Using geovisualizations to educate the public about environmental health hazards: What works and why

Authors:
Catherine E. Slavik[1] PhD, MPH [ORCID: 0000-0002-3077-239X]
Carolyn Fish[2] PhD [ORCID: 0000-0002-2366-5035]
Ellen Peters[1,3] PhD [ORCID: 0000-0003-0702-6169]

[1]*Center for Science Communication Research, University of Oregon, Eugene, OR, USA*
[2]*Department of Geography, University of Oregon, Eugene, OR, USA*
[3]*Department of Psychology, University of Oregon, Eugene, OR, USA*

Corresponding Author Details:
Catherine E. Slavik, cslavik@uoregon.edu
School of Journalism and Communication, University of Oregon
1715 Franklin Boulevard, Eugene, OR, 97403, USA

Abstract

Purpose of review: Informing the public about environmental risks to health is crucial for raising awareness around hazards, and promoting actions that minimize exposures. Geographic visualizations—geovisualizations—have become an increasingly common way to disseminate web-based information about environmental hazards, displaying spatial variations in exposures and health outcomes using a map. Unfortunately, ineffective geovisualizations can result in inaccurate inferences about a hazard, leading to misguided actions or policies. In this narrative review, we discuss key considerations for the use of geovisualizations to promote environmental health literacy.

Recent findings: Many conventional geovisualizations used for hazard education and risk communication fail to consider how people process visual information. Design choices that prompt viewers to think and feel, leveraging processes such as individual attention, memory, and emotion, could promote improved comprehension and decision making around environmental health risks using geovisualizations. Based on the studies reviewed, we recommend six strategies for designing effective, evidence-based geovisualizations, synthesizing evidence from the cognitive sciences, cartography, and environmental health. These strategies include: Displaying only key data, tailoring and testing geovisualizations with the desired audience, using salient cues, leveraging emotion, aiding pattern recognition, and limiting visual distractions.

Summary: Geovisualizations offer a promising avenue for advancing public awareness and fostering proactive measures in addressing complex environmental health challenges. This review highlights how incorporating evidence-based design principles into geovisualizations could promote environmental health literacy. More experimental research evaluating geovisualizations, using interdisciplinary approaches, is needed.

Keywords: environmental health; geovisualization; maps; hazard education; risk communication; exposure mitigation

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Introduction

The extent to which populations, globally, are exposed to environmental hazards is immense and can be difficult to grasp; some 13 million people die each year as a result of environmental risks such as air pollution and radiation [1]. Yet, public awareness surrounding the health impacts of many environmental hazards—and strategies to mitigate them—remains low [2]. Enhancing environmental health literacy is viewed as a critical first step towards encouraging individuals to shift behaviors and empowering communities to protect themselves from harmful environmental risks [3]. Thus, reducing the environmental burden of disease necessitates public education on environmental health risks, emphasizing who is at risk and when and where exposures occur.

Visuals are a powerful tool for learning. They attract attention, are processed more quickly than text alone, and are easier to recall [4,5]. This may explain why geographic visualizations, or geovisualizations, have become a popular tool for environmental health risk communication. They typically consist of static web-based thematic maps, interactive online dashboards containing spatial data, or some combination of the two [6]. Geovisualizations are designed to enable individuals to perform tasks like identifying specific locations on the map, retrieving information about the level of risk there, and gauging the distance between oneself and the risks displayed [7]. Hence, unlike other visuals (e.g., graphs), geovisualizations offer viewers a tangible representation of the world and leverage people's ability to connect information to particular places [8]. Visualizing data on the distribution of environmental exposures using maps is also thought to help viewers interpret information about environmental hazards and apply it towards risk-informed decision making, thereby promoting environmental health literacy [9]. Yet, many geovisualizations are never evaluated to determine whether they achieve these goals [10,11]. When testing with users has occurred, it has been found that many geovisualizations developed for public education about disease risk factors are too complicated for the average person to use and interpret, especially without assistance [12–15].

Misunderstanding geovisualizations can have major consequences. It can lead to the dismissal of serious risks from hazards like earthquakes—resulting in large losses to life—when maps don't adequately communicate risk probabilities to community members [16]. On the other hand, it can lead to risk overestimations if maps lead viewers to infer that the mere presence of a hazard (e.g., historical industrial contamination) will cause a disease [17]. This is a common concern in cancer epidemiology where incidence maps depicting cancer disparities across regions have the potential to mislead individuals into falsely attributing cancer causation solely to environmental factors in one area, without considering other influential risks [18]. Most recently, some COVID-19 geovisualizations have faced criticism due to poor design choices that impacted viewers' interpretation of disease risks and did little to improve knowledge about COVID-19 [19,20]. These examples underscore the importance of designing geovisualizations that enable people to make accurate and informed judgments of health risks, enhancing individual decision-making processes.

The design of effective geovisualizations requires considering how individuals will process the information presented. Some individuals with lower numeracy or graph literacy may lack the technical skills to easily extract information from a map and form accurate risk judgments [21–23]. In fact, some people appear to rely more on personal experiences or feelings to help them interpret maps [24,25]. This type of information processing based on heuristics (e.g., the *affect heuristic*), which has been studied extensively in psychology and cognitive science, has been found to impact risk comprehension and decision making by influencing people's emotional reactions and perceptions of risk [26–28]. Some recent works in the geographic information sciences, particularly in cartography, have also called attention to the need to explore how emotion and other cognitive mechanisms may be used to process information from geovisualizations [29–31].

