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A user-centred design framework for disaster risk visualisation

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ABSTRACT

Visualisations are powerful communication tools that have the potential to help societies assess and manage natural hazard and disaster risks. However, the diversity of risk management contexts and user characteristics is a challenge to develop understandable and useable visualisations. We conducted a systematic literature review to understand the current state developing disaster risk visualisations following design best practices and accounting for the heterogeneity between end-users and disaster risk contexts. We find that, despite being widely recommended, tailoring visualisations to users through the process of user-centred design remains a relatively unexplored topic within disaster risk. To address this, we present a unifying user-centred design framework for disaster risk visualisation, based on existing visualisation frameworks. The framework contains three phases: the Define phase, which aims to define and characterise the disaster risk management context and end-user group who will benefit from a visualisation; the Design phase, which is highly iterative and presents an opportunity to test how users interpret different design elements; and the Refine phase, which focuses on evaluating how users understand, respond to, and make decisions based on the visualisation. The framework is sufficiently flexible to be applied to any disaster risk management and natural hazard context to identify challenges and design effective disaster risk visualisations that are understandable and useable.

1. Introduction

1.1. Communication within disaster risk management

Minimising the societal impact associated with natural hazards through improved disaster risk management (DRM) has become a global priority in recent decades, as the frequency and magnitude of natural hazards are forecast to increase substantially over the next century [1–3]. Disaster risk management acknowledges the long-standing legacies of maldevelopment and their impact on the vulnerability of different populations, as well as the destructive hazard event itself [4,5]. Efficient reduction and management of disaster risks thus requires knowledge of the relevant natural phenomena, societal exposure and vulnerability, key stakeholders at different levels of the DRM process, and available resources and capacity, which all vary across different decision-making contexts and scales [6,7].

During the development of the 2015–2030 Sendai Framework for Disaster Risk Reduction, significant gaps in scientific capacities

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and information were highlighted as a key challenge to those implementing legislation and actions for DRM [1,2]. A disaster is considered an intersection of three opposing forces: those generating vulnerability and the physical exposure to a forecast hazard, which is represented by the widely applied *At Risk* formulation: *Risk = hazard x vulnerability x exposure* [2,8,9]. Applying this equation, is challenging due to a lack of data and information for each context, which is exacerbated by the inherent uncertainties within forecasting natural hazards. As a result, communicating the resulting disaster risk is also challenging, yet essential to support evidence-based decision making and trust in the outcomes of decisions [10,11]. In addition, decisions within DRM contexts are often made under extreme pressure, so it is crucial that decision makers have confidence in the information they are using [12,13].

However, the complex factors that impact risk understanding and evidence uptake are not all fully understood or considered in designing communication tools. Policymaking and decision making happens in a context of well-established beliefs and values, so new evidence or information requires a shift of attention and successful persuasion of the decision maker to be effective [14–17]. Non-scientific audiences have their own knowledge and expertise, use and value different sources of information, and have a limited time to evaluate the usefulness of scientific knowledge [12,18]. Communication is therefore most effective if it frames evidence in relation to the beliefs and perceptions of their audiences [19,20]. Effective communications within DRM are further complicated by both the social amplification of risk and individual perceptions of risk, as risk is conceptualised partly as a social construct and partly as an objective property of a hazard or event [21,22]. Hazards interact with psychological, social, institutional, cultural, and personal experiential processes in ways that can heighten or reduce perceptions and interpretation of risk, which in turn shapes behaviours through either exaggeration or downplaying [23,24]. These interactions are highly variable between individuals, and therefore, involving different level stakeholders in designing disaster risk communication is necessary to account properly for these aspects.

Participatory design shows promise for disaster risk management, as a way to further understand the processes which affect reduce perceptions and interpretation of risk between individuals [25,26]. Participatory rural appraisal, community-based participatory research and community driven development are only some of the ways of involving local stakeholders in the research process, empowering them to define the challenges they face, examine them with the help of professional scientists and set their own goals. In the context of disaster risk deduction, both the Hyogo Framework for Action (2005–2015), and the Sendai Framework for Disaster Risk Reduction (2015–2030) stress that disaster risk management is most effective when aimed at working with local communities [27], inspiring a plethora of participatory approaches that range from participatory modelling [28,29] to citizen science [30,31]. During participatory approaches, end-users are actively involved as equal partners throughout the entire research process, resulting in greater buy-in to the project [32–34]. Participatory approaches are praised for their empowering effect on stakeholders by recognizing them as active agents of change [35].

Within the context of visualisation, user-centred design (UCD) may be a useful approach to engaging users and enhancing participation. UCD involves tailoring communications to specific users or user groups, rather than solely focusing on the information being conveyed. UCD originated in the product and software development field, and is a process whereby designers consider explicitly the characteristics of a product's end-users, those who will eventually use a product, throughout the whole design process [36,37]. When a UCD process is followed end-users' intellectual, emotional, experiential and moral characteristics are taken into account, improving the likelihood that products will be considered useful, understandable and useable by end-users [38–40].

A key area to explore user-centred design for disaster risk communication is in the development of visualisations, which are increasingly recognized as powerful tools that engage societal actors with unfamiliar and complex concepts [33,41,42]. They have the potential to improve decisions, change behaviours and trigger action, more so than other communication forms such as the written word or numerical formats [33,43]. However, this potential is not yet realized fully, especially within the natural hazard context [17, 42,44].

We use the term "visualisation" here to denote any static representation of data, information or knowledge. The term implies that intentional decisions have been made around the design elements of the visualisation: line, shape, form, value (creation of mood and depth), colour, space, texture and typeface [45]. The purpose and design of a visualisation determines how to evaluate its success [46, 47]. Within disaster risk visualisation this is particularly important, as the purpose of a visualisation will determine which data and information are visualised.

1.2. An overview of user-centred design

User-centred design originated in the product and software development field but has since been applied across many disciplines and contexts. The characteristics of a product's end-users (i.e. their wants, needs, contexts, limitations etc.) are thoroughly researched and explicitly considered by designers throughout the whole design process when a product is developed through UCD [37]. End-users' cognitive, affective and behavioural points of view are also considered, as well as the social, organisation and cultural content within the UCD process is occurring, and the product will be used [48]. Implementing a UCD approach requires an iterative design process, testing the usability of prototypes and evaluating the efficacy of the design from the end-users' perspective [49].

