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Communicating natural hazards science advice: Understanding scientists', decision-makers', and the public's perceptions of the scientific process

Emma E. H. Doyle^{a,*}, Jessica Thompson^a, Stephen R. Hill^b, Matt Williams^c,
Douglas Paton^{d,1}, Sara E. Harrison^e, Ann Bostrom^f, Julia S. Becker^a

^a Joint Centre for Disaster Research, Massey University, PO Box 756, Wellington, 6140, New Zealand

^b School of Psychology, Massey University, Private Bag 11-222, Palmerston North, 4442, New Zealand

^c School of Psychology, Massey University, Private Bag 102-904, North Shore, Auckland, 0745, New Zealand

^d College of Health and Human Sciences, Charles Darwin University, Darwin, Australia

^e Earth Sciences New Zealand, Avalon, Lower Hutt, New Zealand

^f Evans School, University of Washington, PO Box 353055, Seattle, WA, USA

A B S T R A C T

How individuals perceive scientific processes impacts their interpretation of, trust in, and use of, science advice particularly when managing uncertain natural hazard risk. We explored a) how diverse stakeholders understand how science of natural hazards is produced, and b) how this relates to their ontological, epistemological, and philosophical views of science. Using inductive analysis of semi-structured interviews with 31 participants involved in the management of natural hazards in Aotearoa New Zealand (including non-scientists), we produced three leading themes describing their views: 1) 'Science is a way of seeing the world'; 2) 'Science has limitations'; and 3) 'Knowledge evolves'.

Across Scientist, non-Scientist, and Lay public groups, there was broad agreement on the fundamental steps of the scientific process, aligning mostly with a hypothetico-deductive process. However, many discussed how others may have different perspectives of scientific approaches, truth, and reality. These are informed by training, disciplinary biases, cultural practices, and personal experience of hazards and associated science.

We propose that individuals who recognise different worldviews and philosophies of science will experience higher levels of communication and cognitive uncertainty, which encourages information seeking behaviour and can improve communication efficacy, particularly during high pressure events. We conclude with three communication lessons: 1) be transparent about the processes and causes of change in natural hazards science advice; 2) communicate as both trusted individuals as well as through collective Science Advisory Group (SAG) systems; and 3) provide accessible structures and language to help lay people articulate scientific processes they often intuitively understand, rather than just simplifying information.

1. Introduction

The management of, and response to, natural hazard crises requires communication of science between a wide range of individuals, organisations, and communities; some of who may have very different perspectives and beliefs regarding the science itself. This creates a communication challenge, where assumptions about each other's beliefs and philosophies about science can result in miscommunication. This detrimentally affects levels of trust in both a message and its communicator [1–3], poorly influencing decision-making, and potentially compounding the impacts of an event. As stated by Moon & Blackman [4], p. 1168) when researchers “fail to

* Corresponding author.

E-mail address: E.E.Hudson-Doyle@massey.ac.nz (E.E.H. Doyle).

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understand the principles and assumptions of other disciplines it can limit (or worse, distort) their interpretation of the research outcomes” (see also [5]). This is particularly challenging given audience knowledge, values, and views can be influenced by numerous sources beyond science via a form of extended cognition [6]. We present here a study that explores these factors and how individuals understand the scientific process and the science endeavour associated with understanding and managing natural hazards. Through this we provide lessons that may improve the effective communication of science advice.

In a natural hazard context, scientists are often communicating with individuals who will have a diverse range of scientific expertise, training, and experience; from other scientists and engineers to civil defence and emergency management, government decision and policy makers, stakeholders from across agencies and lifeline organisations, and community members, volunteers, and interest groups. Thus, there are numerous communication pathways within which an individual, acting either on behalf of themselves or their organisation, will make assumptions about the science being shared with them [7,8]. However, these may or may not be correct. The individual’s assumptions may differ greatly from how that science was produced, or from the beliefs that underpin its design and the assumptions that were made in its generation. A mismatch in the assumptions made by the receiver about the science, and the assumptions made by the scientists themselves in the generation of that science, creates an environment where miscommunications can occur. Scientific information may then be applied beyond the scope of the scientists’ intention. In complex contexts, where numerous models, research findings, and community knowledges may be incorporated together to inform decisions [9], an additional challenge exists as the numerous underlying assumptions are often not communicated to the decision-maker in a transparent or structured way (see review in Ref. [10]). In addition, such science communication must also consider the plural nature of knowledge [11]. Such plurality arises from alternative reasonable interpretations of scientific evidence, and is also shaped by the scientific questions, assumptions, values, intentions, and context influencing the formation of that evidence (see also [10,12,13]).

To improve the communication of science effectively across the diverse individuals and organisations involved in managing risk, it thus becomes important for scientists to understand, clarify, and make transparent the assumptions, beliefs, and value judgements² underlying the science, assessments, and models [10,14–19]. It is equally important for those scientists and communicators to develop an understanding of the assumptions and beliefs their audience might have about the science, and science in general. Through this greater understanding, communications can adapt and encompass any differences that may exist [20–24], and hopefully enhance the trust in, use of, and uptake of, science into decision-making.

Developing this greater understanding of people’s understanding of science, as well as the hazard, requires approaches that enable them to explain and discuss how their understanding influences their trust and risk perception (as called for by Siegrist et al. [25]). As reviewed in Doyle and Becker [26], several frameworks and models exist for the effective communication of risk and science, each of which consider different approaches for incorporating such audience values (e.g., Ref. [27–33]). A simplified consideration of these can be considered to involve three key steps: 1) understanding the world views, values, and beliefs of your ‘audience’; 2) understanding and clarifying the values and assumptions underpinning the scientific assessment; and 3) identifying a way to bridge the gap between [1] and [2] such that the information can be effectively conveyed. Examples of how such approaches have been adopted and explored exist in domains beyond natural hazards, e.g., in Ebola communications [34] or to communicate climate change [35].

The beliefs that underly our understanding of science are broadly understood to relate to several core perspectives and philosophies (see e.g., Ref. [4,36]), including: those relating to ontology (e.g., the elements of the physical system), epistemology (e.g., how we produce scientific knowledge), and whether, for example, individuals view science as an endeavour that seeks verification (through proofs and a positivist view), or whether it seeks to understand (constructivism), or liberate (critical theory). Additional influences include those related to culture (e.g., the interface between Mātauranga Māori and Western European Science approaches [37–41]), socio-political views (e.g., based on our experience of an agency communicating the science [42]), our perception of scientists’ political orientation [43,44], or our political orientation [45], education (e.g., whether we have been educated about paradigm shifts), organisational practice (e.g., the influence of training and procedures), and our mental models that represent our understanding of how the world works [24,29,30,46–48]. Beliefs in each of these domains thus informs an individuals’ values, and what they may consider and judge to be ‘good’ science [19]. In addition, individuals may muddle concepts such as falsification, proof, and confirmation, believing good science provides proof (like a mathematical proof) rather than falsification [49]. This misunderstanding is sometimes deliberately used to influence policy, where a lack of proof is seen as a lack of scientific certainty and a justification of action or inaction [50].

