greater consistency in user tasks is needed to promote comparability across user studies and map use situations (Griffin et al., 2017). For instance, Kahneman (2003) worked across his career to establish simple and complex cognitive tasks in behavioral economics. These tasks represent an experimental paradigm for understanding different aspects of reasoning and decision-making. Once established, these tasks were reused by various researchers, perhaps with small, clearly specified modifications, to collectively build understanding. Kahneman's work on cognitive tasks ultimately led to a Nobel Prize in Economics.

Research in interactive cartography and visualization is coalescing around a core set of *benchmark tasks* to assess the quality of user interaction strategies across spatial, temporal, and attribute representations (Andrienko, Andrienko, & Gatalsky, 2003; Roth, 2013a). These low-level benchmark tasks promote control and repeatability in quantitative studies – and also inform the description of user profiles and use case scenarios during early stages of UCD – but accordingly focus on specific interaction exchanges at the expense of overarching user goals. In contrast, exploratory visualization and visual analytics applications are designed to support high-level, complex, and ill-defined tasks such as open exploration, spatial decision-making, and knowledge construction (Andrienko et al., 2007;

Demšar, 2007; MacEachren et al., 2004). There is an opportunity in these situations to shift emphasis to the *analytical products* derived across the entire interaction session, particularly as they relate to generation of new *geographic insights* such as changes, anomalies, outliers, clusters, spikes, patterns, and trends (Roth et al., 2015). One potentially useful model from information visualization is the qualitative coding of user reported insights according to their complexity, depth, quality, novelty, and relevance (e.g. Chang, Ziemkiewicz, Green, & Ribarsky, 2009; North, 2006; Saraiya, North, & Duca, 2004). Future work is needed to fully define high-level, insight-based tasks for interactive cartography and geovisualization.

Opportunity: complement laboratory and online studies with field studies

One of the constitutive choices regarding study procedure is whether to conduct the test in a laboratory or in the field. Interactive and especially mobile maps are difficult to test in real-world settings, as the environment cannot be controlled (e.g. weather, lighting, noise, congestion), complicating comparison across field participants (Kiefer, Giannopoulos, & Raubal, 2014). As a result, most user studies of interactive maps and visualizations are conducted in a laboratory setting, limiting the ecological validity and generalizability of results (Bleisch, 2011). An opportunity exists to conduct field studies of interactive maps and visualizations 'in the wild', or in their actual context (Edsall, 2007, p. 337), to confirm laboratory findings (Elzakker & Griffin, 2013); field studies also are likely to identify new aspects of interactive map design requiring follow-up laboratory research. While online or distributed user studies offer interesting potential for evaluating web maps in a natural setting, they also lack control over the equipment used (e.g. screen size and resolution, color and contrast settings, processing speed, bandwidth) as well as the behavior of the participant during the test (e.g. divided attention, consulting others). Thus, results from online studies using VGI or crowdsourced services (e.g. Mechanical Turk) should be ground-truthed with smaller, laboratory studies and triangulated with qualitative, in-person observation.

4. Adapting methods for UCD studies

While UCD studies are now common in information visualization and scientific visualization, opportunities remain to fully formulate the role of UCD studies in interactive cartography. In this section, we shift attention from opportunities, impediments, and recommendations related to basic cartographic research to those specific to studies designed to evaluate a single interactive map or visualization. We identify both bigger picture issues that need to be resolved in order to cement UCD studies as a modality for empirical cartographic research, as well as additional opportunities to improve and extend UCD studies for practical and critical research.

Opportunity: establish gold standards for administering and assessing UCD studies on interactive maps and visualizations

As introduced above, UCD studies derived from UE have different expectations regarding method design and resulting intellectual products compared to controlled experiments (Sedlmair et al., 2012). Accordingly, UCD studies are encouraged in professional practice but questioned as acceptable academic scholarship, often garnering mixed journal reviews in our experience. This contradiction leads to many open questions about the role of UCD studies in interactive cartography and visualization. Such user studies clearly are valuable to the 'doing' of cartography, but what do they tell us about how maps work on a more fundamental level? How should we assess the quality and impact of transferable and contextual insights generated from UCD studies? Can we conduct design studies to simultaneously approach practical and theoretical goals, and at what point does doing so become harmful to the creative development process (Greenberg & Buxton, 2008)?