Many fields have used UCD to develop visualisations for different purposes for different contexts [49,50], for example developing training manuals [51], educational material for physicians [52], posters for water governance [53], software showcasing energy use [54] and environmental decision support systems [55]. It is also very common in the sphere of "gamification"- transforming activities, systems, services or products or organizational structure into "gameful" experiences [56]. UCD has revealed that user profiles and needs differ to and were more complex than designer's initial expectations in all of these instances, which led to more effective, targeted tailoring and successful products. Within disaster risk communication this is crucial due to the impact that the social amplification of risk and individual perceptions of risk can have on perceptions, interpretations and actions. Thus, limited consideration of end-users and the context in which a product will be used could hamper one's ability to effectively communicate [57].

During the first step in the UCD process, designers generate a complete picture of the end-users' real-world situation, needs, requirements, and the problem the product aims to address [37,58]. This is a time-consuming but important process that informs the iterative design process where prototypes are tested for usability, and feedback about their efficacy is obtained from the user's perspective [59]. The iterative design process that follows, provides multiple opportunities to gauge end-users' understanding and perception of the design [60] These insights are then applied towards the development of a tailored product [61].

The last phase of the UCD process is the evaluation of the final end product to assess its effectiveness [60]. Users' understanding of the product and use of the product should be evaluated in either actual or simulated real-world situations [49,62]. This provides further insight into users, their context and the effectiveness of the design and communications [40,49]. It also provides feedback on how users perceive and utilise various components of the design, which can then inform future designs or updates to the original design [62].

1.3. The cognitive process of visualisation

Humans assess new information and make decisions based on visualisations with either fast, intuitive thinking, which occurs outside of a thinker's conscious awareness (Type 1), or slow analytical thinking (Type 2) (Fig. 1). Whilst there is disagreement on the exact processes and their differences, there is generally consensus between decision-making researchers that we can make both intuitive (Type 1) and strategic (Type 2) decisions [42,63,64]. Both types of thinking use bottom-up attention, which focuses on external factors (i.e. the visualisation) [18,65]. However, Type 2 processing uses significantly more top-down attention and working

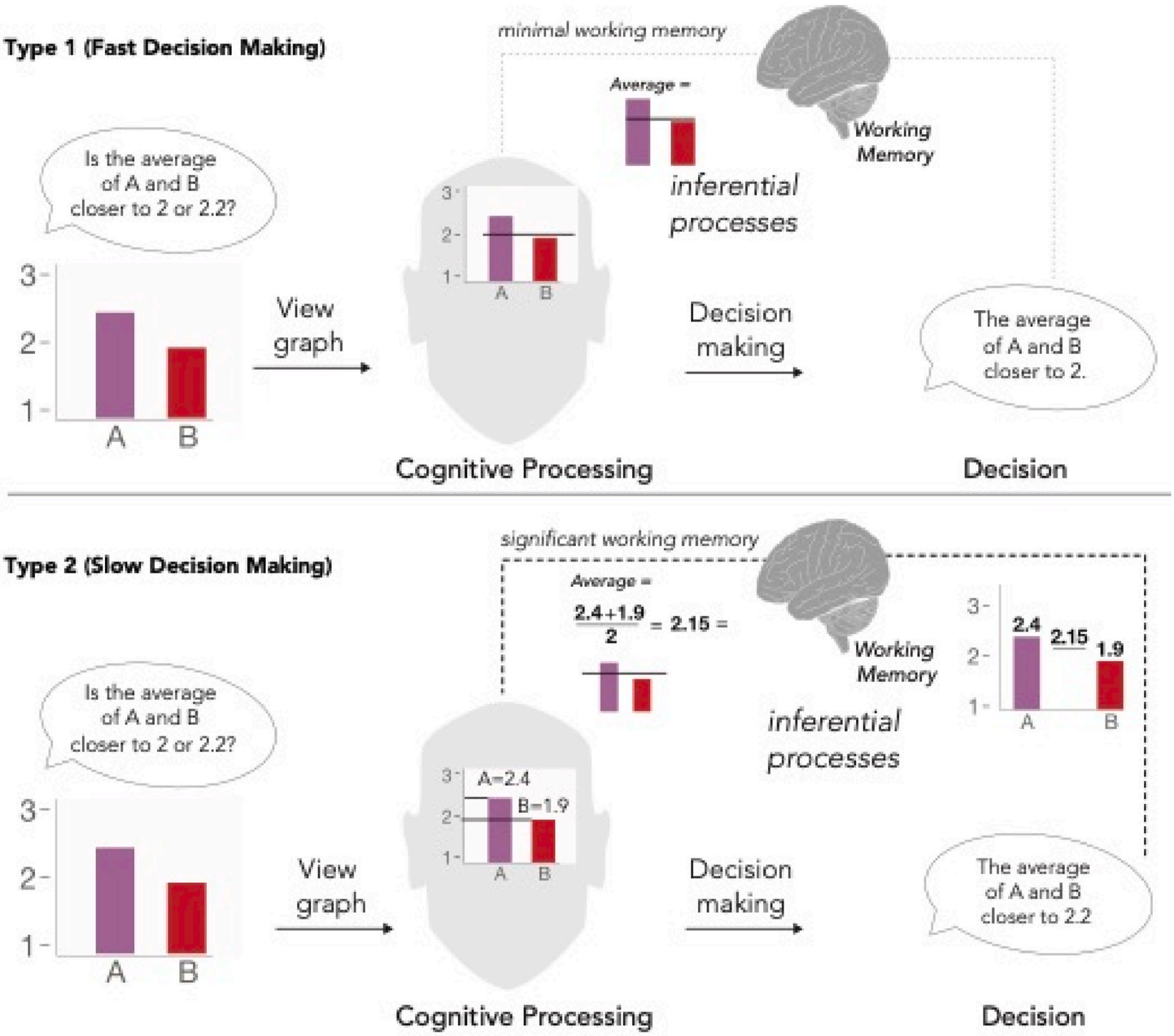

Fig. 1. Illustration of the difference in cognitive processing between fast (Type 1) and slow (Type 2) decision making about visualisation. A viewer is asked whether the average value of bars A and B is closer to 2 or 2.2. The top figure shows how the viewer might use Type 1 thinking to make a fast and computationally light decision, estimating that the middle point between the 2 bars is closer to the tick mark of 2 on the Y-axis and decides that the answer is 2, which is incorrect. In contrast, the bottom figure shows how the viewer might use Type 2 thinking, utilising significant working memory to identify the values of A and B, and going through a separate cognitive process of mentally computing the average (adapted from Padilla et al., 2018).

memory, either deliberately or subconsciously [42]. Thinkers are prone to cognitive biases during both types of processing, but during Type 2 processing they are also prone to moral or social biases [65,66]. It is therefore useful for disaster risk visualisation designers to understand which type of processing is occurring. Cognitive science studies have improved our understanding of how visualisations are cognitively processed, and how designers encode (represent) and users decode (understand) different elements of visualisations.