Unfortunately, insights from the cognitive sciences and cartography concerning how people process visual information are rarely integrated into the environmental health education and risk communication domains to produce evidence-based geovisualizations. Indeed, prior reviews on the use of geovisualizations in public health have largely focused on characterizing the types of maps used and synthesizing strategies for communicating risk information [9,32–34], without much (if any) consideration to how the careful design of geovisualizations can aid comprehension of environmental health risks and promote risk-informed decision making. This presents a problem because—in the absence of knowledge from these disciplines—we risk developing geovisualizations that neither meet the public's informational needs nor reflect how people learn about (and make sense of) their environment. We also risk incorporating ineffective design choices into geovisualizations that end up misleading the public, resulting in incorrect interpretations of information and poor decision making.

The objectives of this narrative review are to: (1) examine key factors influencing the effectiveness of geovisualizations by synthesizing theoretical and applied research from the cognitive sciences, cartography, and environmental health and (2) provide evidence-based recommendations to improve web-based geovisualization design for environmental health education. This review is broadly divided into four sections. First, we begin by reviewing how people process visual information, drawing initially from the cognitive sciences literature, and then from research in cartography on geographic information processing. Second, we synthesize three overarching design strategies for geovisualizations informed by these two disciplines and examine how they have been applied and tested in research from the environmental health domain. Third, we present six recommendations for designing effective geovisualizations that promote environmental health literacy. Finally, we discuss future research directions within this interdisciplinary body of work.

<u>How Visual Information is Processed</u>

Insights From Cognitive Science

Processing visual information primarily involves two mechanisms, bottom-up and top-down processing. In bottom-up processing, characteristics of the visual stimulus influence how information is perceived and encoded by the viewer [35]. In essence, an individual's attention selects the most salient objects in a visual display and, as they engage their visual perception system, they construct an image and form a mental model of the objects [36]. In contrast, top-down mechanisms leverage people's existing knowledge and memories to guide interpretations of a visual display [37]. Bottom-up mechanisms appear to play an important role in a person's initial quick scan for the most salient visual cues displayed, with top-down mechanisms taking over to guide attention towards more targeted or task-relevant objects [38]. Top-down and bottom-up information processing can sometimes prompt effortful thinking (i.e., cognitive information processing), and/or rapid heuristic responses based on feelings (e.g., the *affect heuristic*) [39].

Cognitive Information Processing

As an individual’s attention zeroes in on a given object through the initial bottom-up mechanisms, four basic visual perceptual factors are thought to efficiently help us discern what objects are being displayed [40]. The first factor—perceptual units—help people interpret which object stands out the most due to perceived changes in visual characteristics (e.g., color, shading, patterns). Second, Gestalt Laws help people recognize and organize objects by grouping similar or proximal ones together. Third, varied representations of magnitude (e.g., object size) help people tell different objects apart from one another. Lastly, coordinate systems, which are especially relevant in the context of geo-visualizations, are used to differentiate objects that vary along several dimensions (e.g., over time and space). People’s attention to these four visual perceptual factors influences what information is perceived, encoded, stored, and subsequently used to make decisions or guide future behavior.

In addition to the characteristics of the visual stimulus, people use their own mental schema in a top-down manner to process the information. As people scan the information, they are thought to carry out a mental matching process to identify visual elements that match those already stored in their long-term memory [40]. Visualizations displaying data in familiar ways can kickstart this matching process and help free up mental capacity for other cognitive tasks, such as interpreting displayed risk information or using information to make decisions [41]. This matching process, also known as ‘cognitive fit’, leads to more effective and efficient problem-solving that helps viewers make more correct inferences about the visualization [42]. By contrast, when a mismatch appears—for example, if the information is presented in a nonintuitive manner—working memory must be used instead to temporarily store information from the visual until a judgment is made about how that information should be analyzed [43].

Individual skills also influence people’s cognitive information processing by impacting how effortful it will be. For example, people who are more numerate are more likely to draw correct conclusions from visualizations that present numerical information [41]. When people don’t have to use as much mental effort to decipher data, they appear to comprehend it more quickly and accurately [44]. Fortunately, visualizations can reduce these discrepancies between individuals with high and low numeracy if certain design strategies are employed. For example, including textual information alongside numeric information through the use of labels and captions has helped those with limited numerical skills accurately interpret visual information containing numbers [27]. Thus, people employ powerful cognitive mechanisms, like attention and memory, to process information in a visual.

Information Processing Using Feelings

People also rely on their feelings to process visual information. When looking at a given visual, sensory signals are perceived and can trigger positive or negative feelings in response to some of the visual elements [35]. People use an ‘affect heuristic’, a type of mental shortcut, when they rely on their feelings to quickly make judgments about objects in a visual, rather than by engaging in a more thoughtful and effortful evaluation of the visual information [45]. Visualizations can provoke strong feelings depending on their presentation, subject matter, and other cues (e.g., colors, aesthetics, messaging) [46–48]. For example, evocative visual imagery of wildfire smoke can prompt negative fear-related emotions, which can be effective at promoting health-protective actions (e.g., using an air purifier) to cope with the perceived threat [49]. Visualizations containing positive emotional cues also can support individuals’ healthy decision-making. For example, using labels like ‘excellent’ to highlight regions with good air quality on a map could be useful to an individual trying to decide where to plan a safe outdoor activity. Thus, emotional cues can serve as meaningful information used to inform a judgment about something like an environmental risk (i.e., 'affect-as-information' theory) [50].

An individual's prior feelings towards certain objects or events can also significantly influence what information their attention zeroes in on and which elements of a visual they encode in their memory. For example, a person with negative feelings towards wind turbines may spend more time examining the risks, and less time on the benefits, when given an infographic about renewable wind energy. This kind of information processing relies on a person's prior feelings and experiences to guide interpretation (i.e., 'affect-as-spotlight' theory), further highlighting the importance of emotion in shaping learning and decision making using visuals [50].

