Article

Urban Analytics and City Science

EPB: Urban Analytics and City Science
2019, Vol. 46(9) 1706–1723

DOI: 10.1177/2399808318764122
journals.sagepub.com/home/epb
SAGE

Improving spatial decision making using interactive maps: An empirical study on interface complexity and decision complexity in the North American hazardous waste trade

Kristen Vincent, Robert E Roth, Sarah A Moore, Qunying Huang and Nick Lally
University of Wisconsin-Madison, USA

Carl M Sack
Fond Du Lac Tribal and Community College, USA

Eric Nost
University of Guelph, Canada

Heather Rosenfeld
University of Wisconsin-Madison, USA

Abstract

Spatial decisions increasingly are made by both professional and citizen stakeholders using interactive maps, yet few empirically-derived guidelines exist for designing interactive maps that support complex reasoning and decision making across problem contexts. We address this gap through an online map study with 122 participants with varying expertise. The study required participants to assume two hypothetical scenarios in the North American hazardous waste trade, review geographic information on environmental justice impacts using a different interactive map for each scenario, and arrive at an optimal decision outcome. This study followed a 2×2 factorial design, varying interface complexity (the number of supported interaction operators) and decision complexity (the number of decision criteria) as the independent variables and controlling for participant expertise with the hazardous waste trade and other aspects of cartographic design. Our findings indicate that *interface* complexity, not decision complexity, influenced decision outcomes, with participants arriving at better decisions using the simpler interface. However, expertise was a moderating effect, with experts and non-experts using different interaction strategies to arrive at their

Corresponding author:
Kristen Vincent, University of Wisconsin–Madison, Department of Geography, University of Wisconsin Cartography Lab 550 N. Park St. Madison, WI 53703, USA.
Email: kristen.vincent@snc.edu

decisions. The research contributes to cartography, geovisualization, spatial decision science, urban planning, and visual analytics as well as to scholarship on environmental justice, the geography of hazardous waste, and participatory mapping.

Keywords

Spatial decision making, cartography, interface complexity, decision complexity, expertise, hazardous waste, environmental justice

Introduction

Scholars and practitioners in geography, GIScience, and related fields increasingly are seeking visual solutions for grappling with the complexity of our most pressing social, environmental, and economic problems (e.g., Andrienko et al., 2007; Goodspeed et al., 2016; Jankowski et al., 2001; Jankowski and Nyerges, 2001; Rinner, 2003; Robinson et al., 2017; Thomas and Cook, 2005; Yang et al., 2017). Such visualizations leverage the eye's broad sensory bandwidth to the brain, scaling the cognitive faculties of decision makers to the complexity of the problem (Roth and MacEachren, 2016). For decisions that are explicitly spatial, the primary visualization anchoring reasoning is a map (Jankowski and Richard, 1994; Leung, 2012), and increasingly, these maps are highly interactive and delivered online (Goodchild, 2015; Muehlenhaus, 2013; Peterson, 2003). However, few empirically-derived guidelines exist for designing interactive maps that support complex reasoning and decision making across problem contexts (MacEachren, 2015).

We address this gap through a case study on environmental justice (EJ) in the North American trade of hazardous waste. EJ activism and research employ maps to understand the uneven social burdens of environmental hazards, such as clusters of hazardous waste exposure (e.g., Buzzelli and Jerrett, 2003; Sider et al., 2015) and correlations with marginalized populations (e.g., Kweon et al., 2016; Lara-Valencia et al., 2009). EJ-informed decision making requires consideration of a range of social, environmental, and economic dimensions that vary geographically across specific sites (Coutinho-Rodrigues et al., 1997). Further, communities should be invited to participate in spatial decision making about hazard management (Laurian, 2005), empowering a range of different stakeholders to articulate concerns and discuss alternatives using maps (Elwood and Leszczynski, 2013; Jankowski, 2009; Talen, 1999).

Accordingly, EJ issues in the North American hazardous waste trade provide an important and timely problem context for investigating the design of interactive maps that support spatial decision making. Specifically, we ask three research questions:

(1) *Does cartographic interface complexity influence the success of spatial decision making?* Not all interactive mapping systems work the same way. *Interface complexity* describes the number of interactive operators within the map (i.e., scope) and the precision that each operator can be interactively adjusted (i.e., freedom) (Harrower and Sheesley, 2005). Empirical research suggests that interface complexity influences how a user works with an interactive map (e.g., Dou et al., 2010; Jones et al., 2009; Keehner et al., 2008), and articulation of the influence of interface complexity on reasoning and decision making is a major research challenge in cartography, geovisualization, and visual analytics (Roth et al., 2017).
(2) *Does decision complexity influence the success of spatial decision making supported by interactive maps?* Not all decision contexts are the same. *Decision complexity* describes

the number of decision criteria and potential outcomes (Jelokhani-Niaraki and Malczewski, 2015). While prior research has assessed the impact of the decision complexity on the decision-making process, research is limited on the effectiveness of interactive maps at different decision complexities (see Armstrong and Densham, 1995; Crossland et al., 1995; Speier, 2006). Development of useful and usable interfaces that support the decision-making process is therefore a major research challenge facing spatial decision science and the design of spatial decision support systems (Leung, 2012).

(3) *Is the influence of cartographic interface complexity and spatial decision complexity dependent upon the expertise of the decision maker?* Finally, not all decision makers think the same way. Individual differences impact all map use, interactive or otherwise (Griffin et al., 2017). Here, we specifically examine *user expertise*, a combination of education, experience, and familiarity with a given subject (Roth, 2009). This is particularly relevant in participatory mapping for just environmental decision making, where professional and citizen stakeholders negotiate a range of experiences, opinions, and values through the map interface to arrive at a decision (Elwood, 2006).

We addressed these research questions through an online map study that required 122 participants to assume two hypothetical scenarios in the North American hazardous waste trade, review geographic information on EJ impacts using a different interactive map for each scenario, and arrive at an optimal decision. We followed a 2×2 factorial design, using interface complexity (assigned between groups) and decision complexity (assigned within groups, resulting in the two tested scenarios per participant) as the independent variables and controlling for participant expertise and other aspects of cartographic design.

Related work

Cartographic interface complexity and spatial decision complexity are treated in a range of research streams related to interactive mapping. MacEachren (1994) identifies three continua defining all map use contexts, with each research question listed above addressing one aspect of each axis: human-map interaction (RQ1: *complex* interfaces for exploration to *simple* interfaces for presentation), task (RQ2: *complex* to *simple* decisions), and users (RQ3: *expert* to *non-expert* decision makers).