Once designers understand what type of processing is occurring, design decisions can be made to help end-users to avoid biases by focusing end-users' attention on relevant information (Fig. 2). Designers can promote Type 1 thinking through deliberate design that ensures that visuals do not conflict with users pre-existing perceptions, values and knowledge [67,68]. Designers also have to be aware of where and how the visualisation is presented (the 'signalling environment'), as factors such as room colour and the beliefs of people near the end-user can influence how end-users interpret, act on and process a visualisation [57].

Here we explore how a UCD process can be used for tailoring disaster risk visualisations to end-users. To this purpose we develop and present a useable design framework that integrates the principles of UCD, cognitive aspect of visualisation within a disaster risk management context and presents a framework to guide that process. In Section 2 we provide the methodology for the systematic literature review of the current state of disaster risk visualisation within natural hazard contexts presented in Section 3. In section 4 we present our UCD framework for disaster risk visualisation, aimed at supporting designers, scientists, communicators and knowledge brokers to define end-users, identify challenges and integrate different types of knowledge through specific design choices using suggested methods and tools into visualisations. Section 5 offers brief conclusions and a future outlook on the use of the framework.

2. Methodology

A systematic literature review was conducted to investigate the current state of disaster risk visualisation (Fig. 3).

Our review focused on interdisciplinary literature on disaster risk visualisation between 2000 and 2020 as this is when international efforts to collaborate towards improved disaster risk management began, ultimately resulting in the Hyogo and Sendai frameworks [2]. The key words and strings 'natural hazard "risk visualisation"', 'natural hazard "risk visualisation"', 'disaster "risk visualisation"' and 'disaster "risk visualization"' were searched in two databases - Google Scholar and Web of Science (Fig. 1). Of the 4582 identified studies, we discarded studies that focused on developing visualisations to characterise, understand and predict disasters for the sole purpose of scientific research. We retained only those that applied, or reviewed, appropriate science to specific social, political and cultural context in order to communicate disaster risk were included in the initial review. This screening process produced 35 eligible papers.

Each paper was analysed for the design practices they recommended specifically for disaster risk visualisation based on their experiments. We grouped these practices into 4 groups based on the design elements they refer - colour, amount and type of information, shapes and markings, and medium and type. These were compared to general principles recommended within the field of design, to explore whether the application of design processes to disaster risk visualisation resulted in different recommendations (Table 1).

Each study was then analysed for whether vulnerability and social data were included in the visualisation, since these are inherent parts of disaster risk, and for whether a UCD approach was used and/or recommended, in order to assess the importance of utilising a UCD process when developing disaster risk visualisations as summarised in Appendix A. The ways in which users understood, used and/or perceived the visualisation were also interrogated, since evaluation is a key aspect of UCD. It was noted whether an experiment

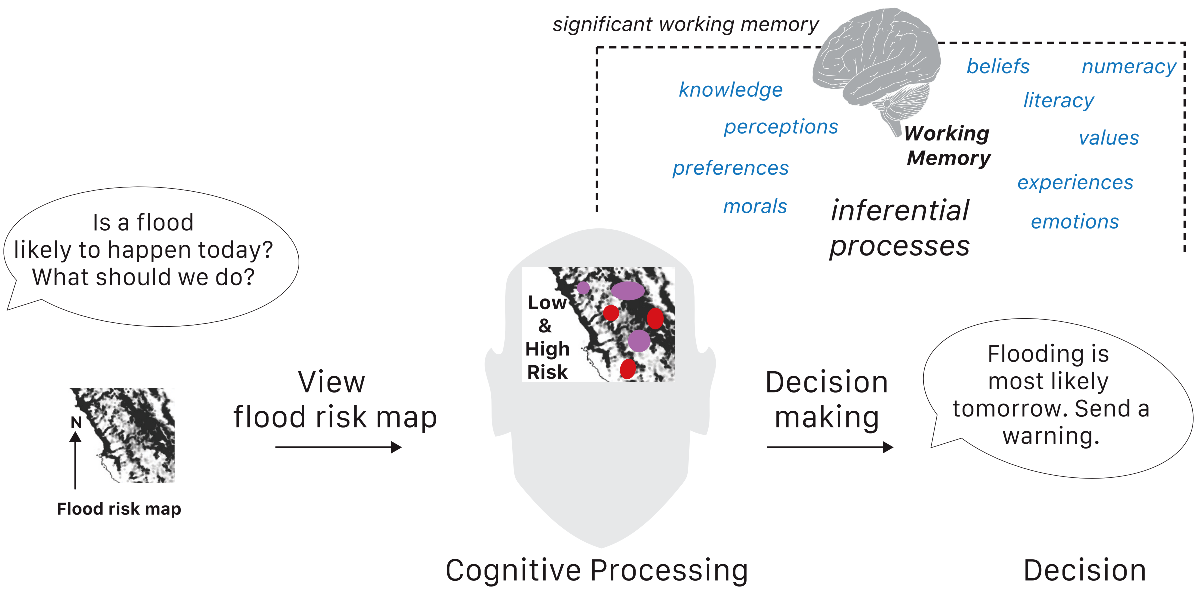

Fig. 2. Influences on the interpretation of risk visualisation products and subsequent decision-making.