Prior research has shown that effective communication incorporates and acknowledges the different beliefs and values of the audience alongside the assumptions that underly risk assessments and scientific information ([51]; see Ref. [52]; see Ref. [26,53]). Direct approaches might include explicitly referencing or explaining these in a message (e.g., as recommended for COVID-19 risk communication, Hooker & Leask [53]). Indirect approaches can include being cognisant of any differences in values during the formation of the science, such as during participatory sciences efforts (e.g., during knowledge coproduction for ecosystem management, Reyers, Nel, O’Farrell, Sitas, & Nel [54]). Recently, participatory methods, such as co-designing an article, have been found experimentally to increase trust in the scientists but did not increase perceptions of the scientist’s expertise or credibility [55]. This further highlights the need to understand the other beliefs and values underpinning interpretations of science, to improve the tailoring of such participatory science approaches.

² A value judgement in this context describes an individual’s judgement that a certain assumption, approach, methodology, metric, or evaluation is appropriate or not. It is informed by social and ethical values and beliefs, as well as epistemic practice and normative influences. See e.g., Winsberg [19] and Cologna et al. [14] for more.

1.1. Considering uncertainty

The presence of scientific uncertainty creates an additional challenge for these science communication efforts. All science contains uncertainty, whether acknowledged and recognised explicitly through the process of science (e.g., measurement errors, parameter choice, range of potential outcomes), or whether it exists implicitly within the science (e.g., the model choice, influences of governance and funding decisions and priorities for science, or the value judgments of the science informing objectives and design) (see review and references in Ref. [10]). Decision uncertainties may thus arise due to a) “incomplete information”, b) “inadequate understanding”, and c) “undifferentiated alternatives” [56]. They can be recognised as arising from the natural stochastic uncertainty and variability of the system through to epistemic uncertainty (lack of knowledge), or to disagreements amongst scientists and conflicting scientific advice [11,13,57–61]. In addition to the scientific uncertainty itself, uncertainty can also exist about not just *what* to communicate, or *how*, but *who* to communicate it to Ref. [8,62].

The complexity of this scientific uncertainty has thus resulted in a diverse array of approaches to conveying it, with varying success [26,50,63–69]. Several international bodies have also created guidelines to help improve this communication, prioritising being honest and transparent communicators to enhance trust and enable robust and flexible decision-making [70–73]. These tend to focus on *how* to communicate uncertainty to the public, particularly during complex, uncertain, and threatening events [60,74–76]. Still, many questions remain unanswered as to how to achieve this effectively with the range of different stakeholders and users of the science [3,63,76–81].

In addition, little instruction exists on how to communicate the more nuanced beliefs and assumptions underlying the scientific information or message, such as the philosophical assumptions discussed earlier. They are thus not usually conveyed alongside scientific assessments [10,82,83]. However, if these assumptions are not conveyed, individuals and decision-makers may make incorrect assumptions about their presence, which influences their understanding of science, and in particular their assumptions of the definitions and distributions of the associated scientific uncertainty [84–86]. When these incorrect assumptions are combined with different tolerance levels of uncertainty [87] or decision-making biases [10,88] it can damage communication relationships [8]. As highlighted by Dhungana et al. [89] differences in disciplinary and experiential training influence choices and preferences for communication of uncertainty, which can cause ineffective communication when there is poor collaboration, impacting the successful incorporation of uncertainty into decision-making. Similarly, due to this training and experience, some decision-makers may make different decisions with the same uncertain information, such as preferring to issue precautionary warnings while others prefer to avoid the possibility of false alarms [90]. Both decision-making behaviours will be influenced by assumptions about the scientific uncertainty present and their perception of the quality of the science. Such judgments about quality will be inferred from the differences between their values about what ‘good’ scientific process is, versus what they perceive the scientific process to have been. Socio-political pressures can also shape these decisions [84], while differences in epistemology can influence interpretations, such as the understanding of initial problem formulation [91]. In addition, when faced with uncertainty, individuals may rely more on prior beliefs and tacit knowledge than on the information provided, shaping their perspectives and decision-making [23,84,92,93].

1.2. Understanding people’s philosophical perspectives of science

If we are to enhance natural hazards science communication through an acknowledgement of the differences between scientists and others in their beliefs and values about science, we must first understand what beliefs and values the communities involved in natural hazard risk management hold (e.g., Ref. [17,22,52]). Previous research into the public understanding of science [94–99] has evolved from assessing people’s ‘science literacy’ or factual knowledge, through to focusing on attitudes and beliefs about science, and further exploring the efficacy of engagement approaches to science communication via the more recent ‘science and society’ approaches [98, 100]. Tools have thus been developed to assess people’s perspectives, such as their levels of scepticism [101,102], levels of trust and credibility in science [45,103,104], attitudes towards positivism [105], their ability to scientifically reason [106], their perceptions about the motivations of scientists [107], and their understanding of the causes of scientific dispute [108,109].

There is, however, limited research exploring people’s beliefs and values about ontology, epistemology, and philosophy of science within a natural hazard risk context. Examples include Rabinovich & Morton [79], who explored how an individual’s beliefs about the nature and purpose of science related to their responses to uncertain climate change risk messages. They found those who aligned more with what they term a ‘classical’ model of science (i.e., a search for unequivocal answers) were less motivated and less persuaded by the presence of uncertainty, while a ‘Kuhnian’ perspective (believing science evolves) were more persuaded and motivated by messages with high uncertainty. They suggest that those who see science as debate may thus trust the source of information more when it includes uncertainty estimates, whereas this may cause mistrust in those with a more classicist view. Similarly, an individual’s *epistemic cognition* is described by Sinatra, Kienhues, & Hofer [110] as encompassing the beliefs people hold about the nature of knowledge, and the application or influence of those beliefs for scientific problems. This also relates to people’s beliefs about certainty of knowledge, and the need for certainty in scientific claims, influencing how they respond to scientific messages that contain uncertain, ambiguous, or contradictory information.

There is limited further research exploring the most effective science communication approach for different epistemic and philosophical views (e.g., Ref. [110]), particularly in the natural hazards context. To understand this relationship however, it is important to investigate the first building block of this communication puzzle: to understand individuals’ perspectives on how natural hazards science is produced and what they perceive to be the values and influences that might be shaping and affecting these scientific processes. In this research we thus seek to study how stakeholders interpret natural hazard science and render it meaningful in relation to their decision context.

Key research questions are thus.

RQ1: How do diverse stakeholders think natural hazards science is produced and the system of science operates?

RQ2: How do such stakeholders relate their understanding of the process of science to other factors, such as their ontological and epistemological views, or their philosophy of science?

