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ORIGINAL PAPER

Navigating the future of tsunami risk communication: using dimensionality, interactivity and situatedness to interface with society

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Abstract Two-dimensional paper maps are well-established tsunami risk communication tools in coastal communities. Advances in GIS, geovisualization and spatial interface technologies suggest new opportunities to deliver tsunami risk communication using 3D, interactive and situated risk visualization. This paper introduces a set of geovisual interface constructs—dimensionality–interactivity–situatedness (DIS)—and evaluates their presence, absence and distribution in 129 examples of existing academic and public visual tsunami risk communication. The resulting analyses reveal structural differences in the distributions of DIS found in each of academic and public risk communication literatures, and opportunities for interactive location-aware risk communication. The second half of this paper reports on three new tsunami risk visualization interfaces informed by and developed to demonstrate how we might explore new undeveloped risk communication territory revealed by the DIS cube analysis. We discuss the design, rationale and implications of: *EvacMap*; *ARRO3D*; and *Tsunamulator*. These risk visualization interfaces deliver location-aware, user-centred risk maps, as well as virtual risk maps and tsunami simulations that can be viewed while standing in situ in coastal environments. This work is a first step intended to help the risk communication community systematically engage an emerging territory of interactive and location-aware 3D visualizations. This work aims to facilitate and encourage progress towards developing a new strand of interactive, situated geovisual risk communication research, by establishing these guiding constructs, their relationship to existing works and how they may inform the design of future systems and usability research.

Keywords Tsunami · Risk communication · Visualization · Augmented reality · Spatial interfaces

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1 Introduction

Effective public risk communication is integral to improving tsunami preparedness; an informed citizenry must understand spatial risk and be able to take appropriate action during these time-sensitive events. Such preparation is of particular importance along seismically active and vulnerable coastlines of the Pacific Ocean basin. Recent research on public tsunami risk perception indicates a high reliance on official emergency communications and inaccurate perceptions of personal risk (Couling 2014). Public tsunami risk communication relies heavily on 2D paper maps and safety brochures for the visualization of hazard zones (Clague et al. 2003), maps and signage at trailheads, and signage along roads. Given the prevalence of visualizations as risk communication tools, audience, intent and design must be considered carefully. Effective academic visualization does not necessarily make for effective public risk communication.

Tsunamis are structurally three-dimensional (3D), temporally dynamic and difficult to predict (Geist et al. 2006). They might vary in propagation, speed and arrival angle, factors that are further complicated by the variability of intercepting coastal topography. Tsunami scientists strive to capture these multivariate complexities using computational models and simulations. Visualization, geovisualization and (geo)visual analysis are used at various stages of the spatial scientific process, to view raw data and models; look for structure, patterns and relationships; observe and compare simulated scenarios; and make sense of unknowns (MacEachren and Kraak 2001; Thomas and Cook 2005; Andrienko et al. 2010). Visualizations intended for public use are derived from these steps. Translating academic research into representative yet comprehensible visualizations for public is challenging, and there is potential to inadvertently modify results. Public and academic visualizations serve significantly different needs and expectations of their respective user bases.

This research effort has four objectives: (1) to review examples from the academic and public risk communication literatures; (2) to identify the constructs of dimensionality, interactivity and situatedness as properties of emerging geovisual interfaces; (3) to reveal the structural distribution of these attributes in academic and public risk communication, as a result of classifying 129 visualizations using these constructs; (4) to demonstrate how these constructs enable the design of new forms of risk communication interface to connect abstract analysis with real space.

Emphasizing disaster prevention through an approach that integrates natural hazard science and people-oriented research has been a recent trend (Haque et al. 2006; Paton 2000, 2003). This paper introduces a 'spatial interface' approach to tsunami visualizations, in which we demonstrate new ways to communicate tsunami information through interface technology and design. We review and classify a sample of existing tsunami visualization work, introducing a conceptual cube of visualization affordances as a way to illustrate existing trends in tsunami risk communication. We reveal how they operate as interfaces to communicate science-based risk analyses to stakeholders and citizens in geographic space. From this review exercise, we derive a set of interface factors that are leveraged to design and develop a new generation of tsunami risk visualization interfaces. To demonstrate this potential, we report on new geovisualization research in which we have used these principles to develop new tsunami risk visualization interfaces: *EvacMap; ARRO3D;* and *Tsunamulator*. Reviewing existing literature using new constructs and demonstrating how they might inform the design of new methods are necessary steps in developing a new strand of risk communication research. This in turn forms a logical foundation for future usability research.

2 Trends in tsunami visualization

In the past (and still to some degree), there was perhaps a tacit assumption that once a map is produced, it would work 'as designed by the cartographer' once deployed and read, be it on a wall, in the hands of pedestrians, or other settings. Numerous scholars have unpacked the 'secret lives' of maps, how they are appropriated, used and interpreted in a multitude of ways never intended nor anticipated by the cartographic author (Wood and Fels 1986). Kurowski et al. (2011) demonstrated how closer scrutiny of the content of 2D tsunami maps varied, and suggested how this limits an ability to represent tsunami hazards and how they (from a cartographic standpoint) differentially communicate risk. *How* readers interact with visualizations (be they 2D paper maps, web interfaces or 3D environments) influences their perception of the geometry of geographic space, spatial relationships between real features and abstract analyses, such as tsunami risk. In this section, we summarize trends in tsunami visualization so that we may begin to understand how tsunami risk perception may be affected by visualization design choices. We provide a summary of the geographic and organizational scales at which public tsunami risk communication maps are currently being produced.

2.1 Public tsunami risk visualization

Public-oriented tsunami risk and hazard visualizations appear to fall within three broad categories, each of which corresponds with differing map scales and organizations responsible for map production. The first category is large-scale national and international tsunami hazard visualizations. Federal organizations such as the West Coast/Alaska Tsunami Warning Center and the Pacific Warning Center provide up-to-date forecasts and warnings on their websites through simple 2D mapping services. These large-scale visualizations are designed to provide regional warnings, rather than communicating localized topography and hazard zones (Pacific Tsunami Warning Center 2014). Light interactivity, such as panning, zooming and map layers, can be integrated into the map interface (West Coast/Alaska Tsunami Warning Center 2014).

The second broad category of public-oriented tsunami visualization consists of local hazard maps produced by smaller organizations, such as municipal governments or contractors. These maps are for public use; however, their intended audiences are *local* stakeholders such as residents, tourists, local business and local government. The majority of visualizations produced in this category are static 2D maps that are often available digitally or in the form of paper pamphlets (City of Port Alberni 2007; District of Tofino 2006; CRD Environmental Services 2006; District of Port Hardy 2014; Wellington Region Emergency Management Office 2011).

An important side note here is that our research considers the properties and potential of geovisual interfaces to better understand how they may mediate or influence tsunami risk communication. We acknowledge that there is sometime a tendency for developers of new (visual interface) technology, to suggest that 'more technology is better' or 'interactivity is better'. This is not necessarily true. Our objective in developing the DIS cube (see Sect. 3) is to tease apart factors that are too frequently conflated in work bringing interactive technologies into applied research domains. This is an essential first step as a basis for systematic development and empirical evaluation of new geovisual tools in the risk communication community. While visual and interactive technologies may be compelling, it is their potential to meaningfully engage and inform that draws us to them. Three-dimensional virtual environments, for example, may be compelling to some because of novel head-mounted displays and modes of interaction. However, it is their immersive, experiential communication potential that should interest us, especially: an ability to modify spatial scale; manipulate time; run multiple alternative scenarios; view the environment from above; or experience it from first-person switch ‘lenses’ (highly scientific for researchers; operational for planners and responders; abstraction-minimized and information content maximized for nonthreatening citizen use).