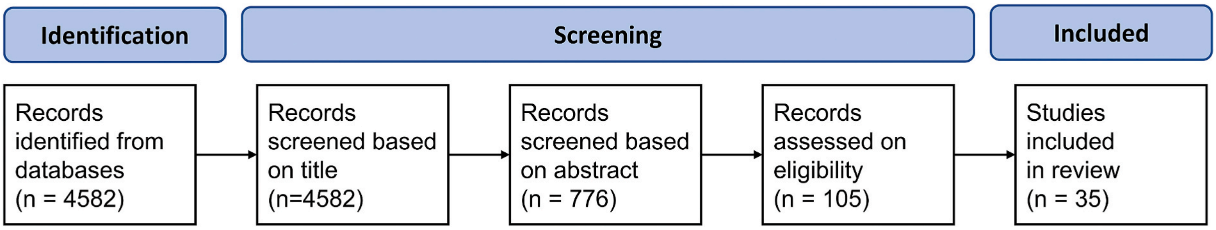

Fig. 3. Summary of the systematic literature review process focusing on interdisciplinary literature on disaster risk visualisation between 2000 and 2020 from 2 databases (Google Scholar and Web of Science).

took place to evaluate the visualisations in each study, since an ideal UCD process involves evaluating the final product in the context in which it would be used.

3. Results

An overview of our systematization of the design guidelines extracted from the systematic review is presented in Table 1. Here we summarise the main trends. In terms of colour, monochrome colour schemes are recommended within the general design principles to help people to easily distinguish trends, and other colours should only be used for emphasis (Table 1). However, due to different cultural meanings of colour, different colour schemes are recommended for different types of data within disaster risk visualisations (Table 1). The advice given within general design principles relating to the amount and type of information emphasises that irrelevant information should be omitted, and that the most relevant data should be both contextualised and attention-grabbing (Table 1). Generally, the disaster risk visualisation advice concurs, but is much broader and subjective depending on the context in which the visualisation will be used (Table 1). The form, size and texture of shapes is considered more important than colour within general visualisation principles, and simple shapes that intuitively convey the salient information are recommended (Table 1). However, there is no clear link between the effects of these graphical elements and users' understanding of a disaster risk visualisation, as the influence of these elements is dependent on individual user profiles (Table 1). Finally, novelty is welcomed within the general design principles so long as it does not impede usability, as novelty promotes interest and excitement, whereas the specific disaster risk visualisation advice recommends utilising mediums and designs with which the user is accustomed (Table 1).

Within all of the disaster risk visualisation recommendations, there is different advice as to context, framing and the influence of graphical elements compared with the general design principles (Table 1). This difference is best exemplified by the divergent advice for visualising uncertainty. Whilst some disaster risk visualisations informed by design best practices have been shown to result in better comprehension and risk perception [81,90], others have found that it depends on what hazard is visualised, as "best practice" visualisations do not necessarily improve risk comprehension and can still result in users taking away unintended judgements and messages due to user heterogeneity [100,106,107]. Many individual characteristics of users have been shown to influence interpretations of disaster risk visualisations including pre-existing knowledge of the hazard [108], socio-demographic profile [95], culture [99], numeracy and literacy [42], preferences [80] and profession [92].

These findings are not surprising, as it is widely recognized within the design field, that design principles are flexible to allow for tailoring of designs to end-users [60,70,72]. The general design principles should be used as a starting point, and as guidance when end-user testing is not possible, but are not set-in-stone as the only principles that must be followed [49,86]. Clearly, tailoring to users is necessary, especially within disaster risk visualisations. General design principles are often not specific enough for useful and useable disaster risk visualisation, or may even conflict with best practice advice given specifically for disaster risk visualisation (Table 1).

UCD presents an opportunity to improve the tailoring process: over half the reviewed studies recommended using a UCD process for the development of future visualisations (Table 1.A). However, of those reviewed, only six studies utilised a UCD process. Developing a decision support system for hazard services through a UCD process led to a system that was optimally tailored to users, as visual elements were more intuitive so the cognitive load on users was minimised which helped them to complete tasks more efficiently [62]. A UCD process in the development of flood risk communications led to four new prototype communications with four different purposes according to user needs, providing relevant data and contextualisation that made them easier for users to understand and use [93]. Elsewhere, the main recommendation stemming from the development of a volcanic hazard map was that future development should involve end-users throughout the entire design process, as users beyond the disaster risk reduction community did not use the maps; individual maps tailored to specific user requirements would have been more useful (Lindsay and Robertson, 2018). Similarly, a review of case studies of volcanic risk visualisation concluded that these tools held potential if designed for each unique situation and setting, and co-developed with end-users (Thompson, Lindsay and Leonard, 2018). Additionally, even though vulnerability is inherently part of disaster risk, only three of the studies reviewed included vulnerability data in their disaster risk visualisations (Table 1.A). Following a UCD process when developing a visualisation can help with the integration of vulnerability data, because UCD inherently analyses social context.

4. A user centred design framework for disaster risk visualisation

Given the interdisciplinary nature of disaster risk management and the diversity of user needs a UCD framework will need to integrate different data, contexts and user needs into disaster risk visualisations. Specifically, we identify the following requirements:

Table 1
Comparison of general design principles for the four design elements of colour, amount and type of information, shapes and markings, and medium and type, and the differing advice specifically for disaster risk visualisation that arises from user heterogeneity.

Design element	General design principles	Design practices recommended specifically for disaster risk visualisation	References
Colour	- Avoid rainbow colour schemes. - Monochrome colour schemes should be used for comparing numerical data. - Sequential colour schemes should be used for spatial data. - Use colour to provide emphasis.	- Sequential colour schemes should be used in maps for data with increasing values. - Diverging colour schemes should be used for data whose values are above or below a critical value. - Qualitative colour schemes should be used for nominal data (e.g. forest, is green). - Spectral colour schemes lead to the fastest and most accurate decisions so should be used whenever possible. - Diverging colour schemes lead to better, more efficient decisions, so should be used whenever possible. - Intuitive colour schemes lead to faster, more accurate decisions so should be used whenever possible. - Cultural meanings of colours can influence the way that users interpret those colours. For example, red has connotations of danger in many Western cultures, is a colour of joy in some Eastern ones, and a colour of life in New Zealand Māori culture.	**General principles:** [69–72] **Disaster Risk Visualisation:** [73–84]
Amount and type of information	- Information should be arranged in a perceptually advantageous order, where a user's attention is drawn to the most salient data first. - Visualisations should not communicate information that serves no purpose. - Exclude irrelevant data. - Contextualise data.	- Conflicting pieces of information confuse users, influence their decisions and increase their perception of risk, so should be avoided. - Too much information is confusing for users and is not useful for making accurate decisions, so it is important not to overwhelm users. - Visualisations should contain the information that users are looking for so that they feel in control of the decisions they make. - Information should framed in terms of potential impact and consequences to improve users' understanding of risk. - Information should be simplified and placed within the natural hazard context.	**General principles:** [49,70,85–87] **Disaster risk visualisation** [88–93]:
Shapes and markings	- Combine words, numbers and glyphs to convey uncertainty. - Change form of shapes, such as position and size, before changing colour to convey a message. - Use simple shapes, as complex shapes can carry an unintended meaning or message. - Choose shapes that intuitively embody the message and saliency.	- Larger shapes and more markings convey greater uncertainty which users interpret as greater risk. - Uncertainty should be conveyed implicitly through icons as it mitigates against misunderstandings around the size of the hazard and uncertainty. - Conveying uncertainty implicitly through icons can anchor users to their biases, resulting in misinterpretations. - Uncertainty should be conveyed through performance bars. - The way that uncertainty is visualised is more important than the visualisation itself for effectively communicating risk. - There are no clear and distinct effects of the ways in which symbols, texture or shapes affect users' interpretation of risk, because it depends on the user's profile.	**General principles:** [33,49,94] **Disaster Risk Visualisation:** [95–100]
Medium and type	- Novel and innovative visualisations tend to perform best because they pique interest. - Medium and form depends on the task that the visualisation is intended to help with.	- Visualisations and mediums to which users are accustomed are preferable. - Visualisations and mediums to which users are accustomed do not nec essarily result in better comprehension or decisions by the user.	**General principles:** [70,101,102] **Disaster Risk Visualisation:** [103–105]