There are a range of design decisions that impact the effectiveness of an interactive map, including user goals and needs, interface complexity, overall usability, browser and device compatibility, and the visual style and layout (see Howard and MacEachren, 1996). Interface complexity (RQ1) describes the scope and freedom of an interactive map (Harrower and Sheesley, 2005), which together combine to determine the total number of unique views that can be generated by a user. We narrow our focus to *scope* in this research, which is defined by the number of unique *operator primitives*, or generic forms of interactive functionality such as panning, zooming, etc., implemented (see Roth, 2013). While a push towards exploratory visualization has resulted in development of a number of flexible mapping toolkits supporting a range of operators (e.g., Bostock et al., 2011; Hardisty and Robinson, 2011), empirical research has suggested that reducing complexity may better support concrete tasks (e.g., Dou et al., 2010; Jones et al., 2009; Keehner et al., 2008). However, most empirical research on interactive maps has produced mixed results on the utility of specific operator primitives (e.g., Andrienko et al., 2002; Edsall, 2003; MacEachren et al., 1998; Poplin, 2015; Roth and MacEachren, 2016), suggesting that the decision to include a given operator depends on the task and user context (Griffin et al., 2017).

We focused on five operators in this study based on two of the most common interface design strategies in web cartography and visualization: a simple web *slippy map* including panning, zooming, and detail retrieval (Sample and Ioup, 2010) and a more complex *information seeking* strategy supporting overlay of data (''overview first''), pan/zoom and filter (''zoom and filter''), and retrieve (''details-on-demand'') (Shneiderman, 1996).

Decision making is a higher level cognitive process through which a person evaluates all available factors to make a choice about a given problem (Payne et al., 1993). Decision complexity (RQ2) describes the number of criteria and outcomes involved in a decision (Jelokhani-Niaraki and Malczewski, 2015). While simple decisions tend to have a correct decision outcome, more complicated decisions rely on *optimality*, or a ranking of prospective solutions by how they minimize or maximize different contextual criteria (Einhorn and Hogarth, 1981). In this research, we vary the number of decision criteria while holding the number of outcomes (i.e., sites) constant to maintain a consistent, elementary-level ranking decision across experimental trials, one common type of map reading task supporting spatial decision making (see Andrienko et al., 2003; Roth, 2012 for overviews of map reading tasks). As with interface complexity, empirical results are mixed regarding the impact of decision complexity on decisions supported by spatial decision support systems and interactive maps, with Jelokhani-Niaraki and Malczewski (2015) finding a significant difference in outcomes by decision complexity and Crossland et al. (1995) and Jankowski and Nyerges (2001) finding no difference in outcomes by decision complexity.

Finally, expertise (RQ3) describes the influence of education, experience, and familiarity with a given subject. While MacEachren (1994) originally described this axis as a distinction between public and private map use, a later focus (MacEachren et al., 2004) was on user expertise, or differences between a general and specialist map user. Again, there are conflicting findings on the role of expertise on map use, with some studies finding increased expertise improves map use and decision making (e.g., Hope and Hunter, 2007; Ooms et al., 2015; Roth, 2009) while others finding no influence (e.g., Aerts et al., 2003; Evans, 1997; Jankowski and Nyerges, 2001).

Methods

Case study: Environmental justice and the transnational hazardous waste trade

We examined the above interface, decision, and decision-maker considerations through a case study about EJ in the North American hazardous waste trade. The case study is part of a larger project to track and map the import of hazardous waste to the U.S. from Canada and Mexico in support of EJ initiatives and participatory decision making (http://www.geography.wisc.edu/hazardouswaste/). Here, *hazardous waste* is defined as waste that could cause harm to humans or the environment and is also ignitable, corrosive, reactive, and/or toxic.

Preparatory research

Before administering the online map study, we conducted four stages of preparatory research. First, we obtained data on the transnational hazardous waste trade through two Freedom of Information Act (FOIA) requests to the U.S. Environmental Protection Agency (EPA) and digitized the provided import manifests into a geocoded dataset of waste flows (see Nost et al., 2017 for details). Second, we held a one-day mapping workshop at the University of Wisconsin–Madison—described as the Design Challenge—to explore the dataset (see Moore et al., in press for details). Third, we completed a set of semi-structured interviews with three domain experts to ascertain background context about

Table 1. Demographics of study participants.

Demographic	Characteristic	Count
Gender	Male	68
	Female	54
Expertise	Hazardous waste experts	12
	Hazardous waste non-experts	110
Education	PhD	2
	Master's degree	12
	Post-bachelor certificate	4
	Bachelor's degree	49
	Associate's degree	15
	High school diploma	40
Age	Minimum	23
	Average	35.5
	Maximum	66

the transnational hazardous waste trade (details in online supplementary materials). We used this input from domain experts to inform the decision scenarios described below. Finally, we conducted a pilot study with a preliminary version of the study with eight students in the University of Wisconsin–Madison Cartography Lab to identify any confusions or problems in the experimental design.

Participants

A total of 122 participants completed the online map study. We recruited 110 participants through Amazon Mechanical Turk to promote diversity in age, education, and experience (Table 1). All participants spoke English as their first language, resided in the U.S. (but not Ohio or Texas; see below), were 18 years of age or older, and completed the study using a non-mobile device. To complement the Mechanical Turk participants, we recruited 12 experts in the transnational hazardous waste trade, nine of whom had previously used the transnational hazardous waste dataset described above.

Materials

Our materials followed a 2×2 factorial design: (1) interface complexity and (2) decision complexity. In the following, we describe the experimental conditions in both factors as *simple* and *complex* for brevity, acknowledging that interface and decision complexity are actually continua and the descriptions of simple versus complex are relative to a context-specific midpoint. We acquired datasets on social and environmental decision criteria for the decision complexity factor from the U.S. Census Bureau, U.S. Geological Survey, Data.gov, and the U.S. Department of Agriculture (Table 2). We included hazardous waste facilities in two different geographic contexts—Ohio, primarily importing from Canada, and Texas, primarily importing from Mexico—resulting in eight unique interactive maps. Using two locations mitigated individual bias for a region, combatted learning of map patterns, and collected two unique spatial decisions during the study, doubling decision trials for analysis. We created the study questions and interactive maps using the MapStudy open source

Table 2. Interface complexity and decision complexity factors.

