Final-Reporting-2

Building a Better Hazard Map: collaborative, interactive, and optimised natural hazard map design (EQC 15/U709)

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Volcanic hazard map, map design, decision-making, eye-gaze tracking, risk perception, visual attention, cognition

Summary

Volcanic hazard maps are used to share knowledge about the location of potentially dangerous volcanic processes with a wide range of audiences during a volcanic crisis. These maps comprise simplified representations of complex, overlapping, and uncertain geospatial phenomena that manifest on different spatial and temporal scales and with different metrics and intensities. Displaying this specialised information so that audiences with a range of volcanic and cartographic experience are empowered make informed decisions presents a number of challenges. While there are many possible approaches to representing hazard information on a map, there is little empirical evidence for how these approaches can influence audiences' map-reading behaviour, inferences made about the information, and decisions made with the map in crisis situations.

Constructing meaning from a map is a complex information-processing exercise that requires cognitive processing of the visual appearance, patterns, and relationships of representative shapes and symbols on the map. Eye-movements and visual attention to elements of a display have been shown to reflect cognition and can give insight into how people draw inferences from graphics such as charts and maps. In this study, we use questionnaires and eye-gaze tracking to explore how 81 adults in the Taranaki region of New Zealand read and make decisions with volcanic hazard maps for a hypothetical eruption event for Mount Taranaki in order to better understand what people pay attention to on volcanic hazard maps in different decision-making contexts and how this is shaped by map design.

We find that top-down cognitive factors such as risk perception, experience, and cognitive loading shape visual attention to hazard map content and decisions made with the map under pressure and uncertainty. Additionally, we find that bottom-up factors in the way that hazard data is combined and displayed on the map can affect these cognitive factors. The findings suggest a complex interplay between top-down and bottom-up drivers of visual attention to volcanic hazard maps and empirically illustrate how cognitive processing of volcanic hazard maps may influence the behaviour of at-risk populations during a natural hazard crisis. Better characterising the role of these factors how they interplay can help us understand and mitigate communication challenges in times of crisis and uncertainty.

Introduction

Volcanic hazard map design is challenging because it requires clear representation of complex, uncertain, and overlapping spatial information of different scales and resolutions. Globally, many different approaches to volcanic hazard map design have been used to tackle these challenges for communicating hazard with audiences worldwide (Calder et al. 2015). There is evidence from past volcanic events and empirical studies that such differences in visual design of hazard maps can play an important role in how audiences interpret information about the hazard (Haynes et al. 2007, Thompson et al. 2015, 2017). The initial interpretations and impressions that audiences take away from hazard maps can be very important in decision-making contexts, as reliance on heuristics and biases are enhanced in high-stakes high-pressure situations such as volcanic unrest (Finucane et al. 2000, Tversky and Kahneman 1974).

Our study aimed to better understand how people read and make inferences from information represented on volcanic hazard maps. However, map-reading and decision-making are complex knowledge construction exercises that requires cognitive processing of visual-spatial information (MacEachren 1995, Hegarty 2011). Empirically, this limits the amount of insight that can be gained from having audiences self-report on how they used and understood the map, as much of this information processing is happening rapidly at a cognitive level. Eye-gaze tracking enables a way to overcome this limitation by giving high-resolution insight into how people respond to map reading tasks - beyond what performance, response time, and self-reports can tell us (Eckstein et al. 2017). Where a person focuses their visual attention can give insight into what information they are cognitively processing. This eye-mind assumption (Just and Carpenter 1976) can be used to infer information about how people use hazard map information to make decisions. Shifts in perceptual attention along a scan path give insight into a participant's visual processing of a scene (Yarbus 1967, Kowler et al. 1995), which can help us better understand how people read maps and make decisions with them (Kiefer et al. 2017).

In our study we used a combination of self-reporting (questionnaires) and eye-gaze tracking to explore how non-specialist audiences near a stratovolcano read, infer, and make decisions with volcanic hazard maps. We carried out our study in the region surrounding Mt Taranaki, an active volcano in the North Island of New Zealand. Mt Taranaki has experienced a large explosive Plinian eruption every 300 years for the last 5,000 years (Torres-Orozco et al. 2018). There is no historical record of the most recent eruption. Participant eye-movements were recorded as they read maps and responded to a series of questions and challenges based on the map content. We were then able to explore where people focus and shift their visual attention when reading and solving tasks with fictional volcanic crisis maps for Mt Taranaki, address potential applications of eye-gaze tracking methods for understanding volcanic hazard and risk communication problems, and discuss implications for volcanic hazard map design.

Objectives

Our project as proposed had the following 8 objectives:

1. Compile a literature review of different crisis hazard map styles published and/or in-practice worldwide, and compare and contrast cartographic representations and classifications.
2. Engage with multiple stakeholders in the Auckland region to explore and identify the collective needs, goals, and priorities for crisis hazard maps (e.g., what hazard(s) should be focused on? What audiences are key to reach? What are the key messages and information that needs to get across?).
3. Use feedback from the engagement process with Auckland stakeholders and expert scientists to develop a crisis hazard map(s) based on a crisis scenario(s) and continuously seek feedback from stakeholders throughout this process.