- Support designers, scientists, communicators and knowledge brokers by suggesting a methodology and tools that can be used instead of subjectivity and personal beliefs, particularly in the evaluation phases.
- Support defining the role of the end-users, identifying when and how to interact throughout the entire design process.

- Support identifying the specific challenges that are relevant to the disaster risk and highlight how these impact interactions with end-users and influence potential design choices.
- Support integrating the needs and knowledge of end-users into disaster risk visualisations.

Although existing risk visualisation frameworks exist, they are not ideally suited for application to user-centred disaster risk visualisations. [109] recognized the lack of systematic approaches in managing and visualising risk, and put forward a risk visualisation framework, intended to be applied within any risk context. However, this framework is born out of understanding financial risk within business systems and aims to elaborate on known risks, identify other risks, and mitigate against their impact. It is a useful starting point for developing questions that need to be answered in order to visualise disaster risk but does not provide an approach to deal with user heterogeneity. The mental models approach for developing communications, put forward by Ref. [110], is useful for characterising heterogenous user groups. Their framework seeks to uncover a wide range of beliefs and understandings about the users of communications products, encourages participatory design, and incorporates recommendations for developing ethically responsible communications [111]. Whilst this framework highlights the importance of tailoring communication to users to avoid misunderstandings it does not focus on information or technology gaps, but rather on the specific information that experts believe users need; users themselves and their knowledge are not considered within this framework.

We propose a user-centred framework for disaster risk visualisation that engages with end-users throughout the entire development process (Fig. 4). The framework unifies the UCD process, with the questions asked in Eppler and Aeshimann [109] risk visualisation framework, and the process of characterising users in Bruine de Bruin and Bostrom [110]'s mental modes approach to communication.

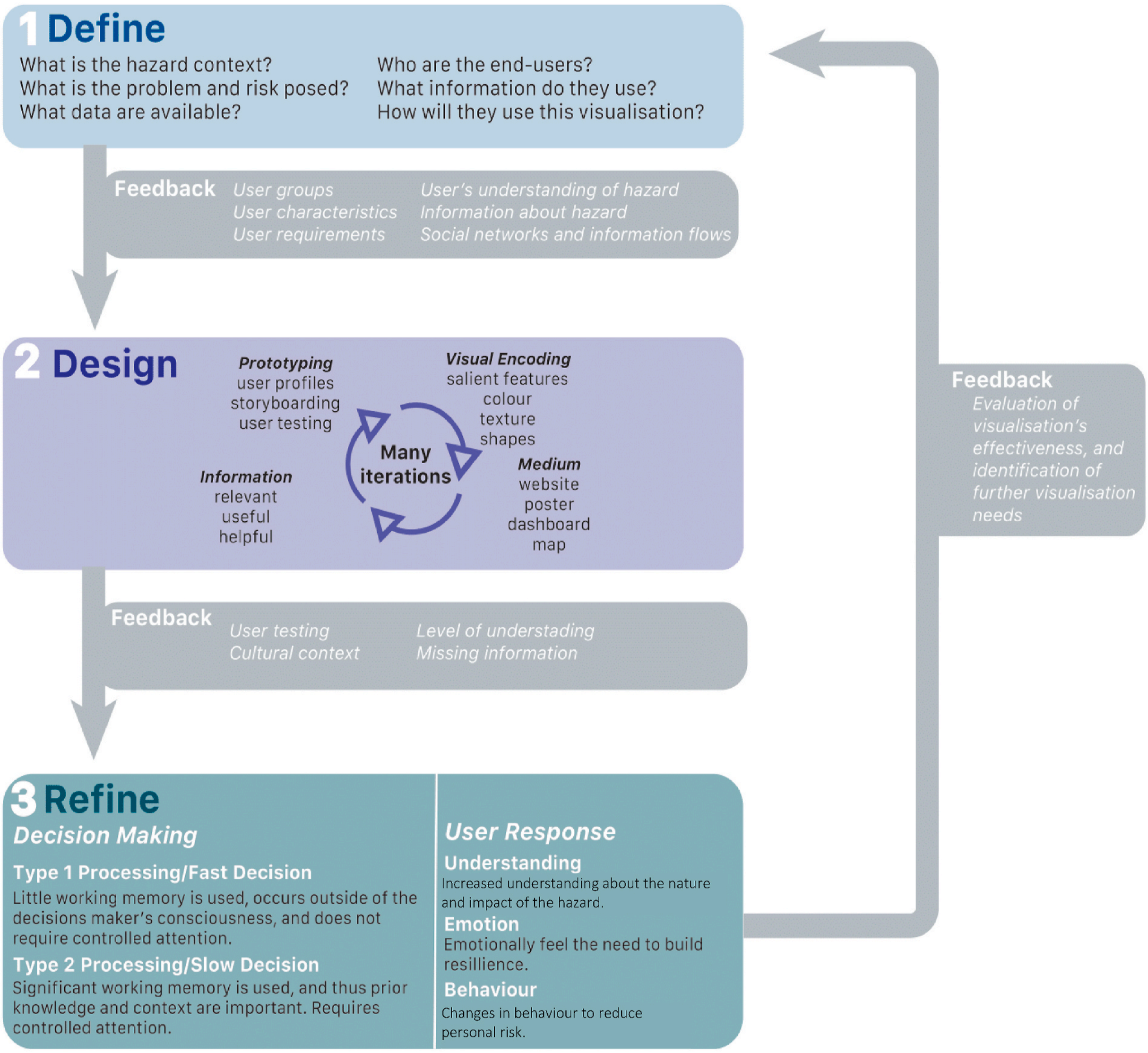

Fig. 4. User-centred design framework for disaster risk visualisation.