Factor #1: Interface complexity		Factor #2: Decision complexity	
Operator	Definition	Criteria	Definition
Pan	Move the map to view other locations	Kilograms imported	An increased volume of hazardous waste at a processing site generally increases the potential risk to the local community and environment, all other things considered.
Zoom	Change the map scale	Percent non-white population	Environmental justice research shows that non-white communities may be more burdened by hazardous waste facilities than white communities.
Retrieve	Obtain additional details about map features	Air quality watches per capita	Processing hazardous waste releases emissions that can negatively impact air quality. An air quality watch is issued whenever air quality reaches unsafe levels.
Overlay[a]	Change the layers depicted on the map	Percent in poverty[a]	Environmental justice research shows that poor communities may be more burdened by hazardous waste facilities than wealthy communities.
Filter[a]	Set the criteria by which map features are added or removed from the map	Soil permeability[a]	Processing hazardous waste releases toxins that can permeate the soil if carried by a water source. The rate at which toxins penetrate into the landscape vary by soil type.

[a]Use in the *complex* condition only.

survey framework developed at the University of Wisconsin–Madison Cartography Lab (http://www.github.com/uwcart/, Sack and Roth, 2016).

We varied interface complexity conditions by interface scope (RQ1). The *simple* condition was constrained to the pan, zoom, and retrieve operators common to slippy web maps and the *complex* variation added filter and overlay. Thus, the *complex* variation did not provide more information about the decision, but rather additional ways to acquire (via overlay) or manipulate (via filter) the mapped information. Both conditions used the same, subdued basemap with limited context features and no labels to promote interaction during decision making. All other aspects of interface design (e.g., usability, compatibility, visual design and layout) were controlled between factors.

We varied decision complexity conditions by the number of decision criteria (RQ2), with the *simple* and *complex* condition including three and five criteria respectively (after Crossland et al., 1995). In both conditions, we included one economic criterion (kilograms of waste imported), balanced the remaining criteria between environmental and social impacts, and mapped seven processing facilities to control the number of decision outcomes. The inclusion of seven decision outcomes is based on the geography of the transnational trade of hazardous waste, as no state currently has more than seven processing facilities. We represented kilograms of waste imported using proportional symbols on the facility and made the other criteria available only through interaction. To determine the "optimal" or "correct" ranking of the seven facilities by the provided criteria, we classified each decision criterion into three categories and assigned values 1–3 (1 = low risk, 3 = high risk) to generate a total risk score across criteria. We selected the criteria so that the total scores were equally spaced across the seven facilities, resulting in a "correct" ranking of the seven facilities when considering all available information (i.e., decision criteria) equally following the EJ focus. In the interactive maps, the classification of each decision criterion was reported and mapped on an ordinal low-high risk scale.

Procedure

The online map study began with background information on project goals. After obtaining consent, participants completed a training block with an example decision scenario and an explanation of the available interactive functionality. The participants were allotted as much time as needed to explore the interactive map and complete the example decision before beginning the experimental blocks (Figure 1a).

Participants then completed two decisions of variable complexity using different geography (*Ohio, Texas*) and different interactive maps. We randomly assigned the decision complexity conditions to vary *within* subjects—resulting in the two tested scenarios per participant—but the interface complexity conditions varied *between* subjects so that participants only learned a single set of functionality in the opening example and thus did not try to evoke functionality that was removed in subsequent trials. The combination of decision complexity and geography, and the order of the two decisions within the online map study, was randomized within subjects.

Both decision trials began with participants reviewing a decision scenario. One scenario required participants to assume the role of a manager of a hazardous waste firm looking to send hazardous waste to the U.S. for disposal and rank their preference for doing business with listed facilities (Figure 1b). The other scenario asked participants to assume the role of a regulator at the EPA in charge of ensuring sound waste processing and rank the urgency of site visits to ensure companies are following regulations (Figure 1c). We derived the scenarios from the preparatory semi-structured interviews and confirmed they were appropriate in the pilot study, resulting in simplified, yet reasonably realistic ranking tasks at an elementary (site-specific) level. Importantly, EJ was the focal point in both decision scenarios, with the description contextualizing all reference to all decision criteria (Table 2) and therefore encouraging participants to consider all available information when making their decisions. The online map study completed with an exit survey capturing participant characteristics and experiences (RQ3). The complete study protocol is included in the online supplementary materials.

Measures and analysis

Participants' decisions associated with each map were captured through rank-order forms (Map Task; Figure 1b and 1c). Along with these responses, all map interactions performed by participants while evaluating each scenario were captured by the MapStudy application and recorded in a database. We did not collect decision response or interaction times given the potential for different loading rates and split attention in an online, uncontrolled testing environment.

We assessed correctness of the ranking decision using the Kendall Rank Correlation Coefficient (Crossland et al., 1995; Mennecke et al., 2000). Kendall analysis provides both a measure of correctness ($\bar{\tau}_b$) on a scale of -1 to 1 and the number of observations that are statistically correct at $p = 0.05$. We collected self-reported difficulty and confidence on