Key opportunities exist to establish gold standards for UCD studies, both in the manner they are administered and the manner their results are assessed. Regarding administration, UCD scholarship is beginning to coalesce around a core set of methods both for interactive cartography (e.g. Marsh & Haklay, 2010; Robinson et al., 2005; Roth et al., 2015) and related fields (e.g. Cairns & Cox, 2008; Carpendale, 2008; Sweeney, Maguire, & Shackel, 1993). However, synthesis and sensitivity analyses of these methods are needed to understand how variation in the study design impacts the results from any single UCD study (e.g. Tullis & Wood, 2004). Other potentially helpful strategies for generating gold standards for UCD studies include 'methods' articles providing extended discussion of a particular method for cartographic research (e.g. Çöltekin, Heil, Garlandini, & Fabrikant, 2009; Haklay & Zafiri, 2008; Ooms et al., 2015; Roth et al., 2011) and 'reanalysis' articles applying a range of techniques to a compilation of previously published studies as a new, methodological contribution (e.g. Davies, 1998; Klippel, Weaver, & Robinson, 2011).

It is equally important to set gold standards for assessing the novelty and impact of results from UCD studies. Because the focus is on transferable and contextual insights, the results of UCD studies must be *actionable* and *believable* so that they can inform future interactive maps and visualizations designed for a similar use and user context (Gleicher, 2012). In this way, UCD studies should be assessed on the novelty of the evaluated interactive map or visualization, the novelty of the user-centered method or process used in the evaluation, or the completeness of the reported user-centered scenario and case study (more discussion on the latter opportunity below). Ultimately, this may mean that cartography journals need to embrace the distinction between research and design papers adopted by some information visualization journals. Accordingly, expectations for peer-review will be different, but not eased or reduced, for UCD studies to ensure intellectual merit. Future work is needed to set these expectations, including publication of both exemplary UCD projects and comprehensive meta-analyses of their empirical results.

Opportunity: streamline and contextualize the UCD process for interactive cartography and visualization

UCD studies focus as much on the *process* of making interactive maps as the final result, and thus represent a variant of ethnographic research for interactive cartography. There are now several processes reported in the literature that adapt UCD to interactive cartography (e.g. Gabbard, Hix, & Swan, 1999; Robinson et al., 2005; Roth et al., 2015; Slocum, Cliburn, Feddema, & Miller, 2003; Tsou & Curran, 2008), with most emphasizing an initial needs assessment, design prototyping, and iterative user feedback and system refinement loops leading from formative to summative evaluation. Despite the number of UCD processes put forward in the literature, opportunities exist to compare and streamline these processes as well as to identify design contexts that require deviation from the user-centered process.

For instance, until recently only minimal research has discussed approaches to articulating user needs and requirements prior to design of interactive maps and visualizations (notable examples include Brewer & McNeese, 2004; Elzakker & Wealands, 2007; Meng, 2005). Other potentially fruitful research opportunities for improving the UCD process include integrating user evaluations with prototyping (Lloyd & Dykes, 2011), distributed usability studies (Mendonça & Delazari, 2012), and crowdsourced user analytics (Veregin & Wortley, 2014). Such research into the UCD process is needed not just to improve interactive, online, and mobile maps, but also to build a corpus of educational guidance to prepare students to fill *user experience* (UX) designer positions (Garrett, 2010); this newly trained wave of interaction designers working in cartography is far more likely to conduct UCD studies than controlled experiments.