In this we consider ‘natural hazard science’ to consider all science that is employed to understand and manage natural hazard risks, such as the physical, social, or economic sciences. Accordingly, we do not constrain the discipline of natural hazard science for participants, discussed further in section 2.1. Findings from this research have the potential to improve natural hazards science communication by providing a more thorough understanding of different audiences’ views on science. When this is combined with an understanding of what actual beliefs and values underpin the scientific assessment (e.g., Refs. [111,112]), we thus have the opportunity to communicate science and uncertainty more effectively, by adopting approaches that adapt to, and incorporate, these diverse perspectives and views [23,24,27,113–115].

2. Methodology

A three-part interview was developed to explore individuals’ understandings of uncertainty in natural hazard science via a mental model mapping task based on the Conceptual Cognitive Concept Mapping (3CM) approach of Kearney and Kaplan [116] and Romolini et al. [117] (see also [21]). The full interview rubric can be found in Supplementary Materials (Appendix 1). Part 1 and Part 2 of the interview explored participants’ definitions of scientific uncertainty, and their perceptions of the sources of uncertainty in natural hazards science, and are reported in Doyle et al. [22,23]. Herein, our focus is on the responses to Part 3 of the semi-structured interview protocol (Appendix 1). This was designed to explore participants’ broader understandings of the production of science, their philosophical perspectives of science, and their beliefs about epistemology (how they perceive knowledge is created - relating to objectivism, constructionism, and subjectivism) and ontology (what exists that we can acquire knowledge from? e.g., considering realism and relativism) (see e.g., Ref. [4,36,79,103,105,109,118–121]). Additional questions also explored socio-political influences. Example questions include.

- o Is there one real world that scientists are measuring?
- o Can scientific questions have more than one correct answer? Please explain?
- o How do we confirm a scientific theory?
- o Do you think the scientific method is the only way to determine what is true or false about the world?

Interviews were conducted by two of the authors (EEHD & JT), either in person, or virtually via Zoom. The total interview took between 60 and 90 min, and was audio recorded and transcribed verbatim for later analysis. The Massey University Ethical Code of Conduct was followed, and this research received a Low-Risk Ethics Notification Number of 4000023593. Participants were given a \$40 supermarket voucher as a thank you for their time.

2.1. Interview scope

Given our study sought to understand participant’s perceptions of science and scientific processes, we did not define these terms for them. We used ‘the’ scientific method as a framing in the questions above (and Appendix 1), not to restrict participants to the view there is a definitive scientific method, but rather to prevent any unintentional leading of the participant by asking directly about multiple, alternative, methods. Several participants did then discuss alternative approaches, discussed further in section 3.1 and 4.2. We also note that when asking about scientific theories, we framed the question around confirmation, rather than falsification, to again open a discussion with participants rather than lead them directly to the concepts of falsification or ‘proof’. In addition, while it is well understood by scientists that science provides falsification not “proof”, see Popper [49], Freudenberg et al [50] identifies that many individuals may call for, and expect, ‘proof’ in science as a tactic to imply certainty and thus they may muddle the concepts of falsification and proof (see also section 4.2).

In addition, at the start of the interview, participants were told that this study is focused on natural hazard science, considering hazards such as volcanoes, severe weather, tsunamis, landslides, earthquakes, etc. They were thus instructed that when they discuss ‘science’ as a concept, and the general scientific processes, they should keep their discussion within the scope of the science that is focused on natural hazards. Thus, they were to avoid other disciplines such as biomedical science, unless directly relevant. However, we deliberately did not limit the ‘type’ or discipline of science they could discuss, whether physical or social, to avoid unduly influencing their discussion. While social science is broadly considered part of trans- and multi-disciplinary natural hazards science in Aotearoa NZ (AoNZ; e.g., in curricula, funding mechanisms, and science advisory group processes), we did not explicitly mention this in our briefing, nor did we exclude it, allowing participants to interpret the scope freely. Finally, we did not constrain or specify the source of the science advice, which in AoNZ often includes agencies, crown research institutes, and consultancies, alongside the academic settings of universities.

2.2. Participants

This study was conducted in Aotearoa New Zealand (AoNZ) as it experiences a variety of natural hazard events (NHE), including earthquakes, volcanoes, severe weather, and its impacts (e.g., flooding, landslides), near-coast and far-field tsunami sources, wildfire and seasonal drought. Therefore, most New Zealanders, whether members of the public or working in natural hazard spaces, have high exposure to natural hazards and information about them, either directly or indirectly. Participants were recruited via advertising and snowballing, and needed to be 18 years or older to participate. Due to the multi-disciplined nature of those involved in natural hazard risk and emergency management, we recruited a broad range of participants ranging from scientists to engineers, central, regional, and local government, other decision-makers and stakeholders, and broader community members who may act upon natural hazards information. The latter category included non-scientists with little to no science experience. No participants were expected to be expert in the philosophy of science.

Thirty-one individuals participated in the study (see also Doyle et al. [23]), and all were residing in AoNZ at the time of their participation. They were each assigned a pseudonym prior to interview. Ages ranged from 25 to 75 years old. Eleven participants identified as male, and 20 participants identified as female. Twenty-three participants identified as NZ European/Pākehā,³ 5 identified as other European (e.g., Italian, English, British), and the rest identified as Māori/NZ European, Latino, or Iranian/Middle Eastern. One participant declined to disclose demographic details. The professions of the participants included 4 physical scientists, 2 boundary or other knowledge transfer scientists, 2 social scientists, 6 policy writers/analysts and planners, 2 engineers, 4 emergency management practitioners, 2 with a law background, 2 administrators/secretaries, 2 teachers, and 5 others including a journalism student, a city council worker, an artist, an independent historian, and an anthropologist. No individuals were excluded from participating in this study.

2.3. Analysis

A general inductive approach (as described by Ref. [122]) was used to code the 31 transcribed interviews. This flexible approach seeks to understand the core meanings within qualitative data and explores them in direct relation to research objectives, by identifying themes or categories that are most relevant to those objectives (see also [123,124]). This was conducted using NVIVO software, in a reflexive consultation between the two lead authors and thus reflects their experiences and expertise through transdisciplinary training in physical and social sciences of natural hazards and disasters and in critical health psychology.

The inductive analysis involved four key steps.

- 1) The transcripts for Part 3 of the interview (Appendix 1) were read by JT and EEHD to build familiarity with the data.
- 2) Sections relevant to the objectives and research questions (see section 1.2) were assigned to 90 unique codes by JT. Example codes include for example: *'how data is gathered'*, *'how theory is developed'*, *'truth and understanding'*, and *'a funding perspective'*.
- 3) These codes were grouped together into categories based on similarities in the main topic of the code by JT in consultation with EHD.
- 4) Overlap and redundancy amongst these categories was reduced by JT in consultation with EHD. This included further grouping on similarity as well as considering shared meaning, experiences, and processes. This produced the three final themes: *'science is a way of seeing the world'*, *'science has limitations'*, and *'knowledge evolves'*.