4. Use eye gaze tracking to empirically test the hazard map usability and satisfaction with different audiences (e.g., emergency managers, first responders, local communities, scientists, businesses) by analysing performance and focus while solving map-based tasks. Conduct supporting survey with eye-gaze tracking experiment to develop social and behavioural insight into map reading results.
5. Use results of eye-gaze tracking and survey to identify both salient and problematic areas on the hazard map(s). Use this to create a revised crisis hazard map.
6. Test revised crisis hazard map through same methodology to identify the influence of these revisions.
7. Publish at minimum three papers in international scientific journals on A) crisis hazard map literature review, B) eye-gaze tracking experiments and insights into map reading behaviour, and C) a collaborative, integrative, interactive approach to hazard mapping in times outside of crisis. Present research and findings at leading national and international conferences.
8. Ingrate findings into emergency management practice in Auckland and throughout New Zealand. Establish recommendations for crisis hazard map design and development relevant internationally.

These objectives reflected the steps of the project. Objectives 1-6 were completed by June 2019. Due to the postdoctoral fellow going on maternity leave before the end of the project there are some minor delays in objectives 7 and 8. However, regarding objective 7, significant dissemination of findings has already been carried out through stakeholder, conference and workshop presentations. Furthermore a review manuscript has been published (Thompson et. al. 2017) and two open-access manuscripts are in advanced draft form. Objective 8 (recommendations for crisis hazard map development) will be incorporated into the open-access manuscripts mentioned above. At an early stage of the project we realised that it would be methodologically more appropriate to combine objectives 4, 5 and 6 through careful design of the questionnaires and eye-gaze tracking experiments. Thus, instead of an iterative process of design then testing then re-design then re-testing, we carefully modified our approach to include *multiple versions of the same map* to test different design approaches during a single suite of experiments.

Also important to note is that objective 2 was expanded to include stakeholders in Taranaki, to maximise an exciting opportunity during this project to complement an existing Natural Hazard Research Platform-funded project in the region. This collaboration added value to both projects, and will ultimately mean that co-created and tested crisis hazard maps for two regions, rather than one, have been explored in this study. The Taranaki component of the study is complete and manuscripts will be submitted after Mary Anne returns from maternity leave at the end of the year. The Auckland study is prepared and ready for data collection. Although the Auckland component will be completed after the close off of the postdoctoral fellowship, support from EQC will of course be fully acknowledged.

Methods

Our target sample included residents and tourists in the Taranaki region of New Zealand. Convenience sampling was carried out in public libraries, museums, and information sites around the region. Three sampling sites were used, one in each district of the Taranaki region – New Plymouth, Stratford, and South Taranaki (Fig. 1). Participants who volunteered to participate were then asked to complete a 15-question survey by hand, and a 15-question exercise on the computer.

The questions on the survey asked about demographic information, experience and familiarity with natural and volcanic hazards, and perceptions about the likelihood and impacts of a future eruption from Mt Taranaki. The self-administered computer exercise guided participants through a presentation in which they viewed hazard maps and answered multiple-choice questions about them.

***Figure 1**. Sampling locations for the study. Sites were selected in public spaces (e.g., libraries, museum) in each of the Taranaki region's three districts: New Plymouth, Stratford, and South Taranaki.*

The experimental exercise computer setup is shown in Fig 2. Locations were chosen based on stable lighting conditions and minimal environmental disruptions. Participants were given a keyboard, mouse, and 23" LCD-screen monitor, with a Tobii X2-30C eye-gaze tracker mounted at the base of the monitor screen. The researcher sat opposite the participant with a laptop to calibrate and observe the exercise recording using Tobii Studio. A 5-point eye-gaze calibration was carried out for each participant.