Insights From Cartography

Unlike standard visuals, geovisualizations contain geographic and spatial data (e.g., coordinates, distance, direction) requiring processing of information that is both visual and spatial. Thus, compared to other types of visual information, viewers perform more complex tasks involving spatial reasoning and problem-solving when processing information from a geovisualization [51]. Cartographers have thought about how different types of map visuals require different design considerations depending on the audience's level of content expertise, map literacy, and the goals of the map. For example, DiBiase [52] demonstrated that experts like scientists may use visualizations to explore data and generate research hypotheses, whereas lay people or public audiences likely use visualizations as a source of information. The former type of map user may desire more opportunities to interact with the visualization to dig deeper and explore complex variables so that the map serves as a tool to stimulate 'visual thinking'; the latter likely desires a much simpler 'visual communication' tool that presents the data in a clear and easy-to-understand manner. MacEachren expanded on this idea with his 'cartography cube' [53] concept, showing that public audiences tend to benefit more from maps that i) communicate visual information in a simple way, ii) are less interactive (i.e., more static), and iii) focus on what is *known* about the information (rather than highlighting *unknowns*). Nonetheless, research from cartography is consistent with the cognitive sciences literature regarding use of both top-down and bottom-up mechanisms to aid processing of geographic information.

Cognitive Information Processing Using Geovisualizations

From a bottom-up perspective, people scan information in a geovisualization by encoding the most salient cues perceived, as they would with other visual displays, and then mentally transform any spatial objects displayed to help make sense of their values, relations, and orientations [54]. Because viewers' gaze and attention are naturally attracted to the most perceptually salient items, they especially notice map features that don't require effort to be read and understood [55]. Salient map items may include points, lines, and zones, which can be varied by size, color, shape, or other properties [40,56,57] to make them stand out in a map display [58]. In fact, many geovisualizations are developed with a visual hierarchy, making the most task-relevant items the most salient features. This hierarchy guides viewers' attention towards perceiving the most pertinent information first, then towards less relevant items during subsequent scans of the visual. In doing so, viewers tend to fixate more on the salient and task-relevant features and spend more time analyzing them [56]. In contrast, placing visual emphasis on less task-relevant information in a geovisualization can divert attention and bias judgments of the data displayed, leading to misinterpretation of important information [59,60].

From a top-down perspective, individuals' short-term and long-term memory are key mechanisms influencing the processing of information in a geovisualization. As individuals focus on areas of a map, they use their working memory to encode visual elements like roads, landmarks, and colors of shapes, into a mental representation of the overall geographic area. To infer relationships between different elements (e.g., the distance between two points on a map), people also use their working memory to compare features and make spatial judgments [61]. Thus, maps with fewer visual elements are likely to be less cognitively-taxing, freeing up working memory to complete other tasks using the geovisualization. An example of a common task includes searching for a personally-relevant location (i.e., one's home), which is a highly goal-directed navigation task engaging top-down processes [37]. In fact, searching for familiar locations in a geovisualization drives a pattern recognition process (similar to 'cognitive fit' discussed above) that enables viewers to quickly match the elements displayed to those stored in their long-term memories [62].

Accurate processing of information from geovisualizations also depends on people's internal spatial visualization skills, including an individual's ability to mentally represent and transform visuospatial information from a display [63,64]. Spatial knowledge can be acquired both directly through navigating environments and indirectly through studying maps [65]. For example, training novice map users on how to read a map, or providing an interpretive guide highlighting key information has been found to aid comprehension of geovisualizations [56,66]. However, even individuals who are familiar with and experienced in reading maps can face challenges correctly interpreting information from poor geovisualizations, underscoring the importance of choosing the right visual designs [67,68].

Processing Geovisualizations Using Feelings

Geovisualizations containing visual elements that prompt positive and/or negative feelings also can support effective and efficient information processing using heuristics. Various cues have been identified by cartographers—for example, vivid map colors, realism, photos, and narrative information—as visual elements that can prompt emotional responses and relay important information to viewers [61,69,70]. Emotional cues can serve as sources of information to help a viewer quickly construct a mental model of the geovisualization and appear to play an important role in decision making [71].

People also rely on emotional cues like colors with extreme contrast (e.g., red, black) to help focus their attention towards key visual elements in a geovisualization [72]. Sequential color schemes, which employ a gradient of a single color hue going from light to dark, can be used to highlight areas with the highest (i.e., darkest) values of the variable displayed [73]. This process helps viewers encode specific visual elements in their memory, improving information recall and driving further information-seeking [74,75]. Furthermore, geovisualizations presenting information relevant to the viewer's own neighborhood can prompt feelings of place attachment and make the information displayed feel more engaging and personally relevant [76,77]. This may be explained by the role that emotional cues can play in motivating behaviors [50]; in this case, feelings motivate viewers to engage more intensely with local information they consider interesting and stimulating.

<u>Geovisualization Design Strategies and Applications to Environmental Health</u>

Research from the cognitive sciences and cartography both point towards geovisualizations helping to harness individuals' powerful visual systems to process information. The literature suggests that geovisualizations that engage both top-down and bottom-up information processing by leveraging key psychological processes like attention, memory, and emotion, could be used to support people's understanding of environmental hazards and promote risk-informed decision making. Fortunately, design strategies supporting these psychological processes have already been evaluated and tested for their effectiveness—using experimental and qualitative methods—to educate the public about a variety of environmental hazards and exposures. Here, we synthesize the results from these studies, outlining three types of design strategies, and examine their practical application in environmental health research. These strategies are summarized in **Fig 1**.