Carefully designed interactive visual interfaces may enable different groups of stakeholders to gain deeper insights into the variability of natural hazards across geographic space and time, and the interplay of different combinations of factors that lead to a range of immediate and longer-term risks. Delivering new types of user-driven risk communication may allow stakeholders to view (explore and experience) what will or might happen under a variety of conditions (such as tsunami magnitude, angle of arrival, differential topography, infrastructure and vegetation). Being able to interactively query, explore and experience alternative scenarios may facilitate new levels of public engagement and risk awareness. Throughout the process of developing new geovisual interfaces for risk communication, it is critical to maintain clear a clear risk message for the intended audience and use context.

The Washington and Oregon State governments demonstrate a final class of public tsunami risk visualization. The governments have made efforts to standardize tsunami visualizations across the region, rather than leaving risk communication to the discretion of the communities. Two series of tsunami evacuation maps of both States’ coastlines have been produced and standardized for coastal communities (Oregon Department of Geology and Mineral Industries 2012; Washington State Department of Natural Resources 2012). These maps are static, 2D and accessible via the Internet or as paper pamphlets in situ.

Tsunami risk-focused organizations typically place priority on signage and educational map pamphlets for public awareness (Dengler 2005; González et al. 2005; Kurowski et al. 2011). The importance of geospatial information and visual representations of risk and hazard are recognized by a variety of fields (Cutter 2003; Dransch et al. 2010). Despite the importance of visual communication, universal standardization of tsunami maps in safety brochures along contiguous hazard zones, such as the Cascadia Subduction Zone (CSZ), remains a work in progress (Kurowski et al. 2011). But, as indicated in the preceding paragraph, the states of Oregon and Washington have worked hard to standardize the content and visualization of tsunami hazard maps in recent years. While such an issue may seem innocuous at first, inadequate (or mis-informative) visualizations can undermine tsunami risk awareness, disaster preparation and response times (Schafer et al. 2008).

Many communities have settled on ‘one map per community’ with which to communicate risk. Single maps are often created to impart a single, clear message to citizens: where is the flood risk and safety and how does one move to safety? As such, it is critical that these maps translate the expertise of science accurately and effectively into public awareness (Kurowski et al. 2011). The one-map-per-community model is perhaps at odds with the nature of tsunamis and what we do (and do not) know about their probability and behaviour. A single, static map of inundation or risk zones is a very limited representation of a dynamic, multivariate phenomenon that can manifest in many different ways (see Sect. 3.1 for further discussion on interactivity).

An important consideration is that typically paper tsunami risk maps do not link the user to their specific location on the map and, therefore, their relationship to risk in geographic space. Users bear the cognitive burden of identifying their location in space, identifying the equivalent location on the map and then identifying the spatial relationships between user location, risk, evacuation and safety.

To the best of our knowledge, most contemporary public tsunami risk communication visualizations do not allow for a high degree of user interaction. This may be the result of the limited capacity for coastal municipalities to produce and support such visualizations. It may also be a result of perceived liabilities associated with a tsunami communication tool that enables more open-ended interpretation, rather than a single message. However, there are some examples of interactive risk mapping tools. Kurowski et al. (2011) reviewed the Northwest Association of Networked Ocean Observing Systems (NANOOS) web mapping tool (NANOOS 2014). This web mapping service allows users to search, pan and zoom while visualizing static representations of inundation risk along the Oregon Coast. So, while most spatial tsunami risk is typically communicated to the public through non-interactive paper maps, there are some exciting advances occurring within the field.

2.2 Academic tsunami risk visualization

The visualization of tsunamis and their associated risks and hazards in academic contexts merits distinction from public risk communication. Tsunami risk and hazard visualization within the academic community is more varied and advanced than what is typically seen in the public realm. We comment on tsunami visualization trends within the academic community so as to contrast what is being visually communicated within the research community and what makes it to at-risk stakeholders.

Academic researchers as a visualization audience have different needs and goals than the public when considering the design of tsunami risk and hazard maps. There is a requirement to illustrate research model mechanics and stages of development, unlike public maps which require simple and clear messaging. Additionally, varying degrees of scientific knowledge and interpretive skills are assumed depending on where publication venue. Furthermore, the peer-review structure, in which research is legitimized, can be quite restrictive. Typically, journals require static, 2D, black and white figures. Variations of this format can incur extra cost. This limitation is changing, as journals and other forums offer opportunities to link readers to online content, including animations, 3D models and even complete research tools, yet it is still present. Effective academic visualizations do not always make for effective public communication. Misinterpretations are a very real risk.

A recent example of misinterpretation is a tsunami propagation map produced by the National Oceanic and Atmospheric Administration (NOAA) that was construed by some members of the public as representing radiation propagation (NOAA 2012). While there are no apparent cartographic design errors, public perception of its intended message was inaccurate. Flood risk management is a similar domain that deals with communicating science to responders and the public. There is an extensive research background highlighting the challenges in communicating concepts such as model uncertainty, accuracy and ownership to emergency managers and the public (Faulkner et al. 2007; McCarthy et al. 2007). Uncertainty and the complexities of fluid simulation present challenges to visualization in flood risk communication; parallels may be drawn with the challenges faced by tsunami visualization.

Tsunami *visualizations* (as opposed to analytical aspects of research) developed within the field of Natural Hazards are typically static representations. Static visualizations include choropleth maps where spatial risk is indicated using colour-coded zones (Eckert et al. 2012; Grezio et al. 2012; Strunz et al. 2011), 2D static maps indicating colour-coded sea surface elevation changes (Borrero et al. 2006; Ribeiro et al. 2011), or at different time intervals (Xie et al. 2012).

Dynamic tsunami visualizations are less common; much of the research is focused towards animated maps revealing tsunami wave propagation at regional and global scales (Sevre et al. 2008; Synolakis and Bernard 2006; Zhang et al. 2008). Despite the dynamism of these visualizations, authors are still limited to presenting static frames of animations.

Dynamic geovisualizations can be powerful tools for communication. It is important to note that there are significant differences between dynamic visualizations as representations of dynamic phenomena, versus interfaces that provide ways to dynamically view visualizations, regardless of whether they are static or dynamic characterizations of the phenomenon. This is an important consideration at a time when tsunami risk communication is exploring opportunities for new forms of public communication and engagement.

Examples of this include Basic and Nuantawee's (2004) flooding interface that allows the user to query and visualize maximum flood level, address, time until maximum inundation and safety precautions. The dynamic properties of the phenomenon itself (speed and direction of flow over time) are not the priority of this information tool. More recent examples, such as Tate et al. (2011) research in the Integrated Hazards Mapping Tool, involve a more complex combination of dynamic representation and interactivity. Increasingly sophisticated representations of tsunamis (dimensionality, dynamism) and emerging interactive visual information tools provide risk communication specialists with new ways to deliver public risk information. We might maximize these efforts with a more developed framework with which to guide the use of dynamism and interactivity for effective visual risk communication.