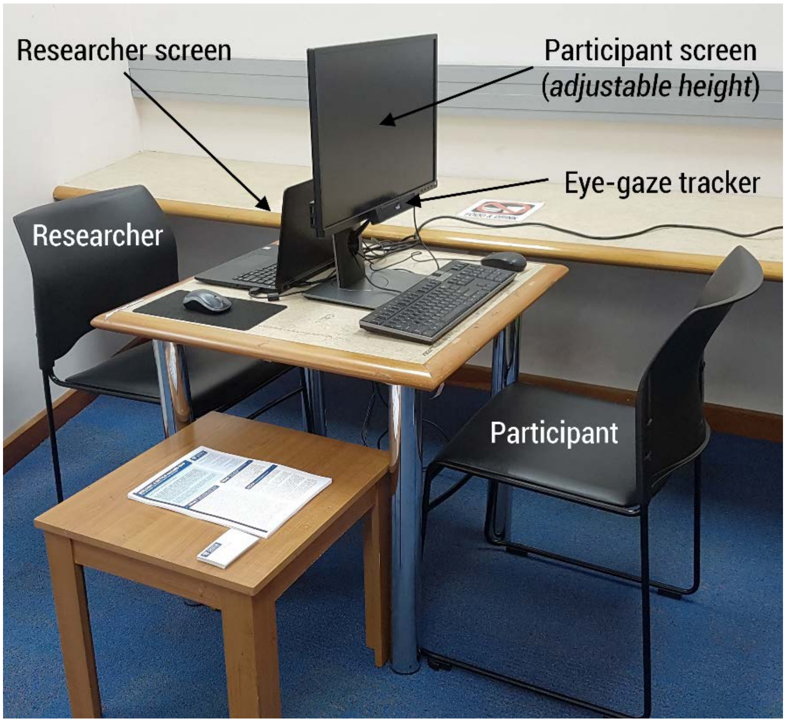

***Figure 2**. Experimental setup. Researcher sits on left side of image at the laptop, and participant sits at right side of image viewing large screen with eye-gaze tracker. Stations were in quiet locations with stable lighting.*

A pilot study was carried out with 18 participants to optimise the experimental set-up and clarify any unclear questions, and a total of 81 participants were recruited for the main study (Table 1). The majority of participants were full or part-time residents of the Taranaki region between the ages of 25 and 64, 41%

were male, and 59% were female (Table 2). Less than one third of participants had personally experienced volcanic activity, such as an eruption or ashfall event, but half of participants reported having been negatively impacted by a natural hazard event in the past (Table 3).

Table 1. *Data collection and sampling*

Date	Days	Location	Site	No. Participants
Pilot				
30 – 31 May	2	Hawera	Library Plus	18
Main Study				
14 – 16 Jun, 1 Jul	3	New Plymouth	Puke Ariki museum and iSite	45
30 Jun, 2 Jul	2	Hawera	Hawera Library Plus	16
12 – 14 Jul	2	Stratford	Stratford Library	20
			Total main study	**81***

** 99 participated in pilot and main study together*

Table 2. *Participant demographics*

Demographic Variable	% Participants	2013 Census*†
Gender		
Male	41	49
Female	59	51
Age		
18-24	16	7
25-44	44	33
45-64	29	37
65+	11	22
Relationship to Taranaki region		
Visitor from overseas	8.6	
Visitor from NZ	7.4	
Full or part-time resident	79	
Prefer not to say	5.0	

**Source: Statistics NZ*

† 2013 Census age percentages based on population over the age of 18

Table 3. *Participant experience with natural and volcanic hazards*

Previous experience	% Participants
Personally experienced volcanic activity	
Yes	23
No	77
Negatively impacted by a natural hazard event	
Yes	50
No	45
Do not know	5.0

Each participant answered the same survey and exercise questions. However, each participant was randomly assigned to one of four exercise groups – 1, 2, 3, or 4. Each group saw a set of five different hazard maps, A - E (Table 4, Fig. 3). Between each group, participants saw a different volcanic hazard mapping style (Table 5, Figs. 4, 5).

Table 4. *Five maps seen by each participant, see Fig. 3*

Map	Description	Markers	No. Questions
A	**Early unrest hazard map** Long-term hazard map with unknown summit vent location area circled	**4 starred locations:** **(1)** high, **(2)** medium, **(3)** low, and **(4)** no hazard areas	5
B	**Early activity hazard map** Hazard areas based on forecasted and modelled VEI 3 activity *Air fall hazard areas* = ballistic hazard zone within 10 km of vent, small ash plume with moderate westerly winds *Flow hazard areas* = modelled pyroclastic flow hazard areas, lahar hazard in river valley where vent clearing debris has created an upstream dam	**6 starred locations:** **(1)** high lahar hazard **(2)** outer/lower ashfall hazard, **(3)** high ballistic hazard + pyroclastic flow hazard **(4)** medium ballistic hazard **(5)** lower ballistic hazard **(6)** no hazard areas	7
C	**Wind change hazard map** Map B with ashfall hazard area changed for forecasted strong south-westerly wind	**2 marked locations:** **1 star** located near the vent **1 square** located downwind from the vent inside the inner isoline	2
D	**Route decision hazard map** Map B with three different possible routes to the airport marked	**3 marked routes**: **(A)** Shortest route through high hazard lahar zone **(B)** Medium length route through a low ashfall hazard zone **(C)** Longest route, complete hazard avoidance	2
E	**Later activity lahar hazard maps** Lahar hazard maps for segment south of the volcano at the end of the explosive stages of the eruption, based on forecasted rainfall and eruption sedimentation in the river catchment	**2 marked locations:** **(A)** upper east catchment location with *high probability* of lahar occurrence, *faster* arrival time, and *greater depth* forecasted, and, **(B)** lower west catchment location with *high probability* of lahar occurrence, *slower* arrival time, and *shallower* depth forecasted.	2