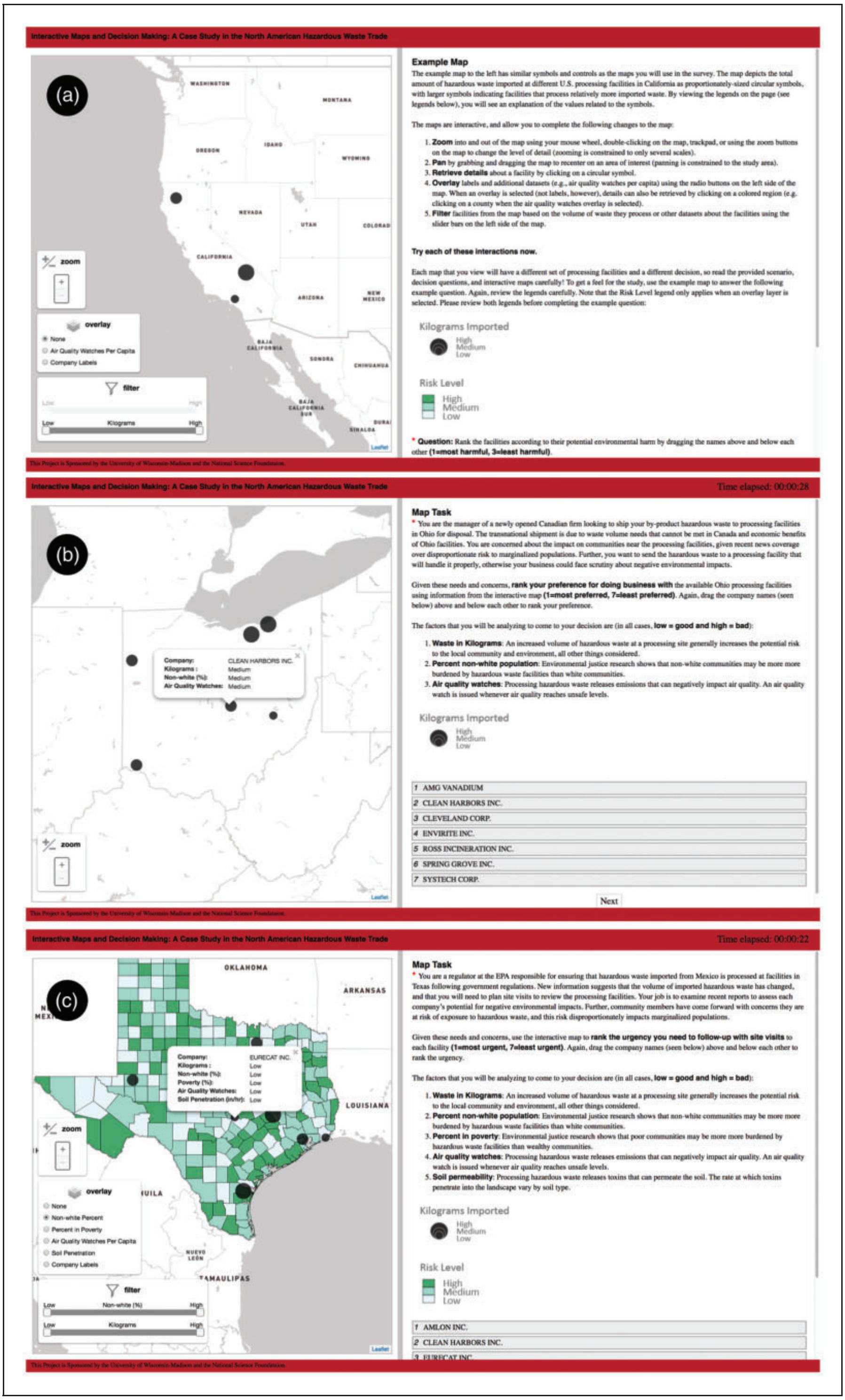

Figure 1. Tasks participants were asked to complete. (a) The example map (for the complex interface) detailing map functionality. (b) Company manager scenario requiring participants to rank facilities based on preference for doing business. (c) EPA regulator scenario requiring participants to rank facilities based on urgency of site visits.

five-point Likert scales. Finally, we coded participant interactions for each decision by operator and summarized operator use by extensiveness (whether or not an operator was used at least once for a decision) and frequency (total interactions for a decision) (Guo et al., 2016; Roth and MacEachren, 2016).

We conducted z-tests for differences in dependent variables between *simple* and *complex* interface complexity variations, and paired two sample t-tests for differences between decision complexity conditions (*simple, complex*), geography (*Ohio, Texas*), order (*1st, 2nd*), and expertise (*expert, non-expert*). Finally, we used χ^2 tests to determine differences in interaction operator extensiveness and frequency.

Results and discussion

Overall decision performance

The overall correctness of the ranking decisions was $\bar{\tau}_b = 0.629$ (SD = 0.449), indicating a positive correlation between observed participant rankings and the expected correct rankings. 56.6% of the decision outcomes were statistically correct at $p = 0.05$. The overall difficulty for all ranking decisions was 2.3/5 (SD = 1.1; 5 = very difficult) and overall confidence was 4.1/5 (SD = 0.9; 5 = very confident). These aggregate results suggest that the two decisions were properly simplified for the study sample and time constraints, while still sufficiently challenging to validly mirror real-world problem contexts on the management and regulation of hazardous waste. See the online supplementary materials for complete results tables.

We did not find significant differences by geography (*Ohio, Texas*) or order (*1st, 2nd*) on decision correctness, difficulty, or confidence. Thus, the study design successfully controlled for confounding effects to isolate the two examined factors.

Participants interacted with the map during 243 of 244 decisions (99.6%) through a substantial total of 5900 combined interactions, an indication that the training block properly introduced participants to the available interactivity. However, there were wide differences in the use of operators by both extensiveness ($\chi^2 = 362.25$, $p < 2.2 \times 10^{-16}$) and frequency ($\chi^2 = 24.834$, $p = 0.003$), meaning that the application of operators was non-random and thus intentional interaction strategies were used when making decisions. Overall, participants made greatest use of retrieving details, followed by panning and overlaying datasets, and relatively limited use of filtering and zooming. We again did not find significant differences in interaction by geography or order.

Interface complexity

Interface complexity (Factor #1) was the primary driver of decision performance in the online map study (Figure 2). Participants performed significantly better when given the *simple* interface that did not include overlay or filter ($z = 4.102$, $p = 4.102 \times 10^{-5}$); 68.4% of decisions were statistically correct for the *simple* condition ($\bar{\tau}_b = 0.732$), but only 41.7% for the *complex* condition ($\bar{\tau}_b = 0.500$).

Participants also found decisions supported by the *complex* interface condition significantly more difficult than the *simple* condition ($z = -3.198$, $p = 0.001$). The inclusion of additional interaction operators in the *complex* condition made the decision appear to be more difficult to participants, even though the decision itself was unchanged. Accordingly, the added interaction scope and its increased perceived difficulty likely explain the decreased decision correctness in the *complex* condition.

Further, participants were significantly less confident in their decisions when using the *complex* interface ($z = 2.941$, $p = 0.003$). Thus, not only did the increased interface