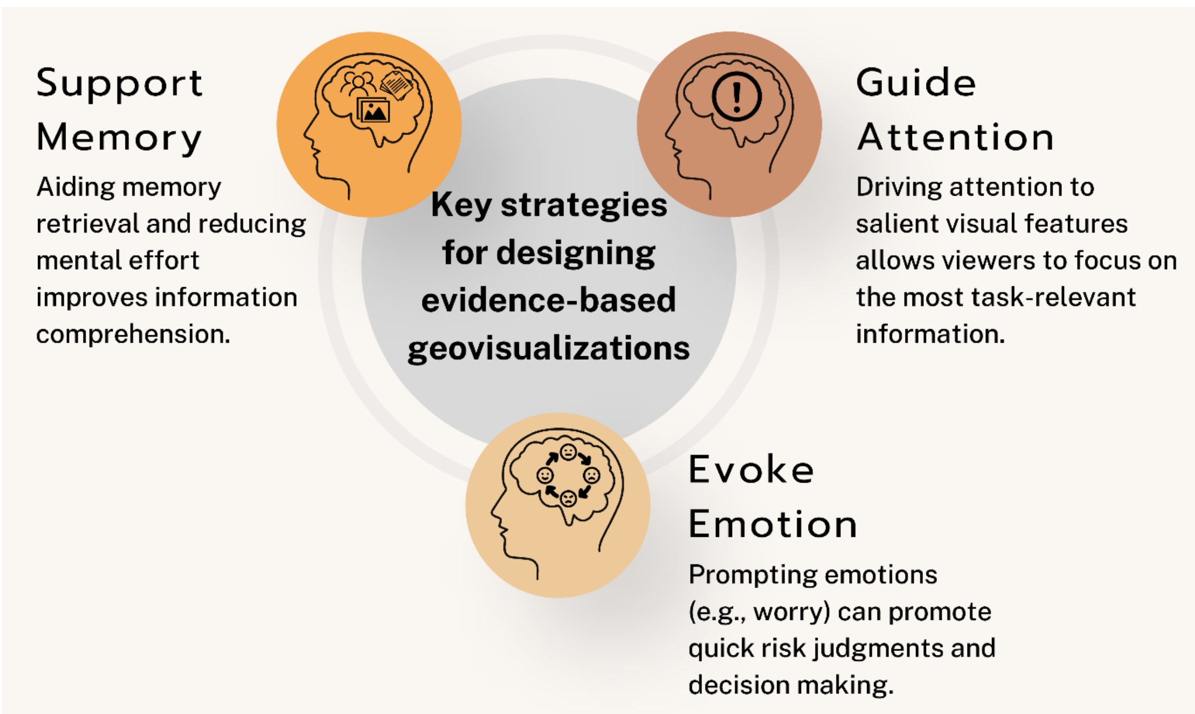

Fig 1. Strategies informed by evidence from cognitive science and cartography that can be applied to environmental health geovisualizations.

Strategies Guiding Attention

The application of design strategies that help direct viewers' attention towards salient areas on a map can improve understanding of the risks of encountering an environmental hazard in a location [78]. Geovisualizations employing sequential color schemes, which rely on lighter and darker shades of a color hue to communicate changes in the data displayed, have been found to help viewers identify hazardous zones; they are also easier to interpret than multihued color schemes [23,79,80]. In fact, using dark colors on light backgrounds to maximize contrast seems to initiate faster decision making, suggesting they can be used to help viewers quickly focus on the most task-relevant information [81,82].

Other strategies involving bottom-up information processing can be used to help guide viewers' attention towards key areas of a map such as employing various shapes or symbols. These types of visual cues have been especially helpful for people with color vision deficiency [83]. However, care should be taken to ensure selected shapes are discriminable and self-explanatory, and don't distract viewers from other key information displayed [84–86].

Strategies Supporting Memory

Design choices that limit distractions will also reduce the mental effort required to interpret the information displayed, thereby benefiting short-term memory. For example, interactive controls in geovisualizations that allow viewers to turn on or off certain visual elements can be used to remove unnecessary information that requires more working memory to process [83]. For viewers with limited map literacy or content knowledge, demonstrations or instructions showing how to navigate the geovisualization can refresh people's memory about how to use maps and improve their understanding of the environmental risks displayed [87–89].

Furthermore, strategies allowing viewers to efficiently apply their pre-existing knowledge and/or long-term memories in a top-down manner can help people recognize important visual features or patterns in the data. Hence, geovisualizations employing logical visual conventions tend to be easier for viewers to extract information efficiently and effectively. For instance, while cartograms are often viewed favorably by map readers, these types of geovisualizations are less intuitive because they distort the shapes of well-known geographic areas such as countries or states. Thus, they may fail to cue memory retrieval that would typically aid viewers to engage in analogical reasoning [90,91]. Alternatively, photographs incorporated into geovisualizations have been found to help viewers identify particular map locations, which may otherwise take longer to recognize [92].

Strategies supporting memory retrieval also appear to enhance viewers' understanding of environmental risks and their risk-informed decision making. For example, using intuitive colors (e.g., orange for fire) to depict features in the geovisualization—that match how people view or perceive those objects in real-life—allows for a more efficient process of information retrieval and interpretation [30,93,94]. Also, since people are generally interested in localizing their own homes in maps, including recognizable landmarks and the names of familiar places can lead viewers to engage more deeply with the geovisualization [86,94,95]. Interestingly, viewers' proximity to a particular environmental hazard does not always lead to increased perceptions of risk. For some hazards like climate change, individuals appear to rely more on their prior beliefs about the hazard—compared to their geographic proximity to the hazard—when forming risk attitudes [96,97].