Opportunity: promote comprehensive UCD case studies

UCD studies are most powerful when reported as part of a *case study* describing the design negotiation across developers, stakeholders, and users (Shneiderman & Plaisant, 2006). These user-centered case studies too often are relegated as overly applied forms of empirical research in cartography, particularly if they are simply describing a single tool without providing details about the broad use and user context. However, case studies are essential for adapting interactive designs to the unique demands of different domain contexts and user groups. Similarly, successful case studies are important for promoting buy-in and uptake of tools by targeted users (Roth et al., 2015; Wijk, 2005), and thus improve awareness of the value of cartography as both an active research discipline and essential set of tools and techniques to address the world's most pressing problems (Robinson et al., 2017). Finally, case studies can highlight use case scenarios in which a new interactive map or visualization is no better than existing practice, using such 'negative results' to inform design choices (Kosara, Healey, Interrante, Laidlaw, & Ware, 2003).

Opportunity: leverage UCD studies for participatory action research

Importantly, UCD studies result in different kinds of scholarly contributions compared to controlled experiments, and thus offer new opportunities – rather than limitations – for cartographic scholarship. First, design studies empower target users to be part of the design process. In this way, design studies shift the human from an object of study (as with controlled experiments) to an active member of the design and development team. Such a shift reflects similar moves toward *participatory action research* in GIS (Elwood, 2009) and HCI (Hayes, 2011), which carries with it the creation of design insights that are situated in lived experience, personal difference, and social context (Sedlmair et al., 2012). Furthermore, UCD complements research on functionalism that assumes an average, measurable, and predictable map user (Montello, 2002), resulting in insights on differences in opinion, values, and preferences, and thus adding a layer of complexity and nuance to existing design conventions and recommendations based on perceptual or cognitive controlled experiments. In this way, UCD studies help us critique and problematize design truisms, while also generate new design considerations warranting follow-up controlled experiments. Future research is needed to fully articulate participatory action research for interactive cartography.

Opportunity: conduct user-centered studies on the political economy of interactive cartography and visualization

Finally, an opportunity exists to employ UCD studies to reveal the contemporary political economy of interactive cartography, a topic garnering increased interest in critical cartography (Crampton, 2010; Leszczynski, 2012; Thatcher, 2014). Needs assessments and usability evaluations provide a unique view into the everyday business operations of interactive cartography, demonstrating and describing the commodification and regulation of interactive maps and visualizations. Business costs are diverse, include more than just measures of time or monetary investment, and are not solely derived from the physical design of the tool itself. For example, costs can be imposed by institutional and social power relationships that shape the context of tool design and use (e.g. lack of access to tools, a range of non-functional requirements, marginalization of potential user groups) (Robinson, Roth, & MacEachren, 2011). Needs assessment studies implicitly define who is and who is not considered a user, and thus reveal how a potentially small set of stakeholders negotiate access to powerful mapping tools, exposing the marginalized non-user. To this end, UCD studies can identify unsupported individuals, expanding the views and voices supported by the evaluated interactive mapping application (McCall & Dunn, 2012). A discourse analysis of UCD studies across cartography is an important, first step toward understanding the political economy of interactive mapping and visualization.

5. Looking forward to key needs in interactive cartography and visualization

In this section, we look forward to key methodological needs for studying interactive maps and visualizations, and needs that impact both controlled experiments and UCD studies. There is a range of open research questions in interactive cartography and visualization that warrant user studies, such as map user abilities and needs, competing interface designs, and underlying mapping technology (Roth, 2013b). In the following section, we highlight several of these unresolved issues that have methodological implications for all user studies on interactive maps and visualizations. Opportunities range from the conceptualization of interactivity in user studies, the purpose of applying interactivity in these studies, and the platform on which interactivity is provided, concluding with an overarching opportunity to integrate time-tested principles on representation design with our emerging empirical understanding of interaction design.

Opportunity: articulate dimensions of interface complexity in user studies

While we advocate for a broad and inclusive definition of interactivity for maps and visualizations, we agree with Harrower and Sheesley (2005) that not all interactivity is created equal. Clearly a desktop GIS is different from a slippy web map, and a coordinated multi-view visualization is different than a way finding mobile app. However, empirical research on interactivity does not always discuss the complexity of evaluated interactive maps and visualizations, making comparison and transferability of findings difficult. The term *interface complexity*, or the scope and freedom of provided interactivity (Roth, 2013b), has been proposed as the interaction complement to prior empirical research in cartography and visualization on *information complexity*, or the density of information represented in a static page (MacEachren, 1982). Modern mapping techniques present a diversity of options for representation and interaction, each requiring a number of design decisions around complexity, flexibility, and constraint (Edsall, Andrienko, Andrienko, & Buttenfield, 2008).