It also builds on other visualisation frameworks put forward within the fields of climate change [112] by recognizing the emotional impact of imagery on a user; decision support systems [55] by utilising methods developed within the field of design; environmental visualisations [49] by focusing on the value added from user-centred design; and cognitive science [42] by analysing the occurrence of Type 1 and Type 2 processing. These frameworks all commonly emphasise the importance of precisely articulating the aim of the visualisation; intentionally choosing the content and medium of the visualisation; and specifically defining a group of end-users for a visualisation who are to be included in an iterative design process.

We identify three phases in the development of static visualisations: Define, Design and Refine. We focus on static visualisations because the cognitive processes when interpreting and using interactive visualisations are highly complex, and still widely disputed [113–118]. Whilst a UCD process is generally recommended for developing interactive visualisations, the specific development process includes additional steps such interface development, partially functional alpha releases and interaction measurement [119,120]. Therefore, design frameworks for interactive disaster risk visualisations should focus exclusively on interactive visualisations, as has been explored elsewhere [120,121].

Each iterative phase of our framework is underpinned by a set of guiding questions that have been developed based on questions within the other frameworks outlined above (Table 2). The framework is focused on producing effective visualisations that are useful, useable and understandable to the end-users. The feedback gained from engaging with end-users at each phase informs the next phase, and thus the entire framework itself is iterative– results from the Refine phase inform the next set of challenges for the Define phase as the context of the disaster evolves, and different end-users are identified. Methods are suggested for each phase of the framework (Table A.1); the list is not exhaustive, and other, innovative, methods may be more appropriate for some UCD processes. This is particularly pertinent within DRM as timescales and opportunity to act could be very short due to the emergency nature of disasters [122].

4.1. Define

The Define phase focuses on defining the disaster context and the end-users who could benefit from a visualisation. Defining the visualisation need based on the characterisation of the natural hazard, the data available and the various vulnerabilities is key, [49]. DRM is context-specific as stakeholder needs, locally vulnerable populations and resources vary across contexts, as does their knowledge of the relevant natural phenomena, societal factors and the extent of the risks involved for each specific context [7,123]. The methods used to define the visualisation need and characterise the DRM context will depend upon the circumstances under which the visualisation is being designed, and the degree of prior characterisation. For example, the Define phase might involve carrying out

Table 2
Guiding questions that underpin the framework (Fig. 4).

Phase of Framework	Important Questions	Methods
Define	What is the natural hazard? Where is the natural hazard? Who is vulnerable? How do those vulnerable understand the hazard, and the risk it poses? What is the actual challenge and risk posed? What data, information and forecasting tools are available? Who would benefit from access to this? Who are the end users of the visualisation? What information about the natural hazard do end users have access to? What medium do end users utilise to access information? What are their trusted sources? How will users use this visualisation? How is uncertainty understood?	• Ethnographies • Contextual studies • Institutional mapping • Stakeholder mapping • Gap analysis • Discourse analysis • Interviews • Focus groups • Surveys • Mind mapping • Expert elicitation • Observations
Design	Is this design colour-blind friendly? How is uncertainty represented? Is this representation accurately understood by end users? Are the symbols and colours accurately understood by end users? Is the information in the visualisation accurately understood by end users? Has the most appropriate medium been used? Is the information useful, relevant and helpful for the end-users? Is more information necessary? Is the visualisation interesting, attractive and useful to the end-users? Is the visualisation clear in its messaging? How would end-users improve the visualisation? What information is missing?	• Prototyping • Personas • Expert review • Surveys • Focus groups • Interviews • Questionnaires • Storyboarding • Mix and match cards • Think aloud reading and tasks
Refine	In what context will the visualisation be used? How are end users intended to make decisions based on the visualisation? To what extent do end users understand the information represented in the visualisation? How do end users make decisions based on the visualisation? How effective are the decisions made based on the visualisation? Do the end users understand the uncertainty represented in the visualisation? How do the end users emotionally respond to the visualisation? What behavioural changes do end users make based on the visualisation? Is Type 1 (Fast) or Type 2 (Slow) cognitive processing occurring?	• Surveys • Focus groups • Interviews • Questionnaires • Observations • Scenarios • Serious games

institutional mapping and gap analysis for a given DRM context to assess where new data, information or forecasts might be useful; it could also involve an ethnography of a team within an organisation to design a dashboard that will inform their work on preparedness; or a contextual study of a community to develop an early warning system.

The types of knowledge available for each stakeholder, and information flows, also differ between contexts [124,125]. Stakeholder mapping could be utilised to understand which stakeholders and information have power within the given context, as this will influence end-users' framing and understanding of disaster risk [126]. Discourse analysis and mind mapping of the communication products that are already in use is useful for understanding this wider context, as well as the way in which potential end-users understand the challenge.

Once the challenge, DRM context, and visualisation need have been defined, the identified end-user group needs to be fully characterised. Socio-demographic profile, culture, numeracy, literacy, personal preferences, profession, prior hazard experience, and pre-existing knowledge of the hazard and vulnerabilities affect a user's risk perception, risk appetite, interpretation and understanding of a disaster risk visualisation. Designers need to understand fully how these characteristics vary between and among end-users, as they will inform the specific interpretation of design decisions such as colour, form and symbols [97,100].

Whilst fully defining the disaster and characterising end-users is highly important, designers must strike a balance and determine when sufficient information has been gathered to start the design process. This will again depend on the context in which the visualisation is developed, available resources, and time limits. Hence, designers and researchers are encouraged to work reflexively during data collection and processing. Depending on time, resource constraints and power dynamics, a full ethnography of a user group may be appropriate, to conceptualise the differences between individuals. Interviews, focus groups, observations and/or surveys could otherwise suffice, if used reflexively and appropriately [55].