Strategies to Evoke Emotions

Several geovisualization design strategies can be employed to evoke emotional responses. These include visual elements such as colors, shapes, evocative imagery, as well as textual elements such as narrative information or emotional appeals. Importantly, geovisualizations that prompt feelings—especially negative emotions like worry—can be used to inform people's perceptions of risks and influence their adoption of protective behaviors to avoid threats to health [87,98,99]. For example, geovisualizations that use specific colors like red appear to increase individuals' risk perceptions (among individuals without color vision deficiency) because they are generally understood to signal danger [80,87]. Cooler colors like blue, on the other hand, may signal lower risk to many viewers [100].

Geovisualizations that increase perceptions of risk through visual stimuli like photos, may also promote the adoption of protective behaviors that reduce exposure to environmental hazards [24,71]. For example, geovisualizations containing evocative imagery of the impacts of floods on communities have been found to increase viewers' intentions to take actions that promote community adaptation to flooding [101]. Additionally, the inclusion of information about safe areas or protective measures that can reduce the threat of harm from an environmental hazard is crucial for guiding viewers' decision making regarding possible risk-mitigating actions [95,102–104].

Recommendations for Designing Geovisualizations for Environmental Health Literacy

Based on evidence drawn across the three disciplines—cognitive science, cartography, and environmental health—we detail six recommendations for designing effective geovisualizations to promote environmental health literacy. These recommendations could be adopted by a variety of stakeholders engaged in environmental health education or risk communication, including researchers, policy advisors, and/or public health officials, to enhance the public's understanding of environmental hazards and facilitate risk-informed decision making.

1. Display Key Data Supporting the Communication Goal

Identify a communication goal for the geovisualization and display only pertinent data to support that goal. People understand visual information best when they can focus on features that are the most task-relevant and reduce their cognitive load [60]. For geovisualizations where comparisons of multiple variables are important, allow viewers to switch variables on or off, allowing them to focus on smaller amounts of information at a time [13,86,105] (See **Fig 2a** for an example). Lastly, include messaging on actions people can take to mitigate environmental risks and reduce personal exposures [102] (See **Fig 2b** for an example); in the absence of guidance, people may not know how or have the confidence to protect themselves and take no action, or they may take precautions that are ineffective [103].

Fig 2a) Example geovisualization allowing viewers to select variables of interest to display and **b)** providing information about how to mitigate radon exposure. Maps display background levels of radon in the State of Wyoming and the percentage of radon test results in an area that exceeded 4 picocuries per liter. **Source**: Wyoming State Geological Survey [106].

2. Tailor and Test Geovisualizations for Target Audience

As with any health risk communication tool, geovisualization design choices should be tailored for those who will use it. Consider whether the audience is likely to be familiar or unfamiliar with the spatial data being displayed. Explainers and interpretive guides displayed alongside geovisualizations can support novice map users [107], but may be redundant for more expert audiences [66]. Even among viewers with high numeracy and high content knowledge, abilities to extract meaning from visual information displays can vary [27,67]. Also, different information may benefit expert versus non-expert audiences more. For instance, expert audiences may benefit from the inclusion of uncertainty information in a map, whereas novice map users likely do not. It is also worth noting that user-preferred visualizations are not necessarily those that are best understood [108,109]. As a result, testing geovisualizations with the intended audience and conducting evaluations that go beyond assessing usability is important and can help us better understand the impacts of geovisualizations on human behavior and health outcomes [110]. Finally, designers of geovisualizations should not assume that complex visual information displays will always outperform simpler communication formats [108]. If demonstrating spatial variations of risk is not a key communication goal, using data presentation formats that are more familiar and user-friendly (e.g., tables, infographics) may be more beneficial.

3. Use Salient Cues to Guide Visual Perception

The human brain is programmed to use vision to think, and we often rely on our perception of visual elements to get the gist of information contained in a visualization without much mental effort. Salient cues—visual features that stand out—can greatly aid viewers' ability to target their attention towards key information in a geovisualization. Use variations in color lightness, shapes, textures, and other elements of salience to draw viewers to the most pertinent information they should focus on [40,56] (See **Fig 3** for example). Labels and other attention guides (e.g., arrows, borders) can also help highlight areas of the visualization that are most important for decision making [21,98]. Consider potential social, cultural, historical interpretations of visual features. For example, some colors may have different meanings in different cultures and may not be appropriate to use for a given audience [69]. Individuals' abilities to perceive different colors also may vary. Thus, opting for color palettes that function for viewers with various color vision deficiencies will allow your geovisualization to be accessible to a broader audience [83,111].