The majority of tsunami *visualization* within the research community is conducted in 2D (Borrero et al. 2006; Eckert et al. 2012; Grezio et al. 2012; Ribeiro et al. 2011; Strunz et al. 2011; Titov et al. 2011). Again, this observation is about the manner in which it is communicated, not the analytical work that was achieved. Comparatively fewer cases have focused on 3D visualization. Exceptions were Zhang et al. (2008) who developed an interface that places images of tsunami propagation in Google Earth (a 3D Globe visualization program); however, these visualizations appear to be 2D images of propagation wrapped around a 3D globe as such it may be misleading to call this a truly 3D visualization. Sevre et al. (2008) developed a series of 3D visualizations representing tsunamis as exaggerated deformations of a mesh. Again, it may be misleading to call these truly 3D visualizations since mesh deformations can be conceptualized as 2D planes with height values as an attribute of a specific coordinate on the plane.

The above 3D visualizations are regional and global in scale. Local-scale 3D tsunami visualizations are uncommon in both research and public communication. Basic and Nuantawee's (2004) local-scale lake flooding visualization research offers an example from a similar problem space; however, their work focuses on final maximum flood heights rather than the dynamic onset of the flood. Perhaps local 3D visualization has been avoided because of perceived difficulties in communicating inundation chronologies, pathways and water dynamics. Communicating such phenomena is particularly difficult if one is limited to static 2D visualizations, as is often the case in both the research community and the public sphere.

3 Using *DIS cube space* to reveal the structure and distribution of existing public tsunami communication

Our summary of trends in tsunami visualization in part 2, above, was based on a sample of 14 academic tsunami visualization and 115 public tsunami risk communication examples. We actively searched for examples of interactive tsunami visualization systems for public

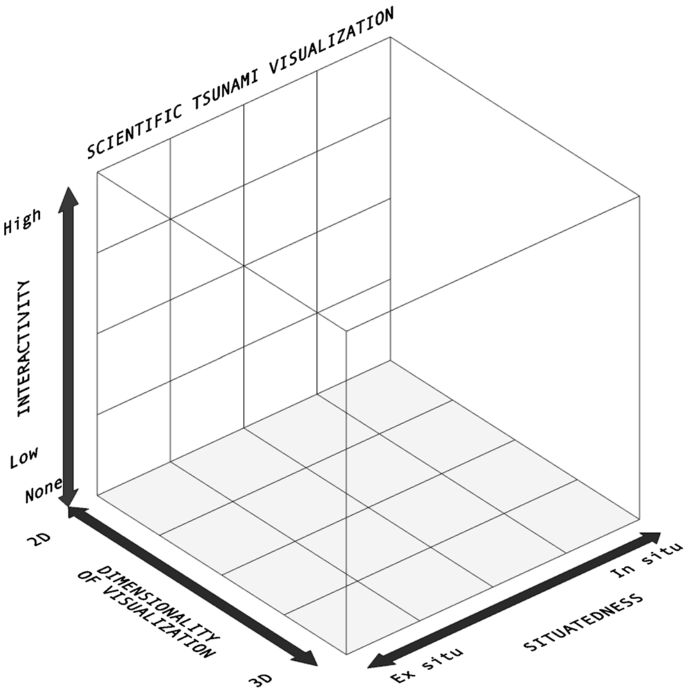

Fig. 1 Dimensionality–interactivity–situatedness (DIS) cube space. A conceptual construct with which to classify current types of public tsunami visualizations

education. Our review was focused through the lenses of *dimensionality* (*2D or 3D*), *interactivity* and *situatedness*. These constructs allow us to derive a composite *dimensionality–interactivity–situatedness* (*DIS*) cube space with which to broadly classify the tsunami visualizations sampled (introduced in Fig. 1, below).

As spatial analytical visualization methods have progressed, it has become possible to create new forms of interactive and three-dimensional visualizations, using a variety of immersive devices. It is for these reasons that we have developed the *DIS cube space.* This conceptualization uses a cube construct similar to MacEachren and Kraak's (1997) cubic conceptualization of map use, a conceptual space which enables classification of patterns in goals of map use by identifying a map's position within the cube. Our DIS cube space is a construct we may use as a 'lens' to review a sample of existing hazards and risk communication visualization in the literature, in order to better understand the frequency and distribution of these methods in each of the academic and public risk communication communities. We define and discuss *dimensionality*, *interactivity* and *situatedness* in the following section.

3.1 Defining terms used in the DIS constructs

The dimensionality we emphasize in our DIS cube review of existing visualization literature refers to the dimensionality of the visualization. We are primarily concerned with the manner in which data are visualized at the conclusion of analysis. Has a flat paper map been produced, or a 3D animation? Of course, we cannot dismiss the importance of considering data and analytical models. Their quality and value hinges on how well the analytical spatial visualization is matched to available data for specific phenomena—this has been at the core of rigorous geographic information science for some time. It is also critical to remember that 3D visualizations may be compelling, but they are not necessarily better than 2D visualizations of phenomena.

In the same way, interactive visualizations are not necessarily better or worse than static visualizations. They are simply different approaches to presenting analytical visualization outputs through user control, visual, auditory and other feedback. If designed well, different mixtures of these ingredients can result in engaging information experiences that may lead to enhanced factual and conceptual understanding of complex spatial phenomena (Shelton and Hedley 2002, 2004). There is risk of audiences failing to receive the intended risk communication message due to only seeing part of the whole visualization 'experience'.

Sevre and colleagues (Sevre et al. 2008) identified the benefits of allowing real-time querying and response for the analysis of tsunami hazards as a basis for future studies. However, we have found almost no examples in the literature that unpack the significance and potential of interactivity for tsunami risk communication and its analysis.

Geovisualization researchers have long argued that interactivity may enable more informative exploration and comprehension of spatial data and messaging in thematic maps (Kraak 1998; Andrienko and Andrienko 1999). The fields of visual analytics (VA) (Thomas and Cook 2005) and geovisual analytics (GeoVA) (Keim et al. 2008; Andrienko et al. 2007) have since emerged to establish principles of interactive visual analysis as a powerful approach to the analysis and communication of complex spatial phenomena.

In the context of tsunami risk communication, single static map products (such as paper risk maps or their digital PDF versions) present examples of low-interactivity visualizations. Most present a single message about one or more variables to express individual or composite risk in geographic space, as the user cannot change the display. The NANOOS (2014) web mapping application discussed in Sect. 2.1 offers an example of an interactive visualization. The interactivity axis of the DIS cube aims to capture the range of possible ranges from low to high and refers to how responsive the visualization is to user inputs.

Development of effective risk communication takes local social, institutional contexts into account (Dengler 2005; González et al. 2001, 2005, 2009). 'Situatedness' is a term that has been in use by social scientists for some time. The term refers to the interplay between physically on-site research activities and the way local contexts and influences shape such activities, perceptions and understandings (Vannini 2008). Cognitive researchers have defined 'social situatedness' as the interplay between agent, situation and context (Rohlfing et al. 2003). Situatedness has also been of great interest to the human–computer interaction (HCI) research community. Suchman's (1987) ethnomethodology acknowledged the significance of interplay between being in situ, activity and technology—ideas that can constructively inform our development of situated risk communication.