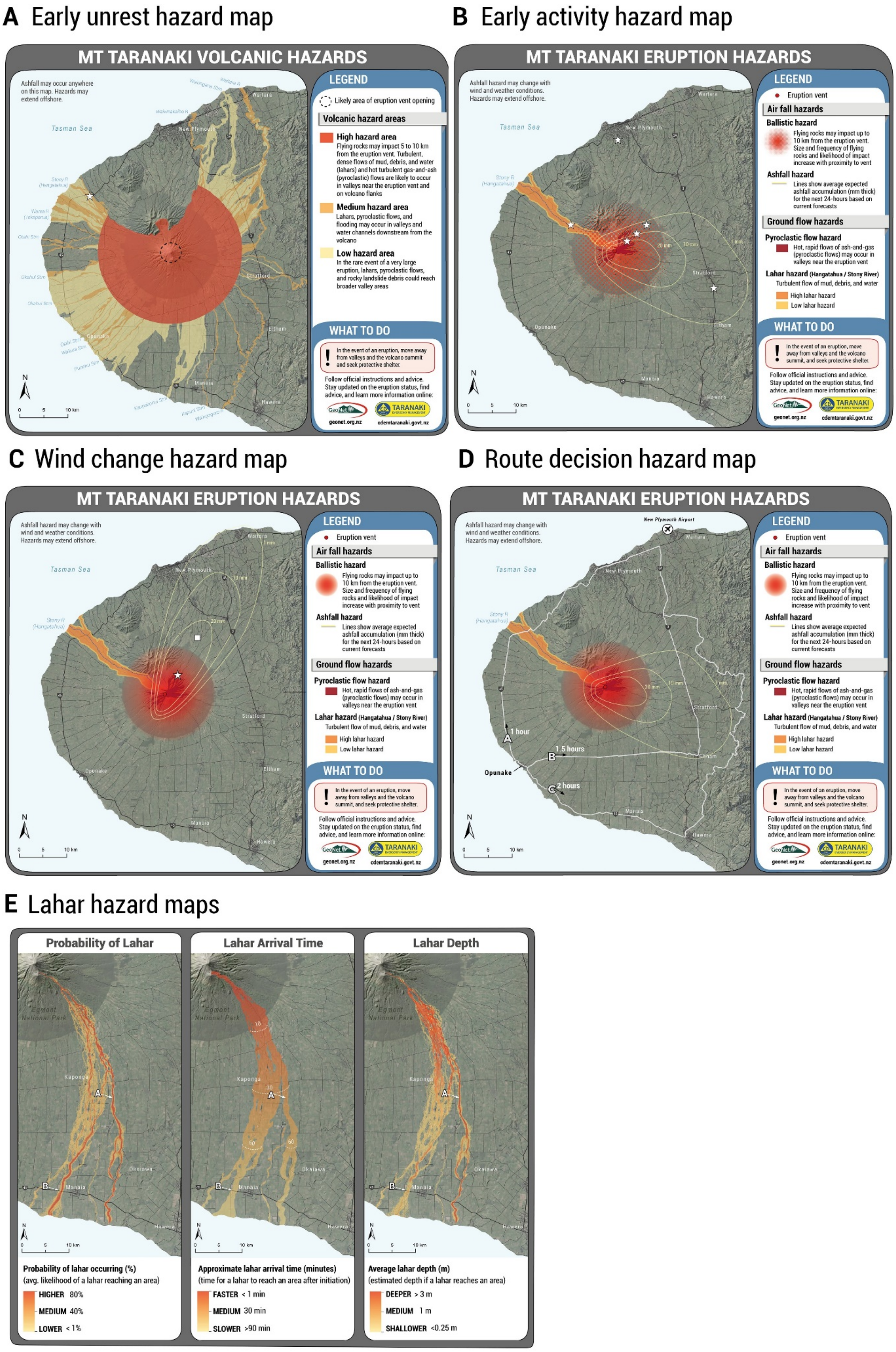

Figure 3. *Example of five maps types viewed by group 1.*

Table 5. *Variations in maps between exercise groups*

Group	Map Style		No. Participants
	Map A (Early unrest) – Fig. 4	*Map B (Eruption commenced) – Fig. 5*	*Main study*
1	**No** river lines **No** offshore hazard	**Hazard phenomena zones** *Gradational transparency ballistic*	20
2	River lines **No** offshore hazard	**Hazard phenomena zones** *Gradational dots ballistic*	20
3	**No** River lines Offshore hazard	**Hazard phenomena zones** *Probability of 1 mm ashfall**	20
4	River lines Offshore hazard	**Integrated hazard zones**	21