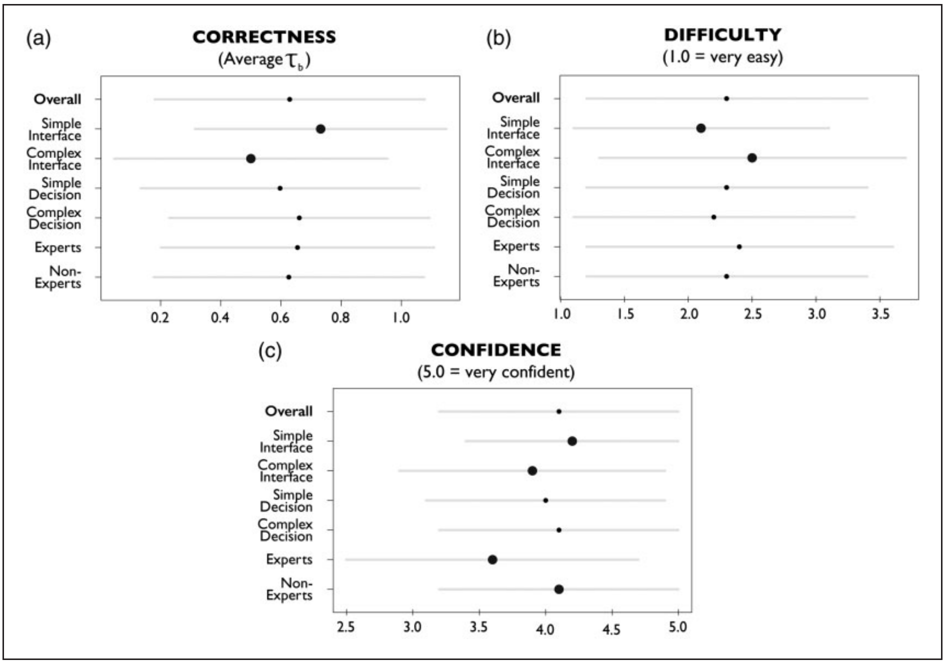

Figure 2. Comparison of means and standard deviations of the various conditions to the overall. (a) Correctness results for simple/complex interface and decision complexities and hazardous waste experts/non-experts. (b) Difficulty results for simple/complex interface and decision complexities and hazardous waste experts/non-experts. (c) Confidence results for simple/complex interface and decision complexities and hazardous waste experts/non-experts. Larger dots indicate significance. See full results tables in online supplementary materials.

complexity decrease correctness while increasing perceived difficulty, it also shook participant confidence. In a real-world scenario, this reduced confidence may make decision makers more likely to rely on prior experience or personal opinion during planning.

The observed differences in correctness, difficulty, and confidence between the *simple* and *complex* interface complexity conditions were clarified by the interaction logs. While participants did interact more when presented with the *complex* condition (19.15 versus 30.51 interactions per decision), we did not find significant differences in overall interactions either by extensiveness ($t = 0.619$, $p = 0.580$), given the overwhelming number of participants that interacted at least once, or by frequency ($t = 0.352$, $p = 0.759$), given the wide variation in interactions across participants. The increase in interaction with the *complex* condition was expected given the wider interface scope, but also further highlights the importance of constraint in interactive decision support tools, as the added time spent interacting did not clarify the decision, but instead complicated it.

However, interactions did vary by individual operators between interface complexity conditions. Participants employed retrieve significantly more times in the *simple* condition than the *complex* ($t = 3.77$, $p = 0.033$). Further, 100% of participants used retrieve at least once in the *simple* condition, but only 80.6% in the *complex* condition, a large although not significant difference ($t = 3.03$, $p = 0.058$). Retrieve accounted for 76.2% of all operators applied in the *simple* condition, but only 35.6% in the *complex* condition. Thus, while participants primarily relied on retrieve to make their decision when using the *simple* interface, participants made more use of wider range of operators in the *complex* interface, such as pan and overlay.

While participants applied pan relatively frequently in both conditions, the reliance on overlay in the *complex* condition is particularly noteworthy and suggests that separate interaction strategies were used between the *simple* and *complex* interfaces: the former relying on retrieve and the latter integrating use of overlay. Interestingly, retrieve and overlay present opposite interactive approaches for weighing decision criteria against decision outcomes, with retrieve presenting multiple criteria for a single outcome (e.g., as a textual information panel anchored to a single processing facility) and overlay presenting one criteria for all decision outcomes (e.g., as a new visual layer added to the map). In the case study, participants were more successful with the textual, retrieve-focused strategy than the visual, overlay-focused strategy. From a geographic perspective, the scale of the decision may have influenced the relative utility of retrieve versus overlay, as the focus of retrieve on a single outcome likely is more useful for site-based, elementary-level decisions (such as the decisions included in this research) while the focus of overlay on a range of outcomes may be more useful for regional-based, general-level decisions.

Finally, qualitative feedback suggested that filtering was not useful for the pair of decisions—further complicating the relationship between exploratory information seeking and decision support tools—and that pan and zoom were primarily used as enabling operators to work with the reduced screen real-estate for the interactive map in the MapStudy split-panel layout (Figure 1). These operators did not appear to influence decision making. Thus, participant interaction strategies did not indicate substantial information seeking using the *complex* interface, despite expectations (after Shneiderman, 1996).

Decision complexity

Decision complexity (Factor #2) was far less influential on decision making than interface complexity (Figure 2). We did not find a significant difference in correctness between decision complexity conditions ($t = -1.352$, $p = 0.179$). However, participants did perform slightly better on *complex* decisions ($\bar{\tau}_b = 0.661$, 59.0% statistically correct) than *simple* decisions ($\bar{\tau}_b = 0.597$, 54.1% statistically correct), a counterintuitive result as the *simple* condition had fewer criteria and therefore was expected to be easier. In the qualitative feedback, several participants noted that the wider array of criteria in the *complex* condition provided more signals to participants on how to complete the decision and modulated individual bias towards focusing on a single decision criterion versus considering all criteria. As stated above, this difference was not significant, meaning that interface complexity, *not* decision complexity, influenced the correctness of decision outcomes for the study.

We also did not find a significant difference between interface complexity conditions in difficulty ($t = 0.810$, $p = 0.419$) or confidence ($t = -0.797$, $p = 0.427$). Thus, greater decision complexity does not always mean greater decision difficulty or reduced confidence. As with correctness, interface complexity and *not* decision complexity influenced both dependent variables.

There were few noteworthy differences in interaction strategies between the *simple* and *complex* decision complexity conditions. As with the interface complexity factor, we did not find significant differences between conditions in interaction extensiveness ($t = -0.127$, $p = 0.902$) or frequency ($t = -0.203$, $p = 0.844$). We also did not find significant differences between decision complexity levels in the use of individual operators. Once again, it was the interface complexity, *not* decision complexity, that determined how participants developed interaction strategies to support their decision-making process.

Expertise

Expertise had a moderating effect on the way that participants used the interactive maps for spatial decision making (Figure 2). Overall, *experts* ($\bar{\tau}_b = 0.655$, 58.3% statistically correct) slightly outperformed *non-experts* ($\bar{\tau}_b = 0.626$, 56.4% statistically correct), however this difference was not significant ($t = 0.294$, $p = 0.769$). This is a plausible result given that only 10% of the sample was expert, a study limitation given the small and relatively inaccessible expert population.