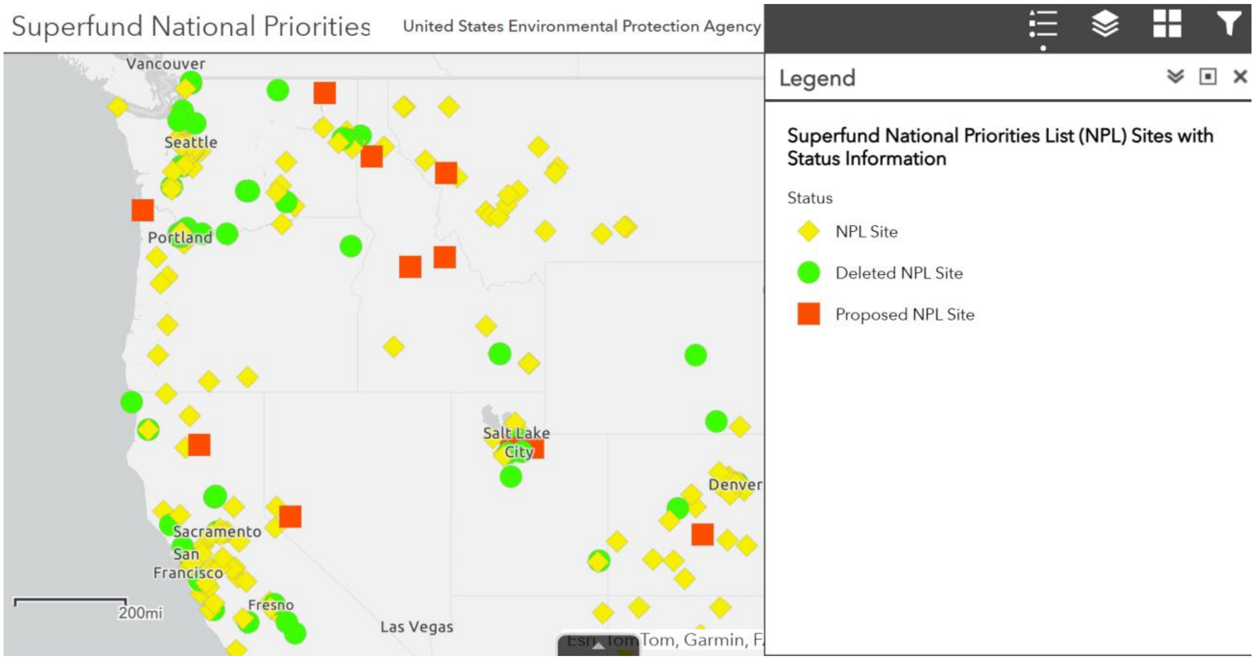

Fig 3. An example of a map using variations in shapes and colors as salient cues. This map uses the cues to display the location of hazardous waste sites in the US that have been prioritized for investigation and clean-up based on their status**. Source**: United States Environmental Protection Agency [112].

4. Leverage the Power of Emotion

Emotional appeals have long been integrated into environmental and health messaging for their ability to impact risk perceptions, foster behavior change, improve information recall, and make statistics feel more personal. Emotional cues using evocative photographs, vivid narratives, or stories can be integrated into geovisualizations (e.g., ArcGIS StoryMaps) to promote action-taking [24,29,101]. Colors can also be applied to promote, amplify, or attenuate emotional responses. For example, the color red is generally understood to signify fear and danger [83]. Avoid the use of colors that are incongruent with the data's theme [47]; cheery colors will likely not be the most appropriate for a geovisualization summarizing mortality data.

5. Aid Pattern Recognition

Geovisualizations are more easily interpreted and more quickly understood when people are familiar with how to extract key information from them. Use consistent features (e.g., symbols) and intuitive memory retrieval cues (e.g., coloring water bodies blue) to help viewers complete a more rapid process of sensemaking to interpret the information displayed without overloading memory [47,90,94] (See **Fig 4** for an example). Simpler geovisualizations that reveal patterns without requiring complex mental transformations (i.e., the cartography cube concept) are more likely to lead to faster and more accurate judgments of risks [53,59]. Ease of use should be prioritized as a design feature to retain individuals' engagement and attention; the addition of complex features that are not intuitive may lead viewers to lose interest and navigate away. Present data logically, in a manner that follows common visual conventions [42], and use self-explanatory colors and shapes to reduce the need for viewers to divert attention towards a map legend [86]. This will help viewers efficiently match the visual elements contained in the visualization to any similar elements stored in their memory.