Incorporating the social, spatial and technological dimensions of situatedness in contemporary visual risk communication design is essential to effective transmission of expert science into society and to connect abstract risk to real landscapes. This is particularly true in an era of spatially enabled mobile devices and in a problem domain that has so much to do with situated information and situational awareness. For example, risk in safety map brochures is often presented as static zones of risk. Connecting these zones of risk to a user in the field might facilitate compression of personal risk and their possible responses. We raise this point, in order to consider to what degree existing risk communication materials, visualizations, and risk information interfaces and information activity are used in situ or ex situ, whether they can be used in situ, versus whether they have been designed for use in situ.

3.2 Using DIS cube space to categorize trends in tsunami visualization

Locating existing tsunami visualization in the DIS cube space enables us to gain a sense of how tsunami risk is being transmitted to society, in terms of whether they use 2D versus 3D visualizations, their degree of interactivity and their degree of situatedness. By doing so, we may show the distribution of existing visualizations; comment on current and emerging trends within these spaces; identify forms of visualization that have not been used; aim to explain reasons for these structural distributions; and identify opportunities (and rationales) for new forms of risk communication. Figure 2 below illustrates the positioning of 14 academic articles and their visualizations reviewed and placed within the DIS cube space.

Figure 3 above shows that academic and public communication communities' tsunami visualizations occupy distinctly different regions of the DIS cube space. The most significant messages we can derive from this distribution are:

1. The majority of current public tsunami risk communications are 2D visualization products, whereas academic tsunami visualization spans 2D and 3D visualization methods.

The differential in visualization dimensionality is, understandably, a function of the objectives and tools in science versus public communication. In the academic community, accurate characterizations of tsunamis' morphology and behaviour are priorities, requiring sophisticated 3D modelling. By contrast, public communication of these hazards and risks is largely delivered in 2D form. This can be for several reasons. From an operational standpoint, municipalities and emergency management teams generally want clear messages to mitigate risk and coordinate evacuation. This need has in part led to a common one-static-map-per-community. Two-dimensional static maps have an almost impossible task to represent and communicate unpredictable, rapid-onset, volumetric and dynamic phenomena, such as tsunamis. While 2D static maps may provide singular, fixed messages for operational needs, they may be at odds with communicating the spatial and temporal complexity of risk, inundation and evacuation. If we were to communicate these events in 3D, we might be able to: convey their structural complexity and behaviour during inundation, rather than just demarcating the high water mark, and convey multiple possible

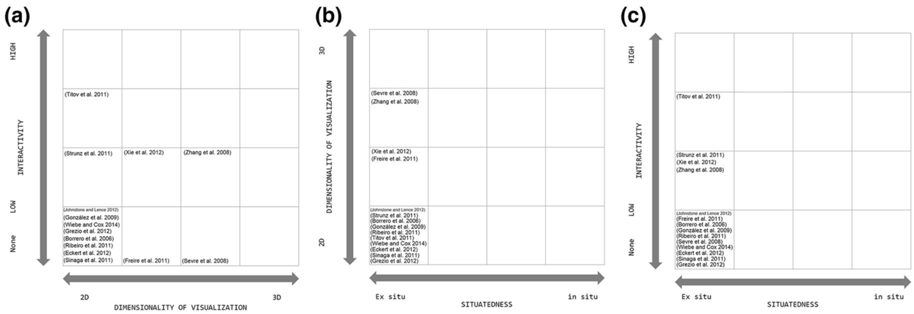

Fig. 2 Positioning of 14 academic articles along the three axis pairs of the DIS cube space; **a** interactivity and dimensionality; **b** dimensionality and situatedness; and **c** interactivity and situatedness

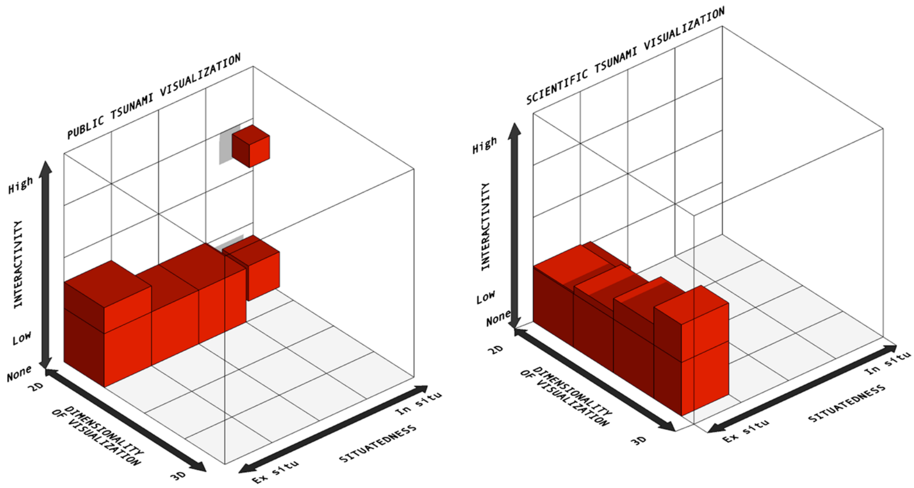

Fig. 3 Dimensionality–interactivity–situatedness (DIS) cube spaces summarizing current types of tsunami visualizations in; public risk communication (L); and the academic community (R)

scenarios, thus accommodating the considerable uncertainty surrounding their case-by-case manifestation.

2. The majority of public tsunami risk visualizations are static 2D maps with no or low interactivity, whereas there is some interactivity in the academic community (mainly associated with the platforms used, rather than with intentional interactive information experiences in mind).

Interactivity in 2D visualizations occurs mainly in 2D GIS or web applications. The visualization component of a 2D paper map itself is not interactive (one cannot change displayed information content). Such interactivity is only possible in GIS and web applications found within the sample. Analytical GIS tools are typically interactive in their ability to modify combinations of spatial data layers for changing the visualization or analysis. Interactive web applications are far less standardised (some are very GIS-like, while others are not). Despite these trends, there is an emerging interest in delivering interactive and situated content in the public tsunami communication domain such as the NANOOS (2014) application.

3. Situatedness in public tsunami visualizations spans whole ex situ-to-in situ spectrum, whereas most academic tsunami visualization still occurs almost entirely ex situ.

Many academic tsunami visualization tools are used within research institutions and government offices of various types. Examples of public tsunami risk communication methods include 2D paper maps and pamphlets, 2D map posters and 2D signboards. A 2D (paper) map, for example, might be put on a wall in an office, mounted on a public signboard in a park, or folded and taken into the field. So, while the map may be useable in the field (as a portable visualization), was it designed for use in the field or for situated risk communication? Similarly, 2D digital maps online may not be specifically designed for in situ use. They could be used on a mobile phone with Internet capability and viewed in situ, but the interface design may not accommodate unpredictable challenges found in field studies.

The dimensionality–interactivity–situatedness (DIS) cube analyses help us perceive the structure of existing academic and public tsunami risk communication and how they occupy different combinations of dimensional representation, interactivity and situatedness. Revealing these differences is important for at least three reasons:

First: tsunami hazards are complex, volumetric and dynamic. Their visualization through static, 2D visual documents is a limited representation of these characteristics. This is common practice in public risk communication due to clear messaging and simplicity in operational emergency management. But, is there opportunity to retain this clarity while presenting more accurate (dynamically and dimensionally) visualizations of the phenomena? Can we deliver public risk communication that provides more sophisticated representation through 3D visualizations?