** Other discrete hazard maps showed average forecasted thickness of ashfall*

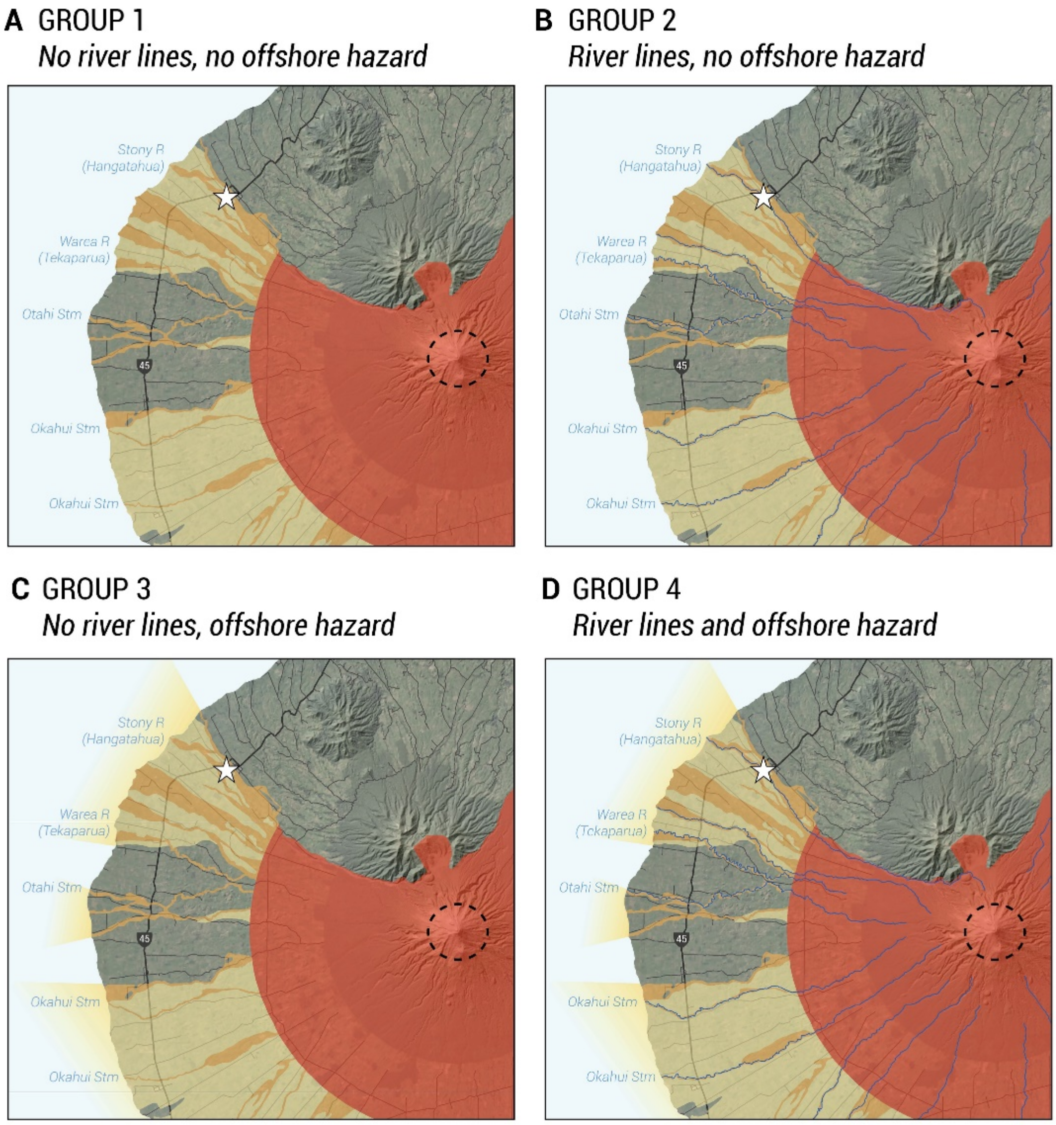

Figure 4. *Variables in Map A presentation*

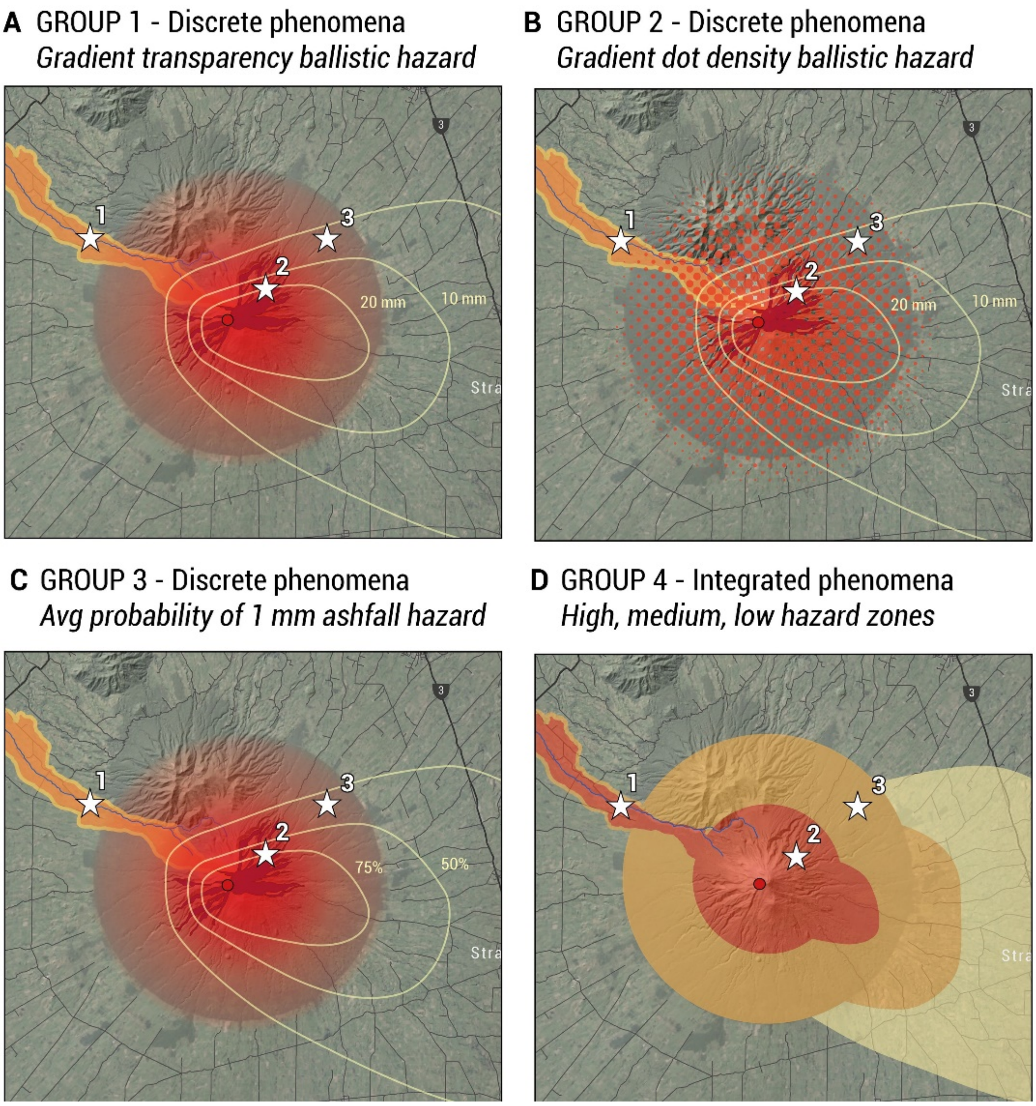

Figure 5. *Variables in Map B presentation, with location of stars (numbers not shown on map but displayed here for reference purposes)*

Conclusions and key findings

Interpretation of scientific graphics, such as hazard maps, is a rapid cognitive process that serves as a minor step in the wider context of overall risk management strategies. However, we provide evidence that inference- and decision-making with hazard maps is complex and influenced by multiple factors, and these nuances can have important effects on life safety decision-making during natural hazard events, such as evacuation.

We find that top-down cognitive factors such as risk perception, experience, and cognitive loading shape visual attention to hazard map content and decisions made with the map under pressure and uncertainty. Additionally, we find that bottom-up factors in the way that hazard data is combined and displayed on the map can affect these cognitive factors. The findings suggest a complex interplay between top-down and bottom-up drivers of visual attention