Interestingly, we found a significant difference between *experts* and *non-experts* in confidence ($t = -2.723$, $p = 0.007$), but not difficulty ($t = 0.467$, $p = 0.641$), with *non-experts* (4.1/5, SD = 0.9) more confident in their responses than *experts* (3.6/5, SD = 1.1). While seemingly counterintuitive, this finding actually may be evidence that the *expert* group demonstrated their prior knowledge by properly assessing the gravity of the decision. *Experts* understood the consequences of their decisions and more fully weighed the costs of their decision (some of which may be uncertain) into their reported confidence. In contrast, *non-experts* lacked exposure to real consequences, leading to increased confidence. This finding is important for participatory EJ decision making, as the general public may not be fully aware of prior consequences in similar locations—and thus need such context in addition to local information—but also have a unique understanding of their own risks important to include in collaborative discussion.

Importantly, *experts* and *non-experts* differed substantially in their interaction strategies. Overall, *experts* (29.54 interactions per decision) interacted with the map more frequently than *non-experts* (only 23.60 interactions per decision) and we found significant differences in the use of each operator by both extensiveness and frequency.

Accordingly, analysis of interaction operators across expertise further clarified differences in interaction strategies. As reported above, participants using the textual, retrieve-focused strategy performed better than participants using the visual, overlay-focused strategy. However, *experts* more extensively made use of overlay than *non-experts* (100.0% versus 80.2%), but less extensive use of retrieve (83.3% versus 92.3%). Because there was no significant difference in correctness between conditions of expertise—with *experts* returning slightly more correct decisions—the overlay strategy was not universally suboptimal, but rather required a degree of expertise to use effectively. One hypothesis is that *experts* more easily interpreted the overlay map symbols, enabling them to review one criterion (attribute) across outcomes (sites), whereas non-experts relied on non-map text contained in the retrieval pop-ups, presenting information for one outcome (site) across all criteria (attributes). *Experts* also more extensively and frequently zoomed and filtered compared to *non-experts*, suggesting greater application of exploratory information seeking on which the *complex* interface design was based.

Conclusions: Improving spatial decision making with interactive maps

In this article, we reported on an empirical study to improve spatial decision making supported by interactive maps, using a case study on EJ concerns in the North American hazardous waste trade. Specifically, we asked three questions:

(1) *Does cartographic interface complexity influence the success of spatial decision making?* Differences in interface complexity significantly influenced decision making. Without considering moderating effects, the simpler interactive map resulted in more correct decisions, reduced perceived difficulty, and greater confidence. These findings

corroborate growing research that more interface functionality is not necessarily better (e.g., Dou et al., 2010; Jones et al., 2009; Keehner et al., 2008), with the appropriate interface complexity depending on the task at hand and extraneous operators potentially resulting in suboptimal interaction strategies (e.g., Edsall, 2003; Roth and MacEachren, 2016). This difference in confidence is important for spatial decision science, as decision makers may be more likely to rely on prior experience or personal opinion when using more complex interfaces.

The interaction logs further explained *how* interface complexity influenced spatial decision making. Two interaction strategies emerged for making the decisions: a textual, retrieve-focused strategy presenting multiple criteria for a single outcome and a visual, overlay-focused strategy presenting one criteria for all decision outcomes. This difference has several important implications. Participants in general were more successful when using retrieve instead of overlay, perhaps because the decision required them to rank individual sites rather than broad regions. Thus, the scale of analysis and reasoning may impact the relative utility of interaction operators for a given decision, with the map and map interactions perhaps growing more useful over text alternatives for general rather than elementary tasks (Andrienko et al., 2003). Finally, participants used filter and zoom relatively infrequently, suggesting that not all problem contexts require engagement with exploration (after MacEachren, 1994) and information seeking (after Shneiderman, 1996).

(2) *Does decision complexity influence the success of spatial decision making supported by interactive maps?* Not all decision contexts are the same, but decision complexity did not impact the decision-making process. We did not find significant differences in decision correctness, difficulty, confidence, or interaction strategies between the simple and complex decisions, a result consistent with Crossland et al. (1995) and Jankowski and Nyerges (2001).

Taken together, these findings on interface and decision complexity are important from a design perspective, as the interactive map design can have more influence over the decision-making process than the decision itself. Thus, interactive mapping tools actually may interfere with the decision-making process when designed poorly or for the wrong problem context. We hypothesize that a threshold specific to every problem context exists where decision complexity, not interface complexity, has a greater influence on the decision-making process and outcomes. In particular, future research is needed to vary the number of decision outcomes in addition to decision criteria to understand the interplay of all components of decision complexity with interface complexity.

(3) *Is the influence of cartographic interface complexity and spatial decision complexity dependent upon the expertise of the decision maker?* Finally, differences in participant expertise influenced the interaction strategies participants used to complete their decision. We expect the role of expertise to become more important as the decision complexity grows. While we did not find a significant difference by expertise in perceived difficulty, experts were significantly less confident in their decisions. This finding corroborates prior work on expertise in mapping and clarifies the above relationship between interface complexity and confidence: while the complex interactive map reduced confidence and therefore would make decision makers more likely to rely on prior experiences or personal opinions, expert decision makers are always better positioned to draw from experience, particularly from their understanding of the potential consequences of their decisions. Further research is needed to understand how to build expert and non-expert trust in interactive maps to support decision making and action. The differences in interaction strategies between experts and non-experts were

striking, with experts making use of a wider range and number of interactions. Based on these results, experts are capable of making use of more complex interactive maps, while non-expert citizens need simple interactive maps to participate in the decision-making process, supporting MacEachren (1994). As experts and non-experts begin to work together for community-driven EJ—and as the expert and non-expert continue to blur in a digital, information-driven age—we anticipate a move away from generic, multi-purpose systems towards custom interactive maps tailored for a specific collaborative assemblage of spatial decisions and decision makers.

Our research had several limitations that point to further research extensions. First, we investigated interface and decision complexity in a single application domain—EJ in the hazardous waste trade—and our findings should be corroborated in other application domains. Second, this study did not consider collaborative decision making, with each participant making their decisions individually. We are planning follow-up field work in the hazardous waste trade to understand how decision makers collaborate on problems to negotiate an optimal outcome using a wider range of information with numerous uncertainties. Finally, our analysis pointed to several additional experimental factors and measures worthy of examination, including additional interaction operators, a wider range of decision complexities, a comparison of site (elementary) and regional (general) decisions, and additional individual differences. We have made our source code available as supplementary materials to enable extension (see also http://www.github.com/uwcart/).