4.2. Design

The Design phase is the most iterative phase of the framework. It involves carrying out many rounds of design, prototyping, and regularly seeking and incorporating feedback from end-users. The types of feedback elicited should consider the DRM context in which the visualisation will be used. End-users should be asked to act as though they are using the visualisation under the same real-world conditions as they will use the final visualisation; and designers should bear in mind this context with every design element decision When using a visualisation during the preparedness, mitigation planning or policy development phases of DRM, users are likely to be able to cross-reference with other information sources, and take time deliberating over decisions [127,128]. By contrast, during the response and early recovery stages of DRM, end-users are likely to be distressed and making quick decisions, potentially leading to different design decisions. Therefore it is the designers' decision to work reflexively, and determine when an appropriate number of iterations have been reached. The appropriate method will depend on the context in which feedback is elicited and the number of end-users available to give feedback. It is advised to prototype rapidly and test designs on users as regularly and as early as possible, to all for feedback and experimentation [55]. Surveys, questionnaires, focus groups and interviews are all useful to gain feedback on prototypes, as well as on the specific design elements. Mixing and matching cards with different design elements and their potential meanings could elicit feedback on risk interpretations [129]. An expert review of the prototypes could reveal hitherto hidden aspects [130]. Participatory approaches could include asking end-users to design their own, idealised visualisations based on the prototypes, or asking users to rank potential visualisations based on different criteria. These ideas could then be incorporated into the final product.

Designers should initially follow the general design principles laid out within the design field when making changes to their designs [70,72]. Designers must then continually test users' emotional and intellectual responses to these aesthetic decisions and make appropriate changes where necessary [42,131]. Colour schemes that are accessible to those with colour blindness [132], and appropriate to users, their contexts and their interpretations, should be used [133]. Tactile visualisations have shown promise for those with severe visual impairments [134]. Digital graphics should also always have an alternative text description, and underlying data should always be represented as a table so that screen-readers are able to communicate the information [135]. Those with cognitive impairments may struggle when using visualisations, and therefore it may be necessary to design significantly simplified versions of more complicated visualisations for this group of people [135]. The Web Content Accessibility W3C Graphics Module Guidelines provide a good overview of principles to ensure visualisations are accessible and inclusive, but these principles should be tested with end-users [136]. It is important for designers to keep up to date with potential changes and limitations regarding the accessibility of different design features and tools that are used to develop visualisations. For example, not all of the widgets built into ESRI's ArcGIS software are fully accessible [137].

Texture and colour convey different messages of uncertainty and are understood differently by users depending on their backgrounds and characteristics, so should be tested directly with end-users [131]. The wording that is used to express uncertainty and probabilities should also first follow general design principles, then be tested and adapted accordingly, as it can affect users' interpretation of risk [138]. This is particularly important if designing an impact-based forecast visualisation, as users will have specific values which will influence the salience of different impacts [139].

4.3. Refine

The Refine phase focuses on evaluating the final visualisation developed during the Design phase and should ideally be tested within the context defined earlier. The visualisation is considered "in use" by users during this phase. It is also possible to evaluate the visualisation in laboratory, workshop or online settings that simulate a real-world scenario similar to the context in which the visualisation is used.

The Refine phase should ideally allow the assimilation of evaluations and feedback from its application during disasters, but ethical issues should be considered. For example, recent disasters may cause distress or overwhelm users during the refine phase, or it might be inappropriate to ask emergency responders about any feelings of fear caused by a visualisation, compared to a community member looking at a public information visualisation [95].

A key element of disaster risk visualizations is that they may evoke emotional and behavioural responses. It is therefore crucial that this response is properly characterised during the evaluation phase. This can be done by asking quantitative questions about the information and data within the visualisation, and qualitatively assessing the reasoning behind decisions and their outcomes [81] It might also be appropriate to test whether Type 1 or Type 2 processing are being utilised by reducing the amount of time allowed to make decisions, as the emergency nature of disasters necessitates quick decisions. Interviews can also be used to reveal how much users are depending on prior knowledge to understand and use the visualisation to inform decisions. Testing for Type 1 or Type 2 decision making will reveal the degree of cognitive load imposed by the visualisation to elucidate whether there are information gaps that end-users complete using prior knowledge [42,81].

Both quantitative and qualitative evaluations can be carried out through interviews, focus groups, workshops and surveys [140]. A scenario, role-play, or serious game could also be used, in which the accuracy of the interpretation of uncertainty data, probabilistic information and the overall visualisation, and how these have informed the decision that is [81,98,141,142]. Ideally an evaluation would take place over a period of time, with ongoing monitoring of actions and behaviours. This long-term observation would highlight other visualisation needs, and feed into the Define phase of the framework.

5. Conclusions

We argue that developing disaster risk visualisations through a UCD process results in visualisations that are more effective than those developed without a UCD process. Having analysed existing graphical design principles and disaster risk visualisation studies, we concluded that in application, traditional approaches often fail to sufficiently account for user heterogeneity and its impact on risk perception. Different design elements have different effects on end-users and their interpretation of risk. Tailoring visualisations to users' needs, understandings, characteristics and contexts presents an opportunity to optimize the interpretation of disaster risk visualisations. As a UCD process is the best way to achieve this tailoring, we proposed a unifying user-centred framework for disaster risk visualisation.

Our framework requires empirical testing and validation, ideally both in field and under controlled test conditions. This testing is especially important for users in developing countries, as the impacts of natural hazards are often most acutely experienced in such contexts. With the proliferation of multidisciplinary research methods and partnerships, such research could be embraced as an opportunity for innovation and experimentation. The absence of combining methodological experimentation, field studies, and empirical evidence of user-driven evaluation of visualisations represents a barrier to more effective visualisation of scientific knowledge across many other fields beyond DRM [143,144].

In order to develop the best practices that inform disaster risk visualisation design, more research into the use and interpretation of existing natural hazard risk visualisations is necessary. Researchers should aim to understand what influences people across different socio-economic contexts, and produce more critically and theoretically informed studies of decision-making which can inform communications [145–147]. Historically, emotions were seen as contrary to rational decision making, but recent research has clearly shown that they are an important tool and must be accounted for within communications [148]. Understanding the current information gaps and user needs should inform a research agenda that assists in the development of effective user-centred risk visualisations. Evidence of how different design elements affect users' perceptions of risk and interpretation of information should inform future visualisation design.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table 1A
Review of disaster risk visualisations.