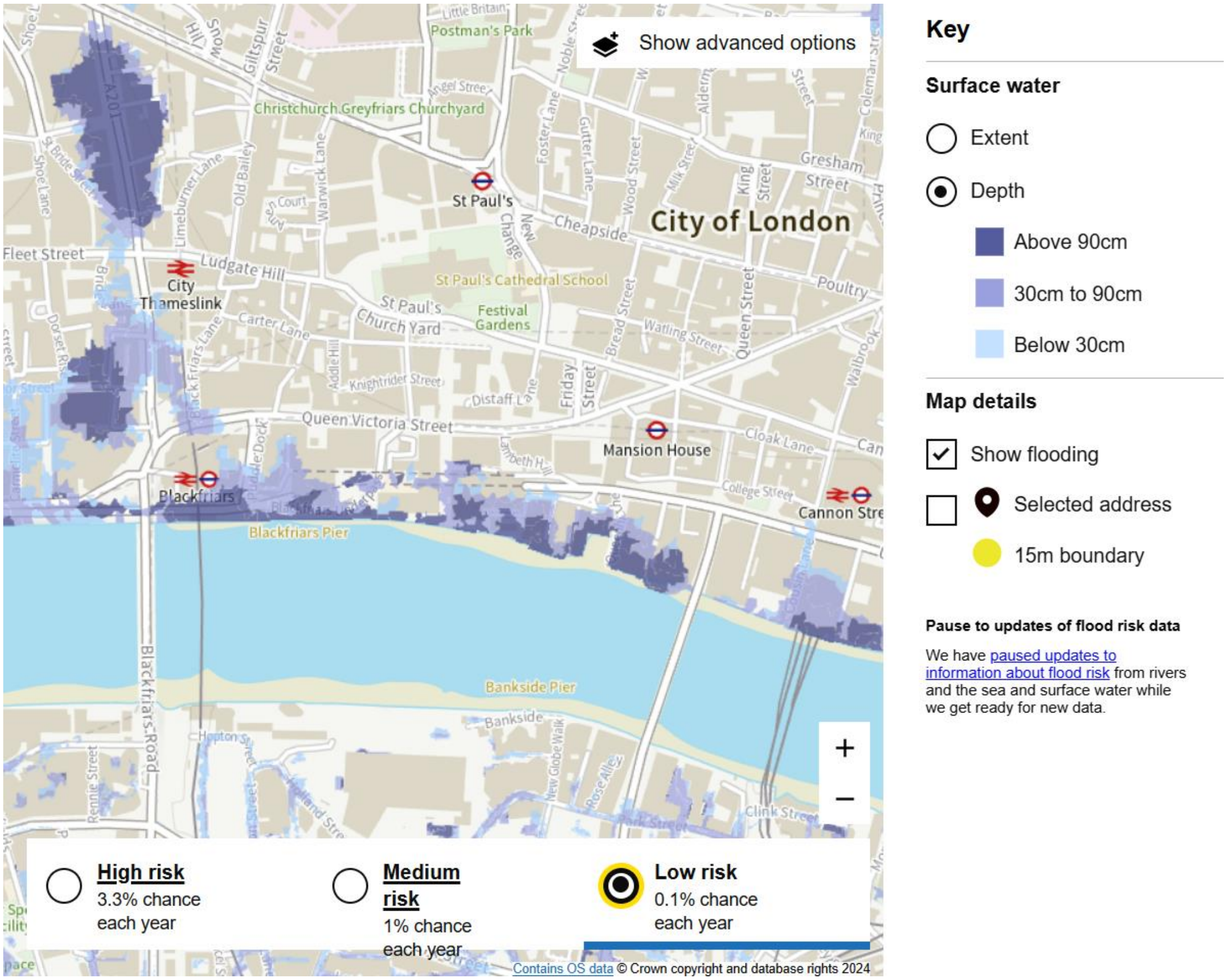

Fig 4. An example of a map using intuitive visual conventions (i.e., blue hues) to depict areas at risk of flooding. This geovisualization allows viewers to check their long-term flood risk from various sources (e.g., surface water) across England**. Source**: Ordnance Survey, United Kingdom Environment Agency [113].

6. Limit Visual Distractions

People learn best without visual distractions dividing their attention. Despite people's curiosity and interest in dynamic maps that employ animations, these types of designs split viewers' attention across various moving objects and impact their abilities to detect changes to an object in a display [65,114]. In fact, animated visualizations do not appear to help people comprehend information better than static visuals, even among different types of learners [115]. Still, animations may have advantages when it comes to showing data variations over time and space [93,116]. In these instances, simple animations that give viewers control over playback speed and the option to pause or rewind should be used to support viewers' understanding of the information. Similarly, geovisualizations employing hyper-realistic imagery (e.g., pictures of simulated hazard impacts) do not appear to improve information interpretation or decision making relative to less realistic displays [116,117]. In fact, incorporating images that look ‘fake’ in geovisualizations may invite skepticism and distrust in the information displayed [31,70]. Too much data displayed in a geovisualization can also be distracting (see Recommendation 1).

Future research

Looking towards the future of environmental health and geovisualization, there remains a pressing need for more experimental studies to rigorously test various map presentation formats and the types of information they convey. Many evaluations of geovisualizations that are undertaken by health agencies and researchers rely on users’ subjective design preferences or perceived usability to measure success. Yet, as noted above, preferred visualizations may not optimize the accuracy of risk judgments [109,117,118], thus highlighting the importance of applying experimental methods to assess the effectiveness of different geovisualizations.

Use of experimental methods also will allow us to better understand how different presentation styles influence comprehension, decision making, and ultimately, behavior. For example, further research examining which emotional cues are most effective at influencing perceptions of environmental risks could provide more insights into how these cues should be leveraged to motivate the adoption of risk-mitigating actions using geovisualizations. Since responses to risks may vary considerably between different populations, and for different types of risks, context is important to study [31].

Still, far too many visual aids used in environmental risk communication are designed without much attention towards the target audience and often lack consideration for users and their distinct information needs [119]. Furthermore, as the world becomes increasingly digitized, many geovisualization tools developed by governments and academic researchers have transitioned to purely web-based platforms, which can pose significant barriers to individuals with limited access to reliable internet connections or devices [3]. Going forward, more attention also must be given to selecting geovisualization design strategies that cater to individuals with visual impairments so that they can be accessible to a broad range of individuals with diverse visual abilities. One example is to add alternative text to geovisualizations for screen readers, ensuring that visually impaired users can interpret and understand the spatial data presented online. Geovisualization designers may find that adopting principles of Universal Design—a design approach centered around creating products or spaces that are accessible for (and usable by) anyone—could lead to the development of visualizations that benefit everyone regardless of ability or skill [120].

Indeed, the scope of geovisualization research should be broadened to include experimental testing with more diverse populations, including people from various cultural backgrounds, ages, and education levels. By incorporating a more diverse range of study participants, researchers can gain insights into how geovisualization tools can be tailored to meet the needs of a wider demographic, ultimately fostering greater inclusivity and effectiveness in communicating environmental health information. Failing to do so may lead geovisualization designers to inadvertently perpetuate certain biases or stereotypes (e.g., relying on traditional gendered color schemes) [121]. One possible way to promote inclusivity is through the implementation of more participatory research models that would encourage co-creation of environmental health geovisualizations with the target end users [122,123]. Co-creation allows for local knowledge, experiences, and information needs to shape the design process [124], which can result in a geovisualization tool that better reflects community realities and offers more meaningful opportunities to engage with local environmental health issues [125,126]. Another avenue for carrying out participatory mapping initiatives has been through the integration of environmental exposure data measured by citizen scientists into geovisualization tools [127,128]. Immersive technologies employing three-dimensional maps and extended reality (e.g., virtual reality) may also be effective for engaging people in environmental health issues [129,130] and enhancing awareness around environmental hazards [131,132].