All three themes and their associated codes are illustrated in Fig. 1 and listed in Appendix 2. This also includes code descriptions and example quotes from each of the 3 participant groups for each code. The theme *'science is a way of seeing the world'* also included a small number of sub-themes, as presented in section 3. However, not all themes produced sub-themes.

Thus, via this reflective process the underlying patterns of shared meaning were considered across these 90 codes, and thus across the responses to all Part 3 questions, producing the three key themes that represent how participants view and understand the process and production of science. As is standard for qualitative and reflective analysis processes, the themes were reshaped through deeper understanding and consultation amongst the authors (e.g., Ref. [125]). We also note that these themes represent insights into our overarching research questions (see section 1.2) rather than being mapped to specific interview questions. The interview questions in Appendix 1 thus represent the discussion prompts that encouraged exploration of ideas across the study objectives.

Additionally, given that the science communication occurs between different communities of practice in the management of natural hazard risk and events, the codes were analysed considering participants in three broad groups. Scientists (n = 11) were those with a tertiary education in a science field and working in a science field, and included natural hazards scientists, engineers, environmental and geoscientists, social scientists, public health, risk and data scientists. Science Literate (n = 10) were those who either had a tertiary education in science or were working in a science field, but not both. Lay Public (n = 10) were those with no tertiary education in science and not working in a science field. The designation of participants to each group was based on how participants self-described their education and employment. This grouping enables understanding of how those with different levels of science experience discussed the themes, and what that means for responsive science communication between those groups. However, we note

³ Pākehā means "New Zealander of European descent" in the Māori language, the indigenous language of Aotearoa New Zealand (Te Aka Māori dictionary, <https://maoridictionary.co.nz/>, last accessed 29/07/2024). Individuals may define Pākehā as representing people with European ancestry and who are of multiple generations in Aotearoa New Zealand, and thus being distinct from more recent European immigrants.

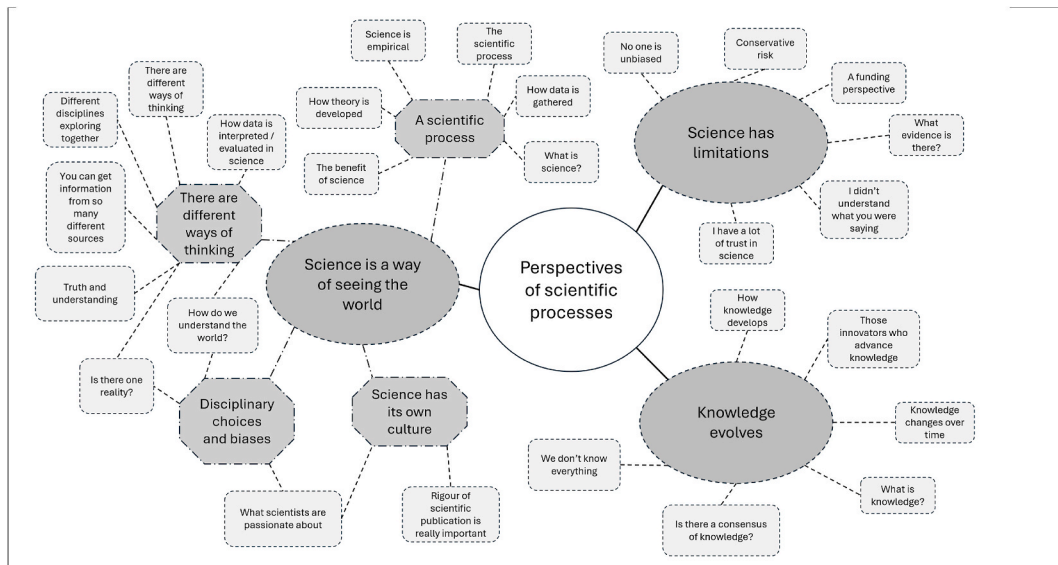


Fig. 1. Schematic diagram of the themes, sub-themes, and codes constructed from an inductive analysis of Part 3 of the interviews. Interview questions can be found in [Appendix 1](#), description of codes and example quotes can be found in [Appendix 2](#).

that most differences between groups were subtle and centred around level of detail when describing thoughts, and the language used (level of articulation). Thus, only those noticeable differences between groups are described for each theme.

3. Results

Through the general inductive analysis of the transcripts, we constructed three main themes from across the responses to all Part 3 Interview Questions (see [Appendix 1](#)). These themes seek to address our study objectives described by research questions 1 and 2. These include: ‘science is a way of seeing the world’, ‘science has limitations’, and ‘knowledge evolves’. The associated sub-themes, codes, code descriptions, and example quotes from each participant can be found in [Appendix 2](#).

3.1. Science is a way of seeing the world

This theme focused on how science is a way of seeing the world and is described by four sub-themes: a) ‘a scientific process’, b) ‘there are different ways of thinking’, c) ‘disciplinary choices and biases’, and d) ‘science has its own culture’. The codes for these can be found in [Appendix 2](#), and examples of these include: a) ‘what is science’, ‘science is empirical’; b) ‘different disciplines exploring together’; c) ‘is there one reality?’, ‘how do we understand the world’, and d) ‘what scientists are passionate about’. Science is a way of seeing the world describes how different groups of people explore and think about the world they live in. The sub-themes describe some aspects of these in greater detail, such as how the process of science shapes what is known about the world, how different ways of thinking shape how people see the world, how personal choices and biases influence science, and how the culture of science shapes how the world is explored.

3.1.1. A scientific process

Participants were asked direct questions about the scientific process ([Appendix 1](#)), including how they understood the scientific method, the development of research questions, and theory confirmation. Across discussions, participants reflected on what they perceive science to be, how it is done (methodology), and what it seeks to achieve. Participants described science empirically in broadly similar high-level steps, generally aligning with the hypothetico-deductive method⁴ [126], starting with a hypothesis, followed by some form of experiment that produced data and results, which are then analysed to assess whether the research question had been answered. For example:

⁴ As stated by Nola & Sankey [126], the hypothetico-deductive method involves developing a theory or hypothesis to test, followed by a deductive part “in which test consequences are drawn from the hypothesis”, after which consequences are deduced and compared with experiments and observations, to see if they pass or fail in order to evaluate the hypothesis. See also <https://www.cambridge.org/core/books/theories-of-scientific-method/hypothetico-deductive-method/A23939B9520B5DF79FF0E96738EEA906> (last accessed 17/11/2024).