to volcanic hazard maps and empirically illustrate how cognitive processing of volcanic hazard maps may influence the behaviour of at-risk populations during a natural hazard crisis. Better characterising the role of these factors how they interplay can help us understand and mitigate communication challenges in times of crisis and uncertainty.

There are numerous findings which will be explored in detail in the forthcoming publications; some examples of key findings are summarised here:

1. Participants presented a large variation in qualitative and quantitative estimates of the likelihood of eruption. That is, people understand “likely” to mean different things in the context of volcanic eruption.
2. Areas “safe from or not exposed to hazards” was top-most requested type of map information, followed by areas that are “most likely” to experience hazards (Fig. 6).

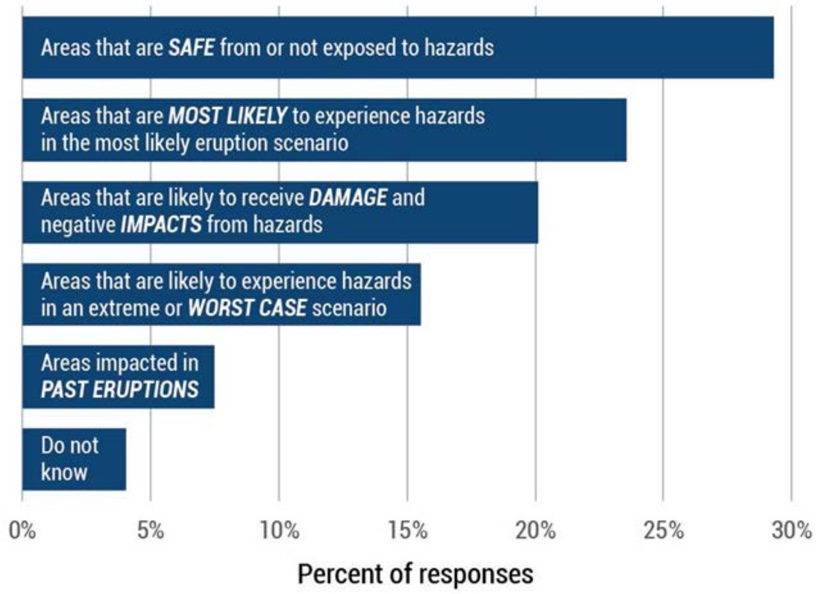

Figure 6. *Responses to the question: “Imagine that Mt Taranaki was showing signs of unrest and could potentially erupt within the next two weeks. If you could only choose to receive a map with 2 of the 5 types of information listed below, which 2 would you choose to receive to help you prepare and plan to respond to this threat?”*