Study	Location	Nature of hazard/ program objectives	UCD approach?	Evaluation?	Vulnerability data?	Social data?	Experiment?
Argylle et al. (2017)	USA	Evaluate and improve the National Weather	Yes: focus groups, interviews and	Yes: through a quantitative task	No	No	Yes: in a laboratory

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Table 1A (*continued*)

Study	Location	Nature of hazard/ program objectives	UCD approach?	Evaluation?	Vulnerability data?	Social data?	Experiment?
		Service Hazard Services	testing with relevant users				
Ash et al. (2013)	USA	Evaluate the impact of hurricane risk visualisation on decision making	No	Yes: through a quantitative task	No	No	Yes: in a laboratory
Bolstrom et al. (2008)	Worldwide	Review of existing earthquake risk visualisation and warning systems	No, but recommended for future development	No	No	No	No
Boon et al. (2018) [108]	USA	Influence of graphical displays on decision making in hurricane risk	No	Yes: through a quantitative task	No	No	Yes: in a laboratory with students
Budimir et al. (2020)	Nepal	Analysis of visualisation in official government flood EWS	No, but recommended for future development	No	No	Gender, otherwise qualitative	Yes: interviews, questionnaire, stakeholder workshop
Cao et al. (2016)	Australia	Evaluate the impact of wildfire risk visualisation on decision making	Yes, but limited	Yes: through a quantitative task	No	No	Yes: online
Cao et al. [90]	Australia	Evaluate the impact of wildfire risk visualisation on decision making	No	Yes: through a quantitative task	No	No	Yes: online
Cheong et al. [81]	Australia	Evaluate the impact of wildfire risk visualisation on decision making	No, but recommended for future development	Yes: through a quantitative task	No	No	Yes: in a laboratory
Conger [88]	North America	Review of existing avalanche risk warning	No	No	No	No	No
Donovan et al. (2012)	Indonesia	Develop a cultural vulnerability and risk map for volcanic hazard	No	No	Yes: through ethnographies	Yes: through ethnographies	No
Eckerstorfer (2008)	Europe	Review of existing avalanche risk warning and recommendations	No, but recommended for future development	No	No	No	No
Gaspar-Escribano and Itturioz [89]	Spain	Review of existing earthquake risk visualisation and warning systems and recommendations	No, but recommended for future development	No	No	No	No
Graziella et al. (2015)	Norway	Development of a landslide early warning system	No, but recommended for future development	No	No	Yes	No
Haynes et al. [78]	Montserrat	Evaluate the efficacy of volcanic hazard maps	No, but recommended for future development	Yes: through a quantitative task	No	No	Yes: in a laboratory with a demographically representative sample
Heil et al. (2014)	Switzerland	Develop a national common information platform for natural hazards	Yes: focus groups, interviews and testing with relevant users	Yes: through a survey	No	No	No: but recommended in the future to inform next developments
Klockow-McCain et al. (2019)	USA	Evaluate the impact of hurricane risk visualisation on decision making	No, but recommended for future development	Yes: through a quantitative task	No	No	Yes: online
Li et al. [91]	China	Development of a flood visualisation tool for a cultural heritage site	Yes: limited qualitative user feedback on the tool	No	Yes: relic vulnerability	N/A	Yes: focus groups, surveys
Lim et al. [96]	Sweden	Effect of different flood visualisations	No	Yes: effect of visualisation	No	No	Yes: in a laboratory with students

(*continued on next page*)

Table 1A (*continued*)

Study	Location	Nature of hazard/ program objectives	UCD approach?	Evaluation?	Vulnerability data?	Social data?	Experiment?
		and risk maps on decisions		on quantitative decision			
Lindsay and Robertson [34]	Lesser Antilles	Development of volcanic hazard maps	No, but recommended for future development	No	No	No	No
Liu et al. [98]	Nepal	Vulnerability capacity assessment mapping	Yes	No	Yes	Yes	Yes: focus groups, interviews, surveys, discussions
Liu et al. [98]	USA	Influence of graphical displays on decision making in hurricane risk	No, but recommended for future development	Yes: through a quantitative task	No	No	Yes: in a laboratory with students
Miran et al. [82]	USA	Evaluate the impact of hurricane risk visualisation on decision making	No	Yes: through a quantitative task	No	No	Yes: in a laboratory
Miran et al. (2019)	USA	Evaluate the impact of hurricane risk visualisation on decision making	No, but recommended for future development	Yes: through a quantitative task	No	No	Yes: in a laboratory
Mulder et al. [92]	UK	Evaluation of different representations of volcanic ash extent forecasts	No, but recommended for future development	Yes: through a quantitative task	No	No	Yes: in person in a workshop
Otkin et al. [105]	USA	Facilitating the use of a drought early warning tool	Yes: limited qualitative user feedback on tool	No	No	No	Yes: two stakeholder focus groups
Padilla et al. [100]	USA	Influence of graphical displays on decision making in hurricane risk	No	Yes: through a quantitative task	No	No	Yes: in a laboratory with students
Rollason et al. [93]	UK	Analysis of existing, and development of new flood risk communications	Yes: qualitative user feedback on existing communications, and development of new communications	No	No	No	Yes: focus groups with affected community groups
Rochford et al. (2018)	USA	Systematic examination of a global seismic risk platform	No: human centred design	Yes: through interviews, surveys and meet ups	No	No	Yes: a simulation in a laboratory
Ruginski et al. [97]	USA	Influence of graphical displays on decision making in hurricane risk	No	Yes: through a quantitative task	No	No	Yes: in a laboratory with students
Schuman et al., 2018 [99]	USA	Evaluate the impact of socio-demographic and cultural user background on decision making for tornado risk	No, but recommended for future development	Yes: through a quantitative task	No	No	Yes: in a laboratory
Seipel and Lim [83]	Sweden	Effect of different flood visualisations and risk maps on decisions	No	Yes: effect of visualisation on quantitative decision	No	No	Yes: in a laboratory with students
Thompson et al. [80]	New Zealand	Evaluation of volcanic risk maps and visualisations	No, but recommended for future development	Yes: through a quantitative task	No	No	Yes: online
Thompson et al. [149]	Worldwide	Review of volcanic risk visualisations	No, but recommended for future development	No	No	No	No

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