All scientific research follows the same process of coming up with a hypothesis or question, gathering information to answer that question, analysing the information, and then coming up with conclusions to answer the question or hypothesis – Kappa (Lay Public)

The scientific method is you have some evidence, or you may not have any evidence, you may go straight to an idea. You design an experiment to test that idea, hypothesis. You collect your data or some information somehow to help you ... You analyse that in some way and then you document that in some way that can be peer reviewed and assessed by other people, other scientists – Upsilon (Scientist)

More generally, participants described science as a “rigorous method” or “systematic process” for exploration and understanding of the world, as a tool that provides structure for investigation and discovery. When discussing data gathering techniques or methodology specific to natural hazards and disaster science, participants noted the use of observational data gathering techniques or case studies as more common than other scientific disciplines. They attributed this to natural variety of the phenomena being studied. That is, because disaster events occurred in a natural environment (and are not entirely able to be replicated in a lab setting), were often unique, were one-off, or sudden events, and they were usually observed in less controlled real-world settings than experimental studies. Thus, they often require opportunistic circumstances to be seen in real time. Beith and Beta comment on the role of these methodologies in natural hazards and disaster research:

Every natural hazard is a great case study because we get to learn from it. So even if it has awful consequences at the time, from a teaching perspective they're really valuable. And then you get to understand the science behind it – Omega (Science Literate)

Sometimes science needs to be replicated, but in some cases, you cannot replicate an event. Like, oh yes, I study earthquakes in the 2018, but it's 2020 and there's no more of that kind of similar conditions, so it's not replicated. So there is not an accurate method to apply to all of them – Beta (Scientist)

Here, Omega (Science Literate) highlights the value of case studies, while Beta (Scientist) explains why replication isn't usually possible in hazards science. Across all three groups, participants stated that research questions arose from observations, from recognised gaps, from scientists' curiosity, from government and funding priorities [22], from what needed to be done, and from what might affect the end user (often described as the public, particularly in the context of NHEs).

We now look at the second sub-theme: there are different ways of thinking.

3.1.2. *There are different ways of thinking*

Participants discussed the existence of different ways of thinking about the world, due to the influence of different cultures and how scientists themselves varied in their thinking both individually and across disciplines. Participants thought people *should* have these different ways of thinking as it broadened research and could help change perspectives and understanding when required. Alpha and Eta summarise some of these sentiments.

And yet that's the Western approach to it. If you look at the Eastern approach, so if you go to China, they look at things in terms of a system and where the context is an important part of that, whereas we have a rules-based society here in the West – Alpha (Science Literate)

The importance of diverse thinking was reiterated in discussions of different scientific disciplines working together. Here participants generally agreed that information-sharing and collaboration amongst researchers and different disciplines occurred and was beneficial, highlighting the positive impacts of pooling knowledge, collegiality, and collaboration. Omega and Rho express these thoughts below.

From what I understand is that there's a team of academic scientists that do research projects and that research project generally lasts over years, or like can be months ... and then they pool their knowledge, produce papers which then goes to educate non-scientists in those fields. So like if you wanted to find out <about> natural disasters you might team up with the Geology Department or the Volcanology Department and do it that way – Omega (Science Literate)

I think there's a real power in people from different disciplines exploring something together in groups, rather than getting a whole lot of people with the same background and expertise working on a problem – Rho (Scientist)

Across participant groups, the Scientists and Lay Public groups discussed collaboration much more than the Science Literate group, who hardly discussed it. However, all three groups framed their discussion in similar ways, considering collaboration to be a positive thing. The Scientists and Science Literate groups however also noted that collaboration could fail if colleagues were unable to move past their egos. Some participants also thought collaboration could be unhelpful when research was not relevant to the AoNZ context, or, when findings were inappropriately applied. For example, one Science Literate participant noted that disaster research conducted in Nicaragua is less relevant for an AoNZ application because it would not account for local context. This suggests a need to clarify appropriate ways international research can be applied in local settings.

We now look at the third sub-theme: disciplinary choices and biases.

3.1.3. *Disciplinary choices and biases*

When asked about scientists' values and beliefs, participants thought that scientists' different passions and interests influenced the branches of science they entered and the research projects they chose. These interests influence the scientists' viewpoints for research,

which could be both a positive and a negative. Positively, a passionate scientist could be motivated to explore an idea fully. Negatively, a passionate scientist could be less open to data, other research, perspectives or researchers that disputed their findings. Upsilon describes some of these ideas.

I think some people ... they'll be very interested in natural hazards. There's just something about it that really interests them. It's easy to find people that are really passionate about the environment; it's probably easy to find people who are passionate about human health. So there might be passion for that particular domain, so the specialisation that you're in. I think scientists probably would almost all have a very strong sense of curiosity - how the world works, and wanting to find out more about that and test it. I should think that all scientists are probably pretty keen on learning as well – Upsilon (Scientist)

Participants thought scientists could not be removed from their research and findings. Therefore, most acknowledged that bias always exists in research (findings). They discussed how experimental or empirical approaches can never be fully objective, often noting the different recognition of objectivity and subjectivity in quantitative versus qualitative research methods. However, most did not consider bias to be a negative undermining research, but rather something to recognise, consider, and acknowledge or reduce as appropriate.

When asked direct questions about whether there was one reality or if there was one real world that could be measured, responses were given that inclusively discussed different cultural groups and lived experiences, and focused on the diverse perspectives people have about the world. Iota and Mu discuss this here.

I just think there is, I don't think it's absolute, but I think that there is one kind of reality but that reality is dictated, not dictated, but it is influenced somewhat by the decisions and choices that are made by scientists in this context – Iota (Science Literate)

No, not at all. No. I don't necessarily believe that everything we can measure with an instrument or with our eyes or with a computer is everything that goes on in the world. People have different ways of relating to reality that are completely different to how I might see the world, how you might see the world. And science has come from a very distinctive place – Nu (Scientist)

Generally, all three groups provided one of two answers. The first, and more common, response was that there was only one world/reality, but how it was measured and perceived would differ by the person measuring/perceiving it. For example, one participant explained that while rain was rain, different people would have different explanations for why it was raining. We can expand on this analogy further, by suggesting a scientist would be able to offer an explanation using a rain cycle, while a religious explanation might include rain as a gift from their god. The second response was that there was not one real world/reality because it was dependent upon how people measured or perceived the world and reality around them. For this perspective, participants thought different backgrounds, such as science, religion, or culture, would perceive reality differently from each other. Therefore multiple realities can be considered to exist as a reflection of those multiple perspectives of reality. Chi describes this:

No. How can there be one world? Yeah, there's no one world. There'll be multiple realities on individuals, where that individual works in that organisation, where that organisation sits in their region and in their country – Chi (Science Literate)

We note here that several participants appeared to struggle to articulate their answer to this philosophical question, focusing instead on different perceptions of reality (like Chi above), rather than their individual understanding of whether there is a single reality (or multiple) independent of our perceptions of it.

Participants were also asked whether they thought some things could be considered 'true or false' in the world. 'True' or 'false' were described in subjective ways, that is, while some participants acknowledged there were certain 'facts' that were known about the world, they thought that what was 'true' for some may not be considered 'true' for others. Thus, participants generally thought that there was more than one 'truth' to the world, and more than one way to understand the world. When considered alongside their discussion of reality above, many participants can thus be considered to interpret the concepts of truth and reality to relate to how people create and acquire knowledge (epistemology), rather than explicitly considering ontological concepts of realism (one reality exists) or relativism (multiple realities exist). Similarly, the concept of truth discussed by some participants also appeared to encompass them describing how people's embodiment of experiences and values can act as their 'truth', rather than an external scientifically measurable 'truth'. Additionally, participants discussed how science was just one way of enquiring into what was 'true or false' about the world, acknowledging indigenous, and different, ways of thinking. Beith and Iota explain these ideas below. Iota also acknowledges that knowledge changes with the emergence of new information.