Second: tsunamis expose coastal environments to risk differentially as a result of many factors that govern their propagation, velocity, angle of arrival and local topography. They are highly variable in space and time, creating considerable uncertainty about how they will behave. Enabling citizens to explore and understand these many possible scenarios is both a challenge and an opportunity for communicating risk. Providing citizens with interactive tools with which to specify starting conditions may be a way to communicate broad implications of broad starting conditions. While balancing level of specificity and representation may be a considerable challenge, there is an opportunity to build new forms of resilience in citizens through 'hypothetical scenario' knowledge gained through interactive cause-and-effect visualization experiences.

Third: tsunamis occur in real geographic spaces, not synthetic computer environments or scientific reports. An opportunity exists for the risk communication community to develop new ways to improve the connection between abstract science and physical space through the use of emerging new data formats, devices, visualization methods and situated information experiences. While these might be used to enhance existing forms of tsunami science visualization and public communication maps, there is an opportunity to create entirely new forms of risk communication. For example, the use of topologically 3D data and 3D visualization might improve transmission of tsunami accuracy to citizens, while careful use of interactivity might enable citizens to view and explore dependencies and outcomes in evacuation scenarios. Developing tools to deliver improved tsunami representations and interactive inundation scenarios in situ may enable us to (re)connect science to geographic spaces.

Existing academic visualizations and public communication maps have resulted from cartographic convention, institutional norms and available technology. Yet, they are only some of the possible ways we might communicate tsunami risk. Our DIS cube analysis shows that there are areas of dimensionality, interactivity and situatedness that have not yet been explored in one or both academic and public tsunami communication domains. Developments in spatial interface research reveal new opportunities to develop visual information systems that deliver public tsunami visualizations that are 3D, temporal, interactive and situated. Spatial interface research is an emerging field, combining the concepts, theory, methods and technology of geovisualization, GIScience, HCI and VA. We discuss how a spatial interface approach allows us to respond to these opportunities in the following section.

4 Considering tsunami visualization from a geovisual interface perspective

Geovisualization is a research field integrating visual, statistical and computational methods to support knowledge creation from geographically referenced data and information (MacEachren et al. 2004). More recently, the field of GeoVA has emerged, combining spatial analysis, geovisualization, user interfaces and spatial cognition (Andrienko et al. 2007). These fields combine an understanding of (spatial) visualization design and human visual perception of visual information through the use of interactive visual interfaces (MacEachren and Kraak 2001; Thomas and Cook 2005; Keim et al. 2008; Andrienko et al. 2010). A geovisualization and geovisual analytics approach allows us to combine dynamic and interactive visualizations to elucidate critical spatial and temporal features in tsunami inundation.

We believe several key technologies and interface research developments have strong potential to link abstract science to geographic space and to enhance risk communication: tangible user interfaces (TUI), mixed reality (MR) and mobile augmented reality (MAR). TUI and MR technologies offer opportunity to improve interface experiences through the improvement of visualization interactivity and situatedness, respectively, two largely undeveloped axes of the DIS cube.

4.1 New opportunities for tsunami visualization interfaces

TUIs might be an elegant way to enable broad stakeholder audiences to engage tsunami risk communication on popular computing devices. These forms of interface allow for the manipulation of non-physical data by physical means, often through physical touch and gestures (Ishii and Ullmer 1997; Ishii 2008). The increasing use and decreasing cost of mobile devices afford an opportunity to improve application interactivity through a relatively new form of human–computer interaction. The most popular approach to public TUI design is the use of interactive surfaces, architectural surfaces that have been transformed into an interface between physical and virtual spaces (Ishii and Ullmer 1997). The screens of mobile devices serve as these surfaces, allowing for gesture and touch-based interaction. Touch-based interaction design has been used in only one identified example (NANOOS 2014) and is limited to view control.

Geovisualizations employing TUIs have been developed for a variety of geographic applications. ‘Urp’, an urban planning interface developed at MIT (Underkoffler and Ishii 1999), allows for physical models to be placed on a surface, while a camera and projector determine the orientation of the models and project-relevant geospatial data onto the scene. Like ‘Urp’, many cutting-edge applications of TUIs focus upon the use of physical objects and spaces in order to bridge virtual and real spaces (Hedley et al. 2002; Cheok et al. 2002; Ishii and Ullmer 1997; Ullmer and Ishii 2000); however, while applicable in controlled settings, such TUIs might prove cumbersome in uncontrolled spaces. For example, non-expert users exploring the relationship between local topography and tsunami hazard would not wish to interact with multi-component workbenches and projectors in challenging terrain. As such, our applied work focuses on mobile devices controlled with simple touch-based gestures to deliver augmented views and simulations of risk in coastal environments, as a way to link geovisual analyses to real-world environments.

4.2 Situated geovisual risk communication interfaces of risk and situational awareness

Given the spatial nature of tsunami risk and hazard, situated tsunami visualizations could offer better methods of communicating risk to coastal populations. Our work seeks to take risk communication in an altogether new direction through the use and application of MR and AR tools that enable users to draw upon natural hazard analyses—to enable two new forms of situatedness: situated geovisual analytics and situated simulation.

MR is defined as a class of interface that combines views of real spaces with content from virtual environments (VE) (Milgram and Kishino 1994; Tamura et al. 2001). Milgram and Kishino (1994) define the 'virtuality continuum', which is a range of possible combinations of (user interface) information experiences between those in real space and those in entirely virtual spaces. Augmented reality (AR) is a subset of MR and is defined as a spatial interface that allows the user to see the real world while digital objects, annotations and other forms of data are superimposed onto their view (Azuma 1997). AR can be found towards the real-world end of the virtuality continuum.

MR has been previously used to communicate spatial and geographic concepts and phenomena (Hedley et al. 2002; Shelton and Hedley 2002; Lonergan and Hedley 2014); however, the majority of this type of work falls within the immersive VE portion of the virtuality continuum (Shelton and Hedley 2004). Examples that may apply to the tsunami problem space include: revealing hidden phenomena (Schall et al. 2009), navigation (Dünser et al. 2012; Tsai et al. 2012; Tsai and Yau 2013) and post-disaster damage assessments (Kamat and El-Tawil 2007). Many of these tools are single-use prototypes with limited application outside of their original problem space (Billinghurst and Dünser 2012).

Several attributes make MR a viable research topic for geographic risk communication. The removal of desktop metaphors that may stand between the geovisualization and the user allows them to experience geovisualizations without having that experience diluted by the barrier of a computer screen, mouse and keyboard interface (Shelton and Hedley 2004). The authors also suggest two properties of AR interfaces that may benefit geographic visualization (ibid). First, the user retains proprioception within an MR interface; that is, the user's sense of self remains continuous. Second, the user's skeletomuscular motions and adjustments are directly tied to the interface. Movement of the interface device by the user results in a one-to-one adjustment of visuals on the display itself, closely linking the user to their virtual spaces.

These enabling technologies offer considerable potential for new kinds of risk communication experiences. In response, this research introduces several prototypes that target unexplored regions of the DIS cube analysis. Hedley and Lonergan (2012), Lonergan and Hedley (2014) have recently introduced *flexible mixed reality*—a cross-platform 3D geovisualization interface architecture that links analytical visualization with real spaces. This system is leveraged to deliver situated tsunami simulation and risk visualization in the following section.