An opportunity exists to articulate the dimensions of interface complexity, both to improve transferability across user studies and to facilitate interaction design. One dimension of complexity may relate to the kinds of interaction operators implemented in the map or visualization, ranging from basic 'slippy' map operators such as a panning and zooming (e.g. Manson, Kne, Dyke, Shannon, & Eria, 2012; You, Chen, Liu, & Lin, 2007) to complex spatiotemporal sequencing (e.g. Roth & MacEachren, 2016; Wood, Dykes, Slingsby, & Clarke, 2007) and spatial calculations (e.g. Ingensand & Golay, 2011; Mendonça & Delazari, 2012). A second dimension may be the degree of freedom with which these interactions can be executed (Malik, Ranjan, & Balakrishnan, 2005), with higher degrees of freedom emulating more natural interactions at the cost of additional cognitive load (Buxton, 2001). Additional dimensions of interface complexity could be the interface style by which the operator is implemented (Howard & MacEachren, 1996), or the form of multimodal input enabling the HCI (Huang, Schmidt, & Gartner, 2012). Formal models – like the Complexity of Interaction of Sequences (CIS) (Appert, Beaudouin-Lafon, & Mackay, 2004) – may be useful to describe and analyze some aspects of interface complexity. Finally, interface complexity may be relative to the intended user, with the experience of simple versus complex varying by user abilities, expertise, and motivation. Regardless, we need a map-specific framework for conceptualizing the dimensions of interface complexity to support both the isolation of complexity in controlled studies and the description of different levels of complexity of UCD studies.

Opportunity: develop strategies to compare static and interactive maps

We opened this research agenda with a number of questions about the value proposition of interactivity for cartography and visualization. But, what are we comparing interactivity against? What is the *baseline*? Conventional wisdom in cartography and related visual disciplines suggests it may not be possible to systematically evaluate static versus interactive trials, resulting in the idiomatic comparison of apples to oranges. Such comparison of static and interactive maps is a challenge, as interactive maps and visualizations typically have a greater learning curve before their efficient and effective use, but once learned, enable access to a greater volume of information. As a result, controlling interface complexity and information complexity across baseline and experimental designs may lead to suboptimal or unrealistic static designs.

Despite these issues, we need empirical evidence on the ways that user needs can be better supported through interactivity (i.e. how interactivity enhances the user experience) in order to understand when the investment to go interactive makes sense in a given map use situation. Static maps can be conceptualized as individual scenes in an interactive sequence, with the interface enabling the user to determine the sequence of the presented static maps rather than having the cartographer prepare this sequence before viewing. Several potentially viable strategies for comparing static and interactive maps exist in the literature that leverage the idea of sequencing, including content analysis of functional designs between static and interactive maps (Fish & Calvert, 2015), use of small multiples for static trials (Fabrikant, Rebich-Hespanha, Andrienko, Andrienko, &

Montello, 2008), and passive playback of video recordings of user interactions in place of static trials (Keehner, Hegarty, Cohen, Khooshabeh, & Montello, 2008). Finally, if comparison of static and interactive maps and visualizations is impossible or unpractical, we need better guidance on how static and interactive maps must be designed and evaluated differently.

Opportunity: investigate the value of interactivity in new map use cases

For the past 25 years, interactivity has been touted as the primary way to support visual thinking in the context of geographic visualization, with the goal of generating new hypotheses in unknown datasets to support scientific exploration (MacEachren, 1994; MacEachren, Buttenfield, Campbell, & Monmonier, 1992). However, the ubiquity of interactive maps presents emerging opportunities to study interaction design beyond exploratory spatial data analysis (Gartner, Bennett, & Morita, 2007). Geovisual analytics and 'big data' science is one important use case (Robinson et al., 2017). Future research also needs to approach interaction design for a general audience, in which the interactive maps and visualizations serve the purpose of communication, personalization, and even entertainment. These very different use and user contexts present different methodological opportunities and challenges regarding participants, materials, and procedures, and the degree to which insights regarding exploratory visualization can be transferred to these different contexts currently remains unclear.