Interactive maps hold substantial potential for improving spatial decision making. In the context of EJ, such interactive maps make otherwise disparate geographic information accessible and usable, enabling decision makers to consider a wide range of social, environmental, and economic impacts as they determine our future landscapes. As geographic information and interactive maps to this information become increasingly central to such spatial decisions, we need future research on what interactions are needed for which types of decisions and decision makers.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was supported by the National Science Foundation Awards #1539712 and #1555267, the University of Wisconsin–Madison Department of Geography Trewartha Research Grant, the AAG Cartography Specialty Group Master's Thesis Research Grant, and the Wisconsin Alumni Research Foundation.

ORCID iD

Robert E Roth http://orcid.org/0000-0003-1241-318X

Supplementary material

Supplementary material is available for this article online.

References

Aerts JC, Clarke KC and Keuper AD (2003) Testing popular visualization techniques for representing model uncertainty. *Cartography and Geographic Information Science* 30(3): 249–261.

Andrienko G, Andrienko N, Jankowski P, et al. (2007) Geovisual analytics for spatial decision support: Setting the research agenda. *International Journal of Geographical Information Science* 21(8): 839–857.

Andrienko N, Andrienko G and Gatalsky P (2003) Exploratory spatiotemporal visualization: An analytical review. *Journal of Visual Languages & Computing* 14(6): 503–541.

Andrienko N, Andrienko G, Voss H, et al. (2002) Testing the usability of interactive maps in CommonGIS. *Cartography and Geographic Information Science* 29: 325–342.

Armstrong MP and Densham P (1995) Cartographic support for collaborative spatial decision-making. *Prodceedings of AutoCarto* 49–58. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi = 10.1.1.488.7480&rep = rep1&type = pdf.

Bostock M, Ogievetsky B and Heer J (2011) D3: Data-driven documents. *Transactions in Visualization & Computer Graphics* 17(12): 2301–2309.

Buzzelli M and Jerrett M (2003) Comparing proximity measures of exposure to geostatistical estimates in environmental justice research. *Environmental Hazards* 5(1–2): 13–21.

Coutinho-Rodrigues J, Current J, Climaco J, et al. (1997) Interactive spatial decision-support system for multiobjective hazardous materials location-routing problems. *Transportation Research Record* 1602: 101–109.

Crossland MD, Wynne R and Perkins WE (1995) Spatial decision support systems: An overview of technology and a test of efficacy. *Decision Support Systems* 14: 219–235.

Dou W, Ziemkiewicz C, Harrison L, et al. (2010) Comparing different levels of interaction constraints for deriving visual problem isomorphs. *Proceedings of VAST* 195–202. Available at: http://ieeexplore.ieee.org/document/5653599/.

Edsall RM (2003) Design and usability of an enhanced geographic information system for exploration of multivariate health statistics. *The Professional Geographer* 55(2): 146–160.

Einhorn HJ and Hogarth RM (1981) Behavioral decision theory: Processes of judgment and choice. *Annual Review of Psychology* 32: 53–88.

Elwood S (2006) Critical issues in participatory GIS: Deconstructions, reconstructions, and new research directions. *Transactions in GIS* 10(5): 693–708.

Elwood S and Leszczynski A (2013) New spatial media, new knowledge politics. *Transactions of the Institute of British Geographers* 38(4): 544–559.

Evans BJ (1997) Dynamic display of spatial data-reliability: Does it benefit the map user? *Computers & Geosciences* 23(4): 409–22.

Goodchild MF (2015) Perspectives on the new cartography. *Environment and Planning A* 47(6): 1341–1345.

Goodspeed R, Riseng C, Wehrly K, et al. (2016) Applying design thinking methods to ecosystem management tools: Creating the Great Lakes Aquatic Habitat Explorer. *Marine Policy* 69: 134–145.

Griffin AL, White T, Fish C, et al. (2017) Designing across map use contexts: A research agenda. *International Journal of Cartography* 3(sup1): 90–114.

Guo H, Gomez SR, Ziemkiewicz C, et al. (2016) A case study using visualization interaction logs and insight metrics to understand how analysts arrive at insights. *Transactions on Visualization & Computer Graphics* 22(1): 51–60.

Hardisty F and Robinson AC (2011) The GeoViz Toolkit: Using component-oriented coordination methods for geographic visualization and analysis. *International Journal of Geographical Information Science* 25(2): 191–210.

Harrower M and Sheesley B (2005) Designing better map interfaces: A framework for panning and zooming. *Transactions in GIS* 9(2): 77–89.

Hope S and Hunter GJ (2007) Testing the effects of thematic uncertainty on spatial decision-making. *Cartography and Geographic Information Science* 34(3): 199–214.

Howard DL and MacEachren AM (1996) Interface design for geographic visualization: Tools for representing reliability. *Cartography and Geographic Information Science* 23(2): 59–77.

Jankowski P (2009) Towards participatory geographic information systems for community-based environmental decision making. *Journal of Environmental Management* 90(6): 1966–1971.

Jankowski P, Andrienko N and Andrienko G (2001) Map-centred exploratory approach to multiple criteria spatial decision making. *International Journal of Geographical Information Science* 15(2): 101–127.

Jankowski P and Nyerges T (2001) GIS-supported collaborative decision making: Results of an experiment. *Annals of Association of American Geographers* 91(1): 48–70.

Jankowski P and Richard L (1994) Integration of GIS-based suitability analysis and multicriteria evaluation in a spatial decision support system for route selection. *Environment and Planning B: Planning and Design* 21: 323–340.

Jelokhani-Niaraki M and Malczewski J (2015) Decision complexity and consensus in Web-based spatial decision making: A case study of site selection problem using GIS and multicriteria analysis. *Cities* 45: 60–70.

Jones CE, Haklay M, Griffiths S, et al. (2009) A less-is-more approach to geovisualization–enhancing knowledge construction across multidisciplinary teams. *International Journal of Geographical Information Science* 23(8): 1077–1093.

Keehner M, Hegarty M, Cohen C, et al. (2008) Spatial reasoning with external visualizations: What matters is what you see, not whether you interact. *Cognitive Science* 32(7): 1099–1132.

Kweon B, Mohai P and Lee S (2016) Proximity of public schools to major highways and industrial facilities, and students' school performance and health hazards. *Environment and Planning B: Planning and Design*. Available at: http://journals.sagepub.com/doi/abs/10.1177/0265813516673060.

Lara-Valencia F, Harlow SD, Lemos MC, et al. (2009) Equity dimensions of hazardous waste generation in rapidly industrialising cities along the United States–Mexico border. *Journal of Environmental Planning and Management* 52(2): 195–216.

Laurian L (2005) Public input in toxic site cleanup decisions: The strengths and limitations of Community Advisory Boards. *Environment and Planning B* 32: 445–467.