I think a lot of people think that science is what's true in the world, but it's more just what we observe or know right now. Personally, I think there should be a lot more room for intuition and definitely for more native knowledge – Beith (Lay Public)

So 'true' and 'false' I don't see as absolute. They're changing concepts and evolving concepts. I don't hold those things as absolute, but I hold them as true – Iota (Science Literate)

We now move on to talking about the fourth sub-theme: science has its own culture.

3.1.4. Science has its own culture of practice

This sub-theme explores the culture of science. Participants described the sharing of research, and the process involved (such as peer review, publication, journals), as being important to science. In particular, dissemination was thought important as it creates debate and evaluation of research, can stimulate the conduct of more research, and can facilitate new ideas. This dissemination process is recognised by participants as a learned and shared practice with specific rules. Participants across all groups held peer review in high

esteem, believing it to give legitimacy to the scientific research being made public. It was also considered important for research integrity and to identify and remove biases, as discussed also in the next theme: science has limitations.

Related to the culture of science practice is the culture of scientific funding: how scientific funding is distributed, and how to effectively *obtain* funding. This creates limitations (as discussed in section 3.2) in terms of what is or isn't funded, and thus which projects or questions are prioritised for investigation over others. Where funders showed interest, research was conducted. Where funding interest or prioritisation was lacking, phenomena could be neglected from research, with very little thus known about it. Alpha and Eta discuss this below.

I'm well aware that there are scientists that have pet projects, pet interests, and they secure funding by various means, and some of them pump out probably really decent knowledge and you look at it and you think "mm, okay, so what?" And it's difficult to join up that knowledge versus people's needs I suppose – Alpha (Science Literate)

I think they develop it primarily through a kind of intersection of what's going on in the world in that field, so what's going on in New Zealand, and what is fundable through various channels, so it's a kind of a mix. And the funding is to a certain extent shaped by what users might need – Eta (Scientist)

Here we can see that Alpha views funding as unequal, as some people secure funding (and sometimes a lot of funding) to be able to investigate what they choose, which may prevent others from doing research that may have more value in terms of what 'people need'. The funding imbalance and inequity limits science, and the scope of scientific enquiry (see Doyle et al. [22] for more). Eta also notes that funding decisions are shaped by what people need, on both a global and national level. While Alpha notes similar, they raise concerns about the value of some research to knowledge more generally, discussed further in the theme 'knowledge evolves' (Section 3.3).

We now move on to the second theme: science has limitations.

3.2. Science has limitations

This theme, which had no clear sub-themes, describes some of the limitations that participants mentioned when discussing science during their interviews, particularly the factors that were perceived to limit science, such as being conservative, use of jargon, and needing 'proof'. Codes and examples quotes for this theme can be found in Appendix 2, and example codes include 'no one is biased', 'conservative risk', and 'a funding perspective'.

Participants talked about how they "trust in science". They discussed trusting in the "rigorous approach" of science and the scientific process, and therefore being able to trust scientists and their research. However, when further discussing being able to trust scientists, there were some differences between the cohorts. Luis, Chi, and Upsilon represent the different ideas.

I don't trust the scientist, I trust the scientific community as a whole, to not let lunatics go running free. I trust that the scientific community is pretty strict in maintaining the scientific process. Like I said, I don't know scientists, I just call it all science. Science as a whole. I don't know one science from another, but I put my trust in, I want to be able to put my trust in the scientific process as a whole – Luis (Lay Public)

I guess it's not trusting a scientist, it's trusting a body of knowledge which is continually tested and independently researched, and there's rigour to it – Chi (Science Literate)

All sorts of things I guess. Their background. Their prior research. Their publication history. What other work that they've done that seems credible to me, if I'm familiar with it. Who they work with. Their methods that they've used, how well they've documented them – Upsilon (Scientist)

Here we can see that Luis (Lay Public) and Chi (Science Literate) put more trust in the scientific process rather than an individual scientist, while Upsilon (Scientist) talked about scientists more as individuals, though focused not on the scientist as a person, but their scientific process, background, and credibility. This may influence science communication in two ways: 1) people who trust science as a discipline may disregard scientists speaking individually (presenting an opinion) or about novel information, and 2) those who trust a scientist's reputation may disregard individuals they deem to be disreputable, discredited, or novel.

A fear of being considered not credible and facing criticism was described by two participants in the Science Literate cohort as contributing to scientists acting conservatively. Conservatism was described as moving slowly with research, not taking risks, or a scientist protecting themselves from public criticism and their research from being discredited or worrying about being wrong. Mu describes this well below.

And when we get into that situation and we have risks of litigation and we have risks of being dragged through the media and we have risks of potential litigation, it is resulting in what I suspect is, we're starting in a conservative baseline, and most scientists' starting point at the moment is in a conservative view. But that's because we are in a world that if you're not, you get rewarded for being conservative, but you get smashed or you get taken to task if you're slightly less conservative or slightly wrong and a consequence results from that – Mu (Science Literate)

A perception of being wrong is motivation for scientists to protect themselves and their reputations, which links back to Upsilon's comment above about trusting the reputation of the scientist. Although some participants did talk about trusting scientists and the scientific process, they also talked about how they 'needed' proof/evidence to be able to trust scientists and their advice. This 'proof' or

'evidence' could be more studies, data, or information to help support (or disprove) what was being said. As the quotes below demonstrate, this need for proof/evidence was also discussed in conjunction with a lack of proof or evidence, particularly in the context of the field and lab work used to build understanding of natural hazards. Alif and Omega comment on this.

So they say they did this and this is the outcome they got, let's repeat what they've done and see if we get the same outcome and prove that it's correct or disprove that it was right – Alif (Lay Public)

So there's <a lot> of field work in some elements. And a lot of lab work. And a lot of, I guess it's just finding the evidence. There's a lot of research going to find the evidence so it's not just the one size fits all. And there's a lot of hypotheses that, because what I believe <of> science it's being disproven is as fair and as truthful as being proven in your hypothesis. Because you use the evidence to come up with that so everything is right, even if it's wrong to your hypothesis it's all right – Omega (Science Literate)

Looking across these evidence codes, the Lay Public group discussed the need for proof, evidence, and the concept of something being proven or unproven, significantly more often (45 mentions) than Scientists (14 mentions) and Science Literate (24 mentions) groups. Generally, all participants discussed proof and evidence in terms of what the public wants to see. However, there were differences between groups. For example, the Scientist group talked about how better evidence helps build knowledge and science more generally. In comparison, both the Lay Public and Science Literate group talked about needing more evidence or proof to support what a scientist is saying. Thus, for these non-scientists, not only is the science perceived as limited if it lacks evidence to support its claims, but they may also discount the scientist themselves if they lack evidence or proof. Overall, participants did not describe what they meant by proof, instead reverting to describing how science is conducted and how to confirm theories empirically. Some described proof as 'confirming proof' or confirming evidence for a proof that already exists. That is, evidence backing up what a scientist says. We note that many of the participants' discussions of proof may indicate some misunderstanding of the nature of 'proof', which implies verifying something with certainty and is more related to concepts like mathematical proof, compared to empirical evidence (see Fruedenburg et al. [50]; discussed further in section 4.2). Alternatively, participants may have used 'proof' colloquially for evidence.