5 Applied work: implementing interactive situated 3D tsunami visualization interfaces

In this section, we report on three visualization prototypes developed to explore the usage of 3D geovisualization, interactivity and situatedness (Table 1) in tsunami risk and hazard communication. The DIS cube approach revealed unoccupied spaces of the cube—which represent forms of interaction, situatedness and dimensionality that have not been used by either the public or academic visualization community. The prototypes were designed to explore and demonstrate what risk communication interfaces in these new territories might be able to deliver.

Ucluelet, British Columbia, served as the study area for the developed geovisualizations. The interfaces were developed using 3D game development software (ShiVa 3D). The interface prototypes were authored to a mobile tablet computer (Apple iPad) as stand-

Table 1 Tsunami risk communication prototypes and DIS classification

	2D (paper map)	EvacMap	ARRO3D	Tsunamulator
2D	X	X		
3D			X	X
Interactive		X		X
Situated	Can be	X	X	X
Mobile AR			X	X

alone applications in order to take advantage of location-awareness capabilities. The titles of the interface prototypes are: EvacMap; ARRO3D; and Tsunamulator.

5.1 EvacMap

EvacMap is a location-aware iPad-based interface that allows users to interactively browse between different evacuation maps of Ucluelet (evacuation by distance, time, transportation type). The purpose of EvacMap is to enable citizen users to customize risk and accessibility maps based on their mode and speed of movement, and their geographic location. Users select their mode of travel (walk, run, bicycle, car) and relative speed (fixed speed ranges within transportation type). Selection of these variables, combined with the device's GPS technology, enables the user to quickly produce evacuation and accessibility maps based on specific parameters and physical location.

This prototype was designed with the limitations of existing static maps in mind. Evacuees are highly variable in their speed and origin during tsunami events. Running, walking and vehicle speed may be different enough to alter recommended routes to safety and ultimate destinations. Paper maps cannot be altered once printed, so great care is taken to ensure they are usable for a variety of people. By allowing users to select their mode of travel, customized evacuation maps can be provided based upon personal circumstance.

EvacMap is positioned within the DIS framework as a highly interactive and moderately situated interface. It shares a similar conceptual positioning with the NANOOS mobile tsunami application (NANOOS 2014). Both represent uncommon forays into situated and interactive tsunami risk communication design; however, they remain clearly 2D and do not offer situated experiences beyond noting the user's current location.

5.2 ARRO3D

Augmented Reality Risk Overlay 3D (ARRO3D) is a prototype interface that links abstract risk maps to real space by enabling risk maps to be placed into the real world. This linkage is achieved through the use of MR, traditional risk analysis and a coastal topographical model. A 20-m inundation map was draped on top of a 3D VE of Ucluelet. The interface is MR-enabled; that is, the scene is viewable from a first-person perspective that integrates a live view of the real world. By adjusting the angle and orientation of the visualization device, users can see if they are standing within the 20-m inundation zone (Fig. 4).

The MR component of this interface places this prototype further along the situatedness axis of the DIS cube than previous location-aware tsunami visualizations. This is because the visual output of the interface depends upon two highly situated inputs: user location

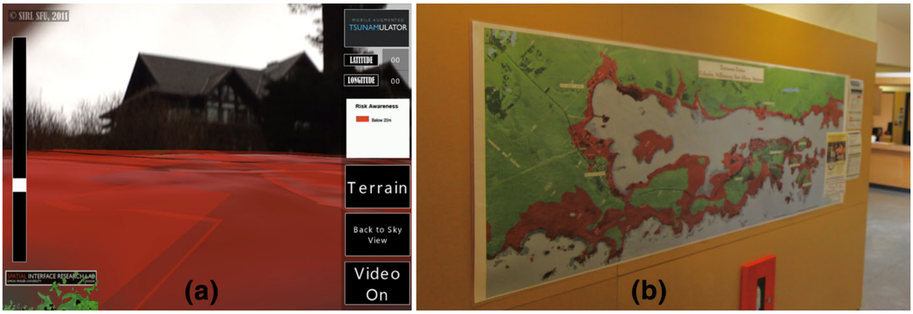

Fig. 4 **a** The ARRO3D interface overlays digital risk information onto a live view of the landscape, indicating elevations that are below 20 m. **b** Existing *red* (risk) and *green* (safe) zoning map in a community centre

and visual input of the camera device. The combination of these factors with the digital risk overlay links the abstract geographic risk with everyday space.

As seen in Fig. 4, traditional forms of risk communication in local communities can be presented in ways that are disconnected from the landscape they portray. A map on a wall requires mental rotation and translation if a reader is to locate objects represented in real space. ARRO3D is designed with this challenge in mind. By allowing users to view representations of abstract risk in real space, we may avoid a potential misinterpretation of data.

5.3 Tsunamulator

The ‘Tsunamulator’ interface is the most advanced example of our new geovisualization interfaces. It combines dimensionality, interactivity and situatedness in one tool, to deliver a new way to link virtual simulations to geographic space for tsunami (risk) visualization. This system seeks to provide a dynamic visualization through which educators might demonstrate basic tsunami principles such as sudden onset and how local topography can alter run-up. While the simulation presented here is simplistic, it serves as a demonstration of how simulations with varying degrees of complexity and rigour might be visualized in situ.

This system is composed of a particle-based tsunami simulator and a VE of Ucluelet. The first interface modality provides a top-down view through which the user defines a tsunami origin point and direction of flow using a multi-touch TUI. Once the origin is determined, the interface switches to a perspective 3D simulation-viewing mode. The camera perspective is then unlocked to allow full control over the viewing angle and orientation by means of touch-based gestures.

The visualization itself generates particles along the linear tsunami origin. These move through the 3D environment along the user-defined vector by means of ShiVa 3D’s physics engine (Fig. 5). The particles behave as rough approximations of water breaking along the shoreline when they collide with the solid topographical geometry. While these particle simulations are certainly less accurate when compared to flow analyses generated by dedicated software, the rougher approximations are not without benefits. This lightweight flow approximation approach enables *rapid* visualization of inundation events on *low-power mobile devices*. While we acknowledge that this particle simulation is not as