3. Risk perception and experience affect how people engage with map information. For example, people with stronger risk beliefs (e.g., those who responded that an eruption would have an extremely severe impact on their livelihood) spent less time analysing hazard map content, and people who had previously experienced volcanic events paid more focused attention to the map when under pressure.
4. People demonstrate different map-reading behaviours in different reading contexts. That is, visual attention was different between bottom-up (no task) and top-down (task-based) map reading contexts. For example, during bottom-up visual search (saliency and experience driven), participants spent more time viewing the map and legend. During top-down (task driven) visual search, participants spent more time focusing on the “What to do” section (Fig. 7).
5. The way that the hazard was visualised (as discrete hazard footprints or integrated high, medium, low hazard zones) led to differences in visual attention and inferences about hazard information. That is, those who viewed the integrated zone map style demonstrated significantly different map reading behaviour and perceived different levels of threat than those who viewed the discrete hazard maps (Fig. 8).

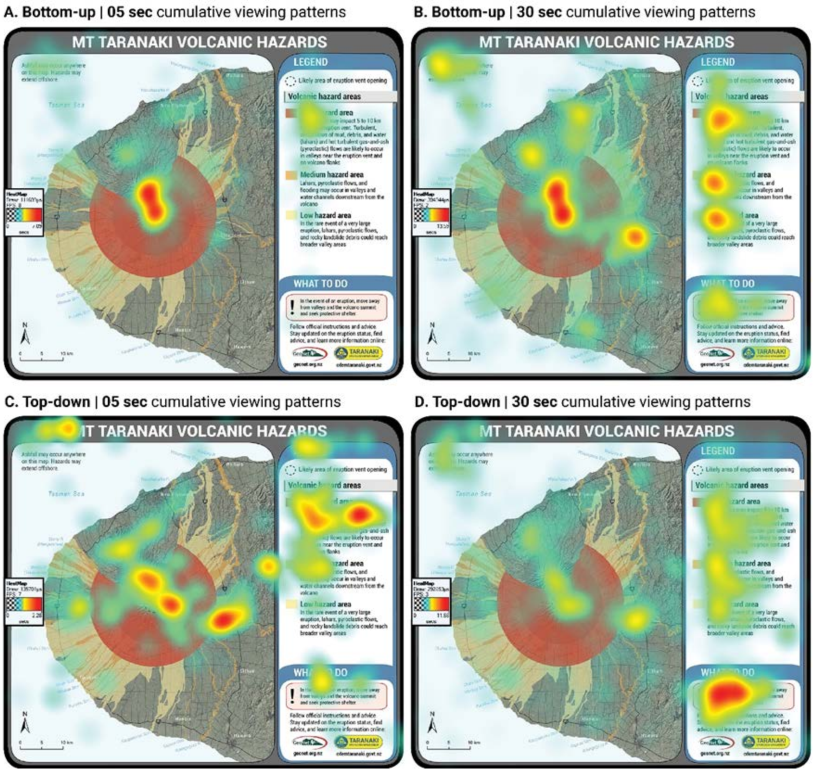

Figure 7. *Eye-gaze tracking heat maps showing cumulative viewing patterns for top-town vs. bottom-up tasks. The warmer colours reflect more time spent.*