As well as the general public perhaps needing 'more' proof to be able to trust the advice they were receiving, participants also mentioned how important it was for people to be able to understand the advice they were receiving. That is, the use of jargon and technical language was mentioned by some participants as something that limited their understanding of science and thus was a limitation of science. Nion, Omega, and Theta explain this here.

Just Stuff or the Herald. They might have links to some articles. And I have to admit that I'll start reading them. And then I'm like, it's over my head. So go back to the Herald or the Stuff article to read it – Nion (Lay Public)

You know when someone words something in a way that you may have heard a thousand times from different people but that person just says it in that one way, causes that penny drop moment. I think you also have to be that ability too, 'cos I think some scientists ... get stuck in the science – Omega (Science Literate)

The way I think that should be done is to work from the perspective of people who are exposed to the hazards, and try to understand what kind of information is going to be most useful to them to mitigate the hazards. Then once you know that, you use that knowledge to create information based on what you know to communicate to these people in the most helpful possible way so that they can, if they need to do anything, they can do that – Theta (Scientist)

Here, all three participants are discussing the same challenge of accessible science communication, but discuss this differently. Nion focuses on their *personal* experience of not understanding a communication about science they were attempting to access through the original source and having to revert back to an online news article instead. Omega alludes to difficulties communicating science information to *other* audiences, noting that 'scientists get stuck in the science', implying poor communication to those with a different level of understanding. Meanwhile, Theta articulates the importance of being able to communicate with someone in a way that they will understand, particularly when the science information may impact their ability to respond to a natural hazard (event). All these perspectives have implications for how natural hazard science is communicated. Managing natural hazards relies upon multiple science disciplines, from geology and hydrology to economics and social science. The breadth and complexity of the sciences included often means individuals have little prior or tacit knowledge to draw upon to assist their understanding of a science communication (see also [23]). It is thus important for science communicators to provide additional accessible materials and explainers in multiple formats, for different audiences, alongside the original source (see also [127]). Examples include policy briefs, science notes, public webinars, and 'behind the paper' blog posts.

Participants frequently discussed bias as a perceived limitation of science. Some focused on data bias, however most focused on scientists' personal biases and lenses that influence the outcomes of their research. Some acknowledged that everyone brings their personal lens to the research they conduct and that this was something that could not be 'removed'. They did not consider this problematic, but rather something to acknowledge and consider when contemplating the scientist's research. Alif and Omega describe this below.

I think scientists probably try to be unbiased and open but I don't think you can help but bring your own thought into it – Alif (Lay Public)

And I think then within that then you've got your biases. Because I don't think there's anyone on the planet that's completely unbiased. Like that person is mythical – Omega (Science Literate)

These quotes show how bias was discussed in a broadly similar way, describing it as inherent part of the process of science due to the scientist's influence from initial research questions through to interpretation. Thus, they thought bias should be something to be mindful of rather than work to overcome.⁵

We now move on to discuss the third theme: knowledge evolves.

3.3. Knowledge evolves

This theme, with no clear sub-themes, describes how participants recognised that knowledge evolves over time. Participants discussed how knowledge develops, changes over time, and how innovators move knowledge forward. They also discussed what knowledge is, if there is consensus, and sources of knowledge. Codes and example quotes for this theme can be found in [Appendix 2](#), and example codes include 'how knowledge develops', 'those innovators who advance knowledge', and 'we don't know everything'.

Participants discussed what knowledge was, how they understood it, and how it differs between people. Here, participants again discussed how different cultural groups and ways of thinking influence what is considered knowledge (see also Section 3.1.2). Not all participants discussed how knowledge develops, however those that did generally reached consensus that knowledge evolves. Particularly, participants discussed that knowledge changes as new data and information are gathered and understood. This was accepted as being an inherent part of science and understanding the world. Beith, Chi, and Zeta articulate this well in the following quotes.

Because historically, when we think we're right, we find out 50 years down the line that we weren't – Beith (Lay Public)

Well science in itself is trying to acquire new knowledge, so any time you've done any research, you've acquired new knowledge that will a) could confirm what you already know, or b) change it. But there's no one set end point, it's evolving – Chi (Science Literate)

Within the environment of the time. Yeah. I think about science is, what we know from science is the most likely knowledge given the data, given what we understand of the constraints and the context at the time – Zeta (Scientist)

As the quotes above show, all groups mentioned knowledge evolves and is a product of its context (space and time). All three groups discussed how science developed knowledge through investigative studies that may confirm what was already known or could change what was already known. Participants expressed open-mindedness and flexibility about accepting new information as it came to light, to help them make more informed decisions. As stated by Iota (Science Literate): "*I'm always open to them [my opinions] being changed ... if ... they [scientists] provide me with a good kind of argument*".

Interestingly though, for general science communication, some participants (such as Delta below) highlighted how changes in advice can be seen negatively by others, affecting credibility and trustworthiness as individuals perceive it as a change of *opinion* rather than a change of *evidence* or due to science evolving. This shows that while some participants accept the evolution of science advice, some receivers may view that evolution critically, presenting a significant communication challenge.

I hate the idea that ... you're not able to evolve your opinion of things. They call it flip flopping. And it's like well no I got more information, I have more information in front of me so I'm able to update my assessment of this, and that's what science is supposed to be. Science isn't supposed to stop once you've completed the hypothesis, what if new information comes up? – Delta (Lay Public)

So there's a certain uncertainty that comes from the fact that our knowledge develops and we change our opinion ... on things – Eta (Scientist)

Here, Eta notes that understanding how knowledge develops and scientific opinions evolve can create a sense of uncertainty. Participants acknowledged that there were limitations to knowledge and that they did not know everything. That is, they accepted some information is just what scientists know in the moment, sometimes no definitive answer exists, and more information is needed. We also note many participants used 'opinions' in this context to refer to an evidence-based opinion, either directly informed by data or indirectly informed by expertise or a (potentially limited) body of knowledge, rather than opinions representing more general beliefs or non-evidence-based interpretations (see Section 4.1).

Interestingly, participants talked about an innovators' role in developing and increasing knowledge. Individual scientists may come forth with outlier theories or research and may initially be disregarded as incorrect. However, participants thought innovators often advance natural hazard knowledge in significant ways. Thus, it was not only important to celebrate and support them, but also those who followed and supported their work. This links back to the discussion of conservative scientists who may resist change and be critical of new research due to ego (not wanting their research to be discredited) or fear of being wrong (see also Section 3.2). Beith and Eta articulate this below.