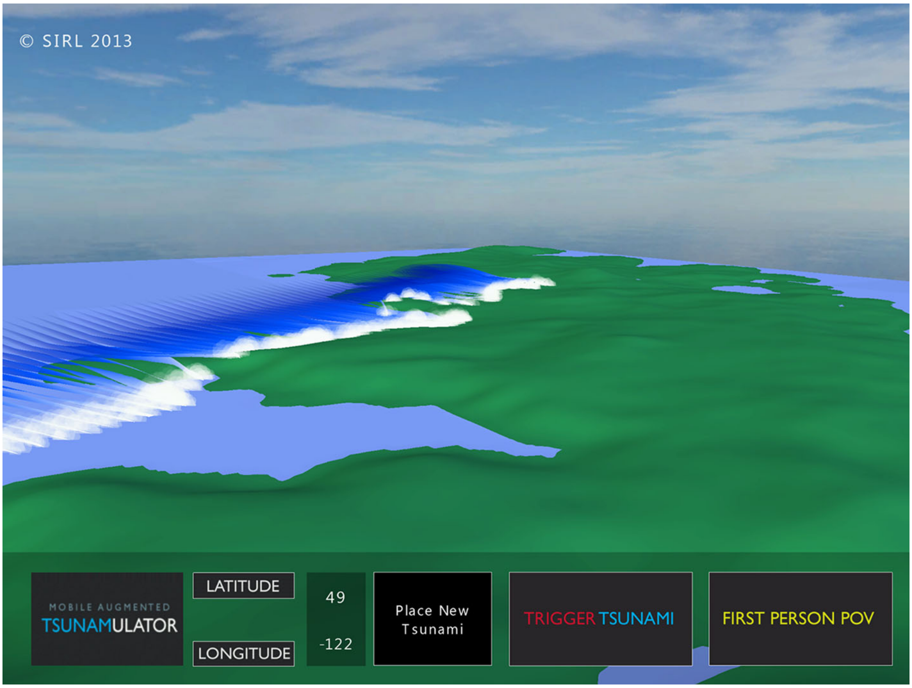

Fig. 5 In the Tsunamulator interface, particles simulate the sudden onset of a tsunami from a 3D perspective view of a virtual Ucluelet shoreline

sophisticated as models used in scientific fluid simulation, this prototype demonstrates the potential of mobile devices to deliver *simulations* in situ as a way to connect science to geographic space. Porting results from more robust models of tsunami simulations into this environment is the next logical step.

From the 3D perspective viewing mode, the user is given the option to switch to a 'first-person VE' viewing mode. This mode allows users to examine the VE from a first-person perspective—resulting from their physical location (coordinates) and manipulation of the mobile device (orientation, panning). We call this mode a *situated portable virtual world*—where a location-aware mobile device can be used as a portable lens through which to look into a scientific virtual simulation 'parallel universe' from the equivalent coordinate in real and virtual spaces.

The final—and most radical—visualization mode that Tsunamulator delivers is situated augmented reality visualization. In the previously introduced 'situated VE mode', the user looks through a device into a parallel virtual environment from a coordinate in the real world. By contrast, in the situated augmented reality mode, the user is able to look at everyday space through a mobile device used as a lens and see virtual simulations run over the real landscape, with virtual particle simulations interacting with the geometry of the coastal environment. Figure 6 below shows how, through this new interface design, we can link abstract virtual simulations to real geographic spaces.

Individually, each prototype explores visual interface techniques to leverage dimensionality, interactivity and situatedness in one or more ways. Together, these tsunami visualization interface prototypes make new inroads into as yet uninhabited space within

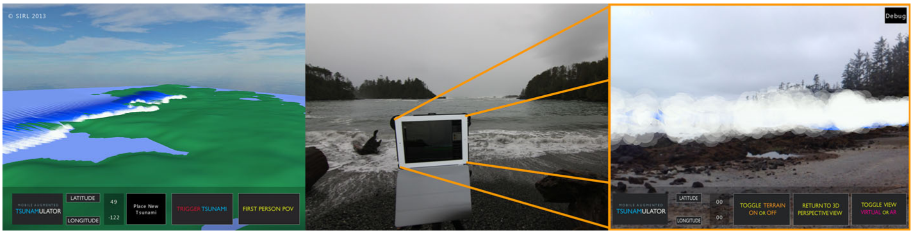

Fig. 6 Tsunamulator delivers the capability to link virtual 3D simulations with real geographic space, using situated and mobile augmented reality. This method builds upon the foundational work of Hedley and Lonergan (2012) to implement live particle simulations in geographic space using augmented reality. (L) The virtual environment version of Ucluelet, BC; (*middle*) a location-aware tablet running Tsunamulator; (R) user view when looking at real-world view through a mobile device—an inundation simulation arriving on a local Ucluelet beach

the 'DIS cube'. While perhaps novel in appearance, their purpose is serious: to find meaningful new ways to link tsunami science, simulations, visualization, users and real space. Tsunamulator is the most sophisticated outcome of this development research. It provides a fundamentally new way to link abstract scientific models, 3D virtual environments to visualize them, situated virtual environments to view them aligned with real-world coordinates (situated VE mode) and mixed/augmented reality situated simulations in geographic space.

6 Discussion

The primary objective of this paper is to help advance the field of tsunami risk communication. We reviewed select academic and public tsunami risk communication examples and classified them using the DIS cube space. This revealed differences in the structure of tsunami science versus public communication realms—in terms of the dimensionality (2D vs. 3D) of visualizations, the level of interactivity of these visualizations and the degree of situatedness they were designed to deliver. These differences suggest that conventional forms of tsunami science and public risk visualizations: do not commonly transmit the volumetric, dynamic characteristics of tsunamis in public risk communication (perhaps for good reason); are not typically interactive (therefore limited in their ability to communicate scenario variability); and each reside in distinctly different parts of the situatedness spectrum (tsunami science typically ex situ, public communication being a mixture of ex situ and in situ, but often not designing maps for in situ use).

The structural differences we have illuminated suggest two main issues. First, as tsunami science is transmitted through existing forms of public visual risk communication, these complex phenomena are transformed into less sophisticated representations—simplifying variability and behaviour over time into static aggregate snapshots as 2D inundation footprints. The reasons for the simplifications are, in many cases, understandable, for reasons of message clarity, ease of emergency management and limitation of liability. Still, we wonder whether oversimplification of tsunamis in current forms of visual risk communication reduces our ability to mitigate public risk. This is true from a cartographic design standpoint (Kurowski et al. 2011). But we believe that an emerging range of interactive, 3D and situated interface methods might be harnessed to deliver significantly more informative risk visualizations.

This leads to a second significant outcome of our DIS cube analysis. Through this analysis, we realized that existing visualization methods (in both academic and public communication communities) are not using all of the 2D–3D dimensionality, interactivity and situatedness that numerous current and emerging interface technologies enable. This fact suggests that transmission of tsunami science to society might be significantly improved if we were able to: preserve the dimensional sophistication of scientific models as they are imparted to the public; use interactive visualization to reduce public uncertainty surrounding tsunami scenario variability (allow citizens to browse and explore collections of science-based hypothetical scenarios to mitigate risk through experiential education); transform on-the-ground public risk awareness by delivering new forms of situated tsunami risk visualization—allowing citizen to see our best science linked to their everyday geographic surroundings.

Our field testing of user-driven risk/evacuation maps (*EvacMap*), risk map overlay (*ARRO3D*) and virtual-MR hazard simulation (*Tsunamulator)* prototypes has yielded observations that illuminate user interaction and interface design considerations for the geovisual risk communication interfaces. User type, interface properties, interface use venue and location of environment at risk relative to location of risk information interface are just some of the factors that will influence the way abstract risk analysis outputs (maps, GIS, simulations) are linked (and translated) to geographic spaces and perceived by users.

EvacMap explored ways in which we might make conventional 2D maps more situated, using location-awareness technology. This might be as simple as 'you are here' in existing 2D risk maps and seeing your location change over time. This 'light' situatedness might also be used to trigger localized evacuation accessibility maps pre-computed for locations across a region—enabling citizens not only to view their location within aggregate risk zones, but also to view evacuation analyses (how far am I in time/distance from safety?) computed for their specific location. *EvacMap* is an example of a user-centred interface. Unlike a generalized, impersonal map of aggregate risk (such as that on a community centre wall), the risk information is 'tuned' to (and by) a user's specific needs (mode and rate of mobility) and location (via a mobile device). The user is able to see their own personalized risk context (and evacuation options), tuned to their geographic location.