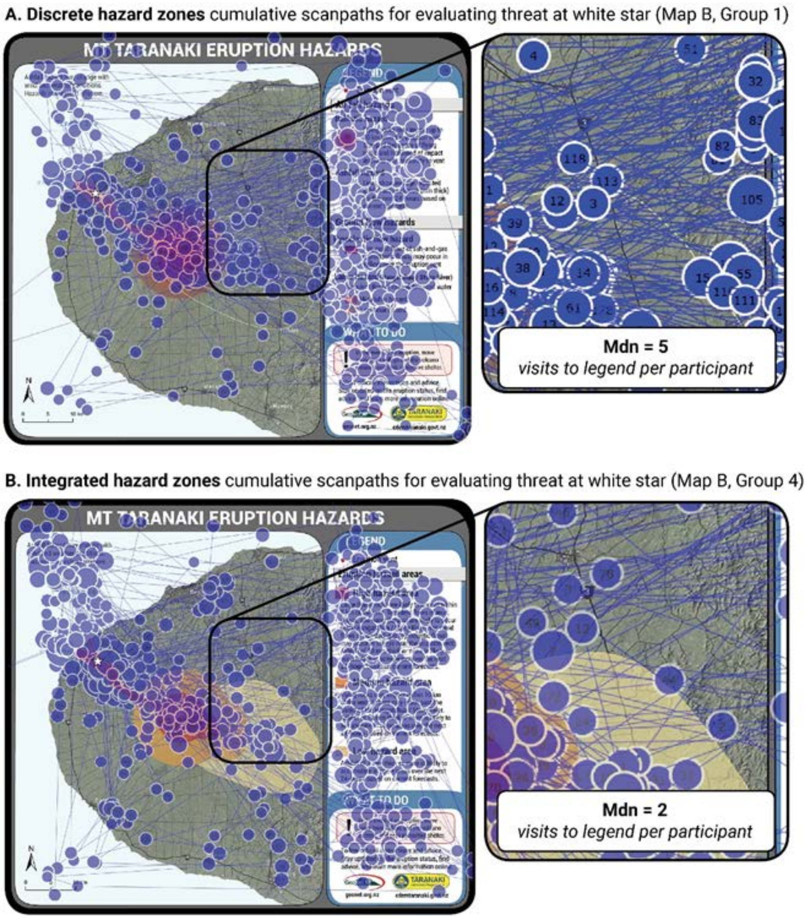

Figure 8. *Eye-gaze tracking cumulative scan paths for maps with A) discrete hazards depicted and B) Integrated hazard zones. Note that those who viewed the discrete hazards map style made more visits to the legend.*

Impact

The results of this work will have implications for the development of both crisis and long-term hazard maps in New Zealand and elsewhere. The key findings will feed directly into an operational Volcanic Hazard Mapping Framework currently under development with researchers (including Thomson, Lindsay and Leonard) and stakeholders in New Zealand as well as an international guidance book being developed by the International Association of Volcanology and Chemistry of the Earth's Interior (IAVECEI) on best practice volcanic hazard mapping.

Recommendations and Future work

We do not yet have a clear suite of recommendations as the results are still being interpreted, however these will be consolidated and communicated in appropriate ways to researchers and stakeholders alike. In terms of future work we have an Auckland study ready to go, and look forward to comparing the results of the Taranaki study with a similar study in a different volcanic and demographic context. We are also involved in the development of an operational Volcanic Hazard Mapping Framework and are interested in exploring the extent to which operational maps can be empirically tested prior to publication. Finally, this study has thrown up many new research questions in the exciting intersecting area of cognition, cartography and decision making that should be explored in future studies.

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Outputs and Dissemination

Stakeholder Presentations by Mary Anne Thompson

Useful crisis hazard maps. Presentation to New Zealand Volcano Science Advisory Panel (NZVSAP), 8 August 2016, Wellington, New Zealand

Visualising Hazard. Invited (and funded) presentation and interactive eye-gaze tracking demonstration at Workshop on Volcanic Hazard Assessments, 1 – 7 Sep. 2016, Garut, Java, Indonesia. USGS/USAID Volcano Disaster Assistance Program, CVGHM Indonesia, SATREPS Japan & IAVCEI Commission on Volcanic Hazards and Risk (CVHR)

Visual communication of volcanic risk: understanding map reading and decision-making. Presentation to Taranaki Civil Defence and Emergency Management , Rural Advisory Group, and Lifelines Advisory Group, 18 July 2017, New Plymouth, New Zealand

Visualising Volcanic hazard and risk: visual communication, map-reading, and decision-making. Presentation to M9 Research and Stakeholder Group, University of Washington, 8 August 2017, Seattle, Washington, USA

Visual attention to volcanic hazard maps. Presentation to Taranaki Civil Defence and Emergency Management, 9 Nov. 2018, New Plymouth, New Zealand

Insight into how people read and make decisions with volcanic hazard maps. Presentation to DEVORA Forum, 26 October 2018, Auckland, New Zealand

Conference Presentations

Thompson MA, Lindsay JM, Leonard GS, Calder E (2016) Do you see what I see? Exploring diverse perspectives in volcanic hazard map development and design, Cities on Volcanoes 9, Puerto Varas, Chile, Nov 2016

Thompson MA, Lindsay JM, Leonard G, Bostrom A, Corballis P, Lutteroth C, Calder E (2018) Visual attention to volcanic crisis maps during evaluation and decision-making tasks: an eye-gaze tracking experiment. Cities on Volcanoes 10, Naples, Italy 2 – 7 Sep. 2018

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Lindsay JM. Are we all on the same page? Communicating volcanic hazard and risk through maps. XV Chilean Geological Congress (CHGC), University of Concepcion Chile, November 2018. Invited plenary.

Peer-reviewed publications with acknowledgement of EQC support

Thompson MA, Lindsay JM, Leonard GS (2017) More than meets the eye: Volcanic hazard map design and visual communication. In: Fearnley C, Bird D, Haynes K, Jolly G, McGuire B (eds.) Volcano Crisis Communication: Observing the Volcano World. IAVCEI Advances in Volcanology, 20 p.
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Thompson MA, Lindsay JM, Leonard GS, Bostrom A, Lutteroth C, Corballis P, Calder E (in preparation for Nature Communications): Visual attention to volcanic hazard maps show how cognitive factors can influence crisis decision-making

Thompson MA, Lindsay JM, Leonard GS, Bostrom A, Lutteroth C, Corballis P, Calder E, Procter J, Wilson TM (in preparation for Journal of Applied Volcanology): Effects of volcanic hazard map design on hazard and risk perception and decision-making

List of key end users

GeoNet and GNS Science
Ministry of Civil Defence and Emergency Management
Department of Conservation
Auckland Emergency Management
DEVORA Research Programme
Taranaki Emergency Management
Taranaki Volcano Advisory Group
New Zealand Volcano Science Advisory Panel