Conclusions

Exposure to environmental hazards places a significant health burden on societies globally. Unfortunately, public awareness is lacking about many environmental health risks, impeding the uptake of protective actions and policies that would reduce the burden of environmental disease. Geovisualizations have emerged as promising digital tools for environmental health education and risk communication. However, the effectiveness of these tools at promoting risk comprehension and behavior change often goes untested. This evaluation gap hinders both the public's and policymakers' abilities to make risk-informed decisions regarding the management of environmental hazards and the protection of public health.

Drawing from insights in the cognitive sciences and cartography, this narrative review examined factors influencing individuals' information processing and how they could be leveraged to build evidence-based geovisualizations. We also reviewed recent studies evaluating three overarching design strategies in environmental health contexts to gain insights into their practical effectiveness. After synthesizing the evidence across these three disciplines, we presented six recommendations for designing effective geovisualizations that promote individuals' understanding of environmental hazards and aid risk-informed decision making.

The six recommendations (summarized in **Fig. 5**) emphasize the importance of considering cognitive processes such as individual attention and memory, as well as emotion, in geovisualization design for public education. They also underscore the need for more audience-tailored approaches in environmental health education. Going forward, experimental testing of geovisualizations prior to their implementation in public health settings could provide further valuable insights into their effectiveness and usability. The recommendations outlined here are anticipated to require periodic reassessment and adaptation, as technological advancements in data visualizations continue to evolve. Nonetheless, they serve as a foundational framework for enhancing the utility and effectiveness of geovisualizations to promote environmental health literacy.

Conflict of Interest

Catherine Slavik, Carolyn Fish, and Ellen Peters declare that they have no conflict of interest.

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Human and Animal Rights and Informed Consent

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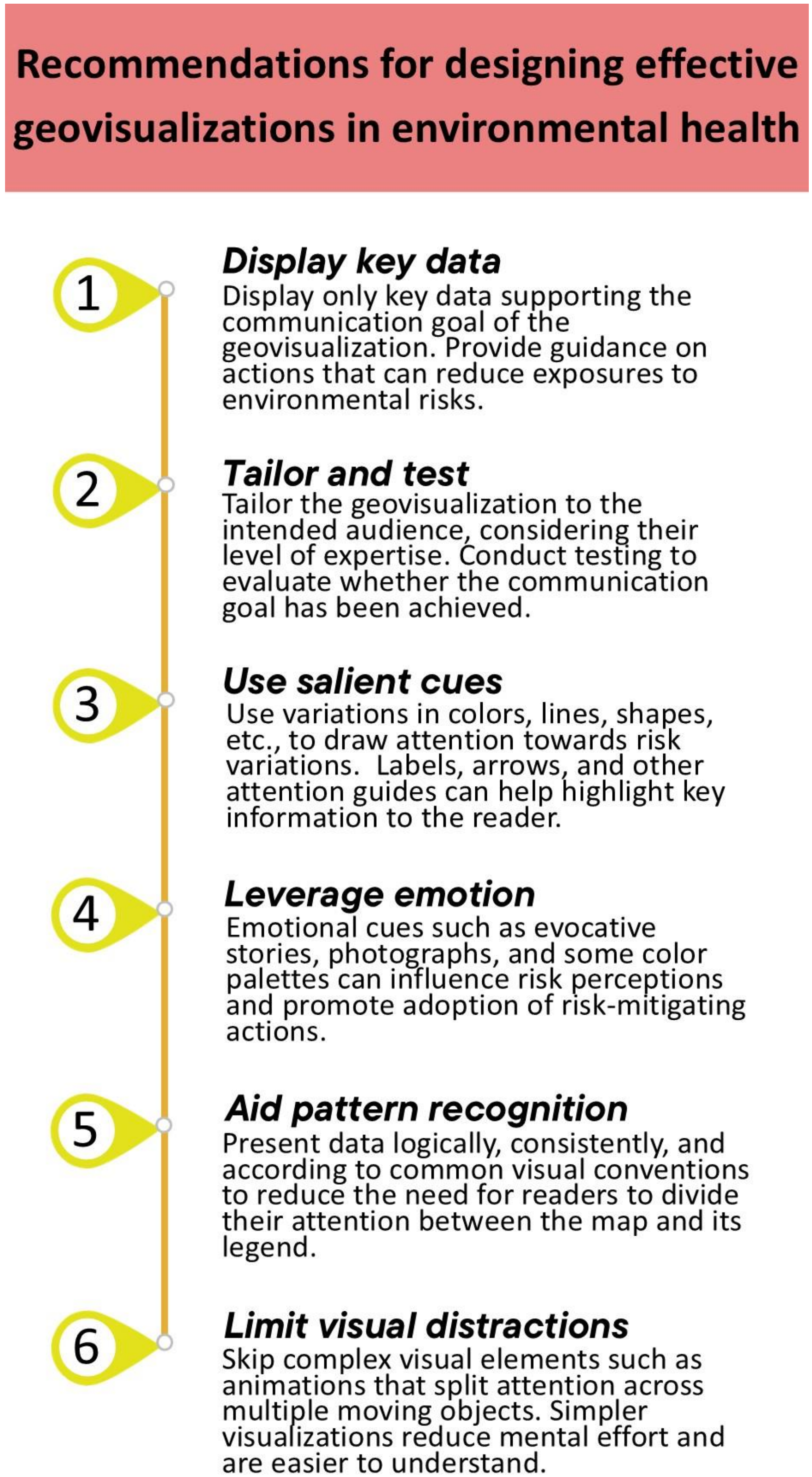

Fig 5. Recommendations for designing effective geovisualizations to help educate the public about environmental health hazards, informed by research from the cognitive sciences, cartography, and environmental health.

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