Another key issue revealed by our work to date is the challenge to mitigate or remove the spatial–visual disjoint common in many existing risk communication venues and to translate risk on maps into risk awareness in geographic space. Risk communication maps or pamphlets inside municipal or other public spaces (see Fig. 4b) are often displaced from the real-world locations for which risk maps have been produced, hidden from view (by walls, vegetation or distance), thus interrupting a citizen's ability to relate, reorient and translate risk information into first-person geographic contexts. A key need of geovisual risk communication interfaces, therefore, is an ability to establish perceptual and spatial congruence between user, geographic space and risk information as a basis for developing situational awareness of risk. In existing venues (such as visitor centres), table-top 3D topographical models are used to give visitors a sense of 'lay of the land' and their current location. However, it is not feasible to have visitor centres and physical models everywhere. A key capability of interactive virtual environments is their ability to allow users to view, query and explore phenomena, places and scales which would normally be inaccessible, invisible or impossible to perceive. Virtual environments (such as the situated tangible VE mode of Tsunamulator or a head-mounted-display-enabled 3D VE) can overcome or mitigate these challenges, by perceptually 'transporting' the user to multiple modes of view, query and exploration not normally possible in first-person reality. Once more, the quality and effectiveness of such virtual environment experiences hinges on careful user-audience-centred interface design, coupled with precise geovisual analytical representation of the hazard phenomena in question.

Another option—instead of transporting the user into a virtual space of risk communication—is to bring the risk information into geographic space (situatedness). Paper maps, pamphlets and signboards do this currently, but many suffer from placement and orientation issues potentially undermining citizens' ability to relate these risk communication media to real space (or even if successful, with what cognitive overhead?). The spatial orientation of the risk communication medium may be very different from the orientation of the risk communication medium, adding unnecessary cognitive overhead due to mental rotation required to align risk information to geographic space and vice versa. The impact of mental rotation on the speed of spatial reasoning is well documented in psychology (see Shepherd and Metzler's (1971) seminal mental rotation paper; see Kastens and Ishikawa's (2006) chapter which links spatial cognitive research to spatial thinking in the geosciences). It is not unusual to find tsunami risk/evacuation maps in public places to be aligned to park perimeters or building architecture, rather than to be orientated to the landscape and cardinal directions.

ARRO3D and Tsunamulator offer two samples of how MR might be applied to improving the communication of abstract science. Traditional geospatial MR applications are mainly limited to digital annotation or static 3D geometries (Billinghurst and Dünser 2012). ARRO3D follows this trend by overlaying 2D risk information in real space. Two-dimensional risk zones are the standard format for communicating risk to the public; do we gain anything by bringing this information into real, 3D space? Tsunamulator represents a more complex approach to risk visualization in real space. By bringing a dynamic tsunami simulation into the real world, we are actively connecting previously separate abstract risk (developed through tsunami science) to the coastal geographic spaces at risk (populated by citizens). While further research incorporating empirical user testing will evaluate their impact on risk awareness, we believe that MR interfaces (that combine virtual environments and real spaces, as per Milgram and Kishino (1994) continuum) have the potential to deliver our best tsunami risk analyses to citizens in everyday spaces.

We have found through our field testing so far (and informal stakeholder feedback) that our somewhat radical mixed reality interfaces (ARRO3D and Tsunamulator) appear to close the conventional separation between abstract risk analyses and communication media, and geographic space—providing dramatic, immediate colocation of risk visualizations all around users in everyday space. These interfaces allow abstract spaces of risk analysis and geographic (and human) spaces at risk to become the same, connected space.

Implementing EvacMap, ARRO3D and Tsunamulator has revealed new questions about mixed reality risk visualization. Some modalities of MR risk visualization will benefit from unobstructed wide field-of-view (FOV) viewpoints to support large-area risk analysis (for groups of planners to validate correspondences between analyses and reality). We have also been experimenting with mixed reality risk waypoints and way-marking, using discrete virtual markers (somewhat like blue-and-white tsunami inundation signage). Full implementation of these prototypes will require elegant solutions to the challenge of object occlusion. Overlays of virtual objects on views of real space need to be designed carefully, in order to avoid spatial–visual orientation dissonance between virtual objects and geographic spaces in the field of view. To mitigate this challenge, it will be critical to design virtual risk information augments that are 'perceptually cogent' (whose geometry, orientation and appearance integrate well with the real environment being augmented) (Hedley 2008; Lonergan and Hedley 2014).

Spatial tracking and orientation of devices relative to geographic space will be key to accurate alignment and overlay of virtual digital augments in views of real space—whether virtual overlays of risk maps (ARRO3D) or 3D simulations interacting with real terrain (Tsunamulator). Poor positional spatial tracking and orientation may result in visual–spatial dissonance in augmented views. To mitigate this, we have already developed a technique with which to 'tune' and stabilize spatial augmented reality displays to geographic spaces, once a high-quality spatial fix is established (see Lonergan and Hedley 2014).

We are also observing some critical considerations in specific stakeholders' spaces of activity. While in-the-hand interfaces (smartphones, tablets) may allow risk information 'tuning' to user-specific locations, poor alignment of mobile devices to geographic space may add cognitive overhead to risk visualization tasks, due to mental rotation. We must therefore not underestimate that users will view and use the same risk information (interfaces) variably—regardless of whether they are digital, MR, paper maps on walls or in pamphlet form.

7 Conclusions and future work

Two-dimensional maps are the most common form of public tsunami risk communication and have been used for a considerable amount of time. As many new spatial data types, visualization techniques and interface technologies emerge, we believe that there are as yet untapped ways to enhance transmission of our best tsunami science to society—through new forms of public risk communication interfaces.

Approaching tsunami visualization from an interface perspective, highlights the fact that a map is only one kind of interface through tsunamis can be visualized and communicated. This paper reviewed and compared the ways tsunami science versus public risk communication has visualized these phenomena. This revealed clear differences in the way these two communities currently use 2D versus 3D representation, interaction and situatedness in tsunami visualization. Currently, the public is highly reliant on official communication (Couling 2014); as such, information transmission needs to be effective. Contemporary and emerging geovisualization methods and interface technologies might have the potential to maximize the communication of tsunami science to society by facilitating interactive sense-making (allowing citizens to explore 'what if' scenarios) and by (re)connecting science-based visualization to everyday spaces, using location-awareness of mobile devices and MR experiences.

This tool has been designed and implemented using a modular workflow. This results in an interoperable ability to combine different mixtures of spatial data, visualization assets and mobile devices. While it is true we have used some devices that may be expensive in developing nations, our modular workflow is designed to adapt to circumstances involving limited data, connectivity and other devices. Our long-term plan is to develop research collaborations in coastal communities of all kinds to explore and build resilience using these tools.

Our review of existing tsunami visualization, using the DIS framework, reveals as yet untapped forms of tsunami risk communication interfaces, whose properties might enhance transmission of science to society. Our applied work demonstrated how new forms of 2D and 3D interactive and situated tsunami visualizations might improve alignment between tsunami science and the communication of risk to society.

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