Questions derived from critical science and technology studies also are needed to inform qualitative research on interactive maps and visualizations, particularly to understand how interactivity empowers – and potentially misleads or marginalizes – its users (Hess, 2001). For instance, how does interactivity differentially impact user access to or trust in the information behind the map (Flanagin & Metzger, 2008)? Does distribution of interactivity primarily through the web and on mobile devices act to further spread the digital divide (Sui, Goodchild, Elwood &, 2013)? Do interactive maps and visualizations that reach marginalized populations disproportionately serve as propaganda or surveillance (Crampton, 2015)? Do they compromise our privacy, or change the ways we construct and negotiate public space (Wilson, 2012)? Both basic research and UCD studies must be adapted to approach such critical questions about new map use cases for interactive maps and visualizations.

Opportunity: evaluate non-cartographic and neocartographic interfaces supporting map design and production

A specific map use case often falling outside discussion of interactivity and UCD in cartography is the use of digital and highly-interactive tools for map production. Here, the purpose of the interface is explicitly to support map design rather than applied map use case scenarios. Professional-quality print and interactive map design both require complex workflows across specialist mapping tools such as desktop or web-enabled GIS and non-cartographic tools such as information management systems, graphic design software, and web development technology (Tolochko, 2016). While streamlining and enhancing design workflows across cartographic and non-cartographic digital tools is practically important to industry (e.g. see the annual NACIS Practical Cartography Day) and government (e.g. Committee, 2003; Howard, Blick, & McNamara, 2009; Stoter, 2005), relatively few descriptions and evaluations of static or interactive map production processes have made their way into the academic literature (e.g. Behrens, Elzakker, & Schmidt, 2015; Davies, 1998; Duchêne, Christophe, & Ruas, 2011; Haklay et al., 2008; Jones, Haklay, Griffiths, & Vaughan, 2009; Roth et al., 2014). User studies also are needed for the design and evaluation of geocollaborative interfaces for managing role-based tasks and responsibilities during cartographic production and use (MacEachren & Brewer, 2004; Sidlar & Rinner, 2009).

The importance of evaluating interactive tools for map design versus map use is further amplified by the rise of *neogeographic* or *neocartographic* tools enabling untrained cartographers to make maps, both static and interactive (Turner, 2006). Arguably, such tools have democratized cartography, dissolving the aforementioned role of the map *user* into the previously professionalized role of map *maker* (Kraak, 1998; Morrison, 1997; Rød, Ormeling, & Elzakker, 2001). The growing availability of neocartographic tools for map production has opened new challenges for user studies on interactive maps and visualizations. For instance, what does it mean to be a professional, amateur, and/or hacker cartographer in an age of pervasive neocartographic tools (McConchie, 2015)? Do interaction strategies and functional needs differ across these user groups (Sack, 2013)? What kind of expert-based learning and support materials are needed for this new fleet of neocartographers (Mead, 2014)? Can expert knowledge on cartographic principles be built into the UI to improve map design (Kumar, 2000)? Finally, have neocartographic and participatory mapping interfaces truly democratized map design and production, or do differences to access and application remain across different segments of society (Cartwright, 2012)?