Leung Y (2012) *Intelligent Spatial Decision Support Systems*. Berlin, Heidelberg: Springer.

MacEachren AM (1994) Visualization in modern cartography: Setting the agenda. *Visualization in Modern Cartography* 28(1): 1–12.

MacEachren AM (2015) Distributed cognition: A conceptual framework for understanding map-based reasoning. In: *International Cartography Conference, Rio de Janeiro*. Available at: http://www.icc2015.org/trabalhos/2/940/T2-940_1428691752.pdf.

MacEachren AM, Boscoe FP, Haug D, et al. (1998) Geographic visualization: Designing manipulable maps for exploring temporally varying georeferenced statistics. *Proceedings of InfoVis* 87–94. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi = 10.1.1.61.8999&rep = rep1&type = pdf.

MacEachren AM, Gahegan M, Pike W, et al. (2004) Geovisualization for knowledge construction and decision support. *IEEE Computer Graphics and Applications* 24(1): 13–17.

Mennecke ME, Crossland MD and Killingsworth BL (2000) Is a map more than a picture? The role of SDSS technology, subject characteristics, and problem complexity on map reading and problem solving. *MIS Quarterly* 24(4): 601–629.

Moore SA, Roth RE, Rosenfeld H, et al. (in press) Undisciplining environmental justice research with visual storytelling. *Geoforum*. Available from: https://doi.org/10.1016/j.geoforum.2017.03.003.

Muehlenhaus I (2013) *Web Cartography*. Boca Raton: CRC Press.

Nost E, Rosenfeld H, Vincent K, et al. (2017) HazMatMapper: An online and interactive geographic visualization tool for exploring transnational flows of hazardous waste and environmental justice. *Journal of Maps* 13(1): 14–23.

Ooms K, De Maeyer P and Fack V (2015) Listen to the map user: Cognition, memory, and expertise. *The Cartographic Journal* 52(1): 3–19.

Payne JW, Bettman JR and Johnson EJ (1993) The adaptive decision maker. *The Adaptive Decision Maker* 45(7): 352.
Peterson MP (2003) Maps and the internet: An introduction. *Maps and the Internet*. Oxford: Elsevier, pp. 1–16.
Poplin A (2015) How user-friendly are online interactive maps? Survey based on experiments with heterogeneous users. *Cartography and Geographic Information Science* 42(4): 358–376.
Rinner C (2003) Web-based spatial decision support: Status and research directions. *Journal of Geographic Information and Decision Analysis* 7(1): 14–31.
Robinson AC, Demšar U, Moore AB, et al. (2017) Geospatial big data and cartography: Research challenges and opportunities for making maps that matter. *International Journal of Cartography* 3(sup1): 32–60.
Roth RE (2009) The impact of user expertise on geographic risk assessment under uncertain conditions. *Cartography and Geographic Information Science* 36(1): 29–43.
Roth RE (2012) Cartographic interaction primitives: Framework and synthesis. *The Cartographic Journal* 49(4): 376–395.
Roth RE (2013) An empirically-derived taxonomy of interaction primitives for interactive cartography and geovisualization. *IEEE Transactions on Visualization and Computer Graphics* 19(12): 2356–2365.
Roth RE, Çöltekin A, Delazari L, et al. (2017) User studies in cartography: Opportunities for empirical research on interactive maps and visualizations. *International Journal of Cartography* 3(sup1): 61–89.
Roth RE and MacEachren AM (2016) Geovisual analytics and the science of interaction: An empirical interaction study. *Cartography and Geographic Information Science* 43(1): 30–54.
Sack CM and Roth RE (2016) Teaching open web mapping. In: *Proceedings of 2016 International Symposium on Automated Cartography (AutoCarto), ICA Commission on Open Source Geospatial Technologies*, Albuquerque, NM, USA, 14 September.
Sample JT and Ioup E (2010) *Tile-Based Geospatial Information Systems: Principles and Practices*. New York, NY: Springer.
Shneiderman B (1996) The eyes have it: A task by data type taxonomy for information visualizations. *Proceedings of Visual Languages* 336–343.
Sider T, Hatzopoulou M, Orlando F, et al. (2015) Smog and socioeconomics: An evaluation of equity in traffic-related air pollution generation and exposure. *Environment and Planning B: Planning and Design* 42: 870–887.
Speier C (2006) The influence of information presentation formats on complex task decision-making performance. *International Journal of Human Computer Studies* 64(11): 1115–1131.
Talen E (1999) Constructing neighborhoods from the bottom up: The case for resident-generated GIS. *Environment and Planning B: Planning and Design* 26(4): 533–554.
Thomas JJ and Cook KA (2005) Illuminating the path: The research and development agenda for visual analytics. *Computer Society* 54(2): 184.
Yang C, Huang Q, Li Z, et al. (2017) Big data and cloud computing: Innovation opportunities and challenges. *International Journal of Digital Earth* 10(1): 13–53.

Kristen Vincent is a GIS Technician at Stantec Consulting Services Inc. Her research interests include interactive cartography with decision-making applications.

Robert E Roth is an associate professor of geography at UW–Madison and the faculty director of the UW Cartography Lab. His research interests include the design and use of interactive, online, and mobile maps and visualizations in support of pressing environmental and geographic problems.

Sarah A Moore is an assistant professor of geography at UW–Madison. She researches the hazardous waste trade in North America and is an author, with Paul Robbins and John

Hintz, of *Environment and Society: A Critical Introduction* published by Wiley-Blackwell (3rd edition, 2018).

Qunying Huang is an assistant professor of geography at UW–Madison. Her research interests are in geographic information science (GIScience), particularly cyberinfrastructure, cloud computing, spatiotemporal big data mining, and large-scale environmental modeling and simulation.

Nick Lally is a PhD candidate in geography at UW–Madison. His research intersects geography, art, and computer programming with a particular emphasis on software studies, social movements, visual epistemology, spatial theory, feminist thought, and contemporary philosophy.

Carl M Sack is the geospatial technologies program coordinator at Fond du Lac Tribal and Community College. His research includes new web mapping technologies and workflows, pedagogies for teaching web mapping, Indigenous-led environmental justice struggles, and resistance mapping for environmental justice.

Eric Nost is an assistant professor of geography at the University of Guelph. He is a political ecologist who draws on science and technology studies to understand how data governance shapes environmental conservation.

Heather Rosenfeld is a PhD candidate, cartoonist, and cartographer at UW–Madison. Her work bridges human geography and science and technology studies to examine the alternative economies and development of extra-institutional medical knowledge at farm animal sanctuaries in the United States.