Opportunity: assess mobile interactions

Preliminary evidence suggests that the majority of digital maps and visualizations may now be viewed on mobile devices, such as smartphones and tablets, rather than personal computers (Alexander, 2013; Lisak, 2012). The transition to mobile-first cartographic design suggests as many opportunities as limitations for cartography (Nagi, 2014). Mobile devices reduce the display size, an issue for static and interactive maps alike. Most of the market-available mobile devices rely on touch functionality, and increasingly include support for voice and gesture input (Muehlenhaus, 2013). However, restriction to multimodal and touch input is a challenge in the context of exploratory visualization, where highlighting and coordinating using brushing is fundamental to successful interaction (Griffin & Robinson, 2015; Robinson, 2011). Furthermore, we need to consider how our interactive map and visualization designs should respond across mobile and non-mobile devices (Marcotte, 2010; Roth, 2015), requiring us to seamlessly design for every possible technology much like multiresolution databases and multiscale mapping now allow us to seamlessly design for every possible place and scale (Brewer & Buttenfield, 2007; Robertson, Ebert, Eick, Keim, & Joy, 2009). Thus, rather than evaluating a single interactive map for a single device, our user studies need to investigate effectiveness, efficiency, and satisfaction across technological contexts. Finally, mobile devices enable indoor and outdoor interactive experiments, requiring integrated basemap designs as well as caching solutions to manage indoor gaps in connectivity. As stated above, understanding mobile use cases requires adoption of field study apparatus and procedures that are still in their infancy.

Opportunity: develop and integrate design guidelines for interaction and representation in cartography

Perhaps the ultimate goal of research in interactive cartography and visualization – empirical or otherwise – is the development of first principles that facilitate the design of our interactions. Attempts to relate optimal and suboptimal interface functionality (operators) to aspects of user needs (objectives) and information elements (operands) is one potentially viable strategy to develop basic principles, much like the visual variables in representation design (Crampton, 2002; Roth & MacEachren, 2016). However, future research is needed to develop overarching design guidelines, including synthesis work to integrate unique interaction design insights across controlled experiments, qualitative research, and UCD studies. Importantly, this effort needs to account for the contingencies and nuances imposed by variable user and use case contexts (i.e. adaptive design *principles* rather than inflexible design *rules*). Furthermore, this effort needs to confront design truisms regarding cartographic representation, rethinking the cartographic canon developed over the past 75 years for the interactive, online, and mobile medium. To-date, only anecdotal research exists on the ways that interaction design should be constrained given the representation solution, and vice versa.

6. Conclusion

In this paper, we present a set of opportunities for empirical research in cartography, setting a research agenda to meet our methodological needs as maps and visualizations become interactive and move online and to mobile devices (Table 1). The focus of our discussion is epistemological and reflects the wide interdisciplinary influences on user studies in cartography. Opportunities abound for both basic research and UCD studies, and thus for researchers and scholars as well as professionals and students. The opportunities are presented as imperatives for cartographic research on interactive maps and visualizations, and we welcome a range of contributions including:

- Methodological theses and white papers providing in-depth discussions of individual empirical methods for interactive cartography and visualization (especially novel or hybridized methods) or specific problems encountered with participants, materials, and procedures in user studies on interactive maps and visualizations;
- Comparative and critical meta-analyses of prior user studies on maps and visualizations, with a focus on similarities and differences of empirical results when evaluating print/static versus interactive maps;
- Comprehensive user-centered case studies that provide consistent and detailed descriptions of the process for designing and evaluating a given interactive map or visualization and that emphasize transferable and contextual insights on interaction design and use;
- A multi-authored edited volume on best practices or gold standards for streamlining, administering, reporting, and assessing user studies in interactive cartography and visualization that spans basic research and UCD studies;
- Exploratory projects that integrate new methodological influences for interactive cartography and visualization from untapped areas of the arts, humanities, engineering, and sciences, as well as bridge-building projects to more effectively promote empirical

insights from interactive cartography and visualization to the neighboring disciplines of psychology, cognitive science, geography, critical software and technology studies, HCI, usability engineering, UCD, information visualization, and scientific visualization, among many others.
- Open educational resources that integrate empirically-derived cartographic design guidelines for interaction and representation to train a new generation of cartographers who work across printed, static, and interactive maps and visualizations.

The possibility of digital interactivity requires us to reenvision the map *reader* as the map *user*, and to address the perceptual, cognitive, cultural, and practical considerations that influence the user's experience with interactive maps and visualizations. In doing so, we must explore and understand new approaches to study this user and the interactive designs he or she employs. The promise of such methodological research is a better understanding of how interactive maps and visualizations 'work' on individual, collaborative, and societal scales.

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