That's also a tricky one, because then you have people who've come up with scientific theories in the past, and they've been the odd one out, and then it turns out down the line, they were actually right – Beith (Lay Public)

⁵ see also Shelton [174] for a thorough discussion of the importance of accepting bias and subjectivity as valuable aspects of research.

I suppose you always have innovators and those innovators might be in methodology, the way of developing knowledge or information, or they may be in simply applying the existing ways of studying in a new way. And those people are quite important, or those experiences of innovation are quite important. But it's then the people that follow next that is the really important one. Because if it's just one crazy outlier in a shed somewhere who has come up with an idea, that doesn't really change the world. It's the next level where people <are> actually able to early adopt these new ideas and start pushing them again, even further. We need in our science both of those - the freedom to be innovative but also the capacity to follow that innovation – Eta (Scientist)

When discussing knowledge evolution, participants discussed whether there was a consensus of knowledge and what that would mean if one was reached. In some circumstances, a consensus of knowledge helped provide certainty or clarity that scientific advice could be followed. There was no distinct difference in views between groups, however consensus was discussed twice as often by the Lay Public group compared to the Science Literate and Scientists groups. The higher prevalence in the Lay Public group may reflect their reliance on receiving scientists' information and potentially the higher degree of confidence and certainty such a consensus may convey. In contrast, the other groups have more experience of differing scientific views and place less emphasis on the need for consensus in knowledge progression. Perspectives on consensus thus affect science communication efficacy, discussed in section 4.3.

While open to new knowledge, participants also expressed wariness regarding sources of information. In particular, while the internet and media could be sources of evolving information about science, they were not considered credible. Below, Kappa and Mu discuss the internet's role in disseminating science information.

I guess the freedom that people have to write whatever they want on the internet can also have an impact on that sort of thing. So, you can kind of get information from so many different sources that it can create more variation than there actually is, and what's actually being studied – Kappa (Lay Public)

If you get that view from the media and then you start going Googling down a thing, you will always find what you want – Mu (Science Literate)

The two quotes above show that Kappa and Mu are aware of misinformation and disinformation online. They are wary that the internet contains all kinds of information, including 'rabbit holes' that could confirm beliefs, no matter what they are. Sources of knowledge (including lay sources) were discussed significantly more by the Lay Public group than other groups. The Scientists group hardly discussing these concepts at all. The Lay Public talked about how Googling for information may be problematic, especially when it is 'someone saying something', that is, people can write whatever they want. They also discussed how people accept the online information that relates to how they already think. Meanwhile, newspapers may publish articles that do not interest someone enough to read them. The media was also considered to influence what was in the public sphere, particularly regarding whose story gets told. Thus, while some participants discussed how they trust science and journals as sources because of their reputation, others thought the media is profit driven, publishing "the most sensationalised information" (Delta, Lay Public) rather than that which is most relevant.

4. Discussion: the challenge of "communication uncertainty"

The three main themes presented above describe our participants' views on how science is produced, including: 'Science is a way of seeing the world' (which included the sub-themes 'a scientific process', 'there are different ways of thinking', 'disciplinary choices and biases', and 'science has its own culture', Section 3.1), 'Science has limitations' (Section 3.2), and 'Knowledge evolves' (Section 3.3). The first theme describes how different people explore and consider the world they live in and what role science plays in those ideas. The second theme describes some of the limitations of science and in science information, such as how bias affects science, what role evidence plays, alongside the ability to trust science. The third theme describes how participants acknowledged that knowledge changes over time, and how knowledge develops and is moved forward.

While the different scientific expertise groups had broadly similar perspectives on the scientific process (section 3.1.1), they discussed and recognised that there are different ways of thinking such that perspectives about reality and truth may differ (section 3.1.3). Thus, while there were not considerable differences between groups in how they viewed the scientific process; there was understanding across all participants that interpretations and judgment of scientific findings or communications and advice can vary between individuals because of these different ways of thinking (section 3.1.2). While these different ways of thinking were considered to broaden research and advance understanding, they were also seen to present a challenge for effective communication, particularly if individuals are unclear about what those different ways of thinking are.

This ambiguity can be considered a 'communication uncertainty'. While most of the uncertainties we have discussed may be a component of natural hazards science or the scientific process and judgments, we define 'communication uncertainty' as the uncertainty that arises due to a mismatch of worldviews, the different ways we think about science, and the different languages we use to communicate science. This uncertainty is less about the uncertainty of/in the science, but rather it *creates* further uncertainty in what and how we communicate when we are unclear about another's perspectives of that science. Such communication uncertainty can occur when there is a mismatch of terminology, classifications, or standards between disciplines (e.g., considering 'up' to be either a negative or a positive Z axis between physics and engineering, or whether hazard calculations already include likelihoods between landslide scientists and disaster researchers). Similarly, when trying to combine multiple scientific assessments, or the outputs of multiple natural hazard models, communication uncertainty can arise due to a lack of clarity or transparency of the individual assumptions within each [3,10,74,128–130]. Different perspectives of the philosophical assumptions underlying a scientific study can thus also create communication uncertainty if people are unaware of their differing opinions, particularly for debates on objectivity

and subjectivity in science and risk assessments ([131–134], chap. 4; [135]), which thus presents a particular challenge when sharing findings across disciplines.

This communication uncertainty, and the lack of knowledge about what another person views or thinks, could also be considered a form of cognitive uncertainty⁶ [136,137], which has commonly been associated with theories about initial interactions [138]. Berger [139], through their uncertainty reduction theory, theorise that during initial interactions individuals assess and have uncertainty about the anticipated behaviour and cognition of others. Individuals thus aim to reduce this uncertainty by seeking further information through explicit communication actions. This theory has been extended by Kramer [138] for organisational and group settings into the ‘motivation to reduce uncertainty’ model (MRU) which highlights that individuals have different levels of motivation for reducing uncertainty about others, and thus the degree of communication behaviour depends upon factors such as their own levels of tolerance for uncertainty, the social or effort cost involved in that communication, or whether they create mental shortcuts such as stereotyping and using classification systems, etc.

Thus, while we might consider the ‘communication uncertainty’ previously to be a negative characteristic, the information seeking behaviour borne about by an associated ‘cognitive uncertainty’, as described above, could be an associated positive characteristic. This thus raises a set of future research questions: does an individual who acknowledges others have different ways of thinking about natural hazards science (including worldviews, philosophies, and views on appropriate study design) experience a higher level of cognitive uncertainty and thus a drive to seek clarification of others’ views? If so, does this improve communication? In contrast, do individuals who have a more singular view of this science (section 3.3), and lower awareness or acceptance of the existence of alternative interpretations and perspectives, experience lower levels of cognitive uncertainty? If so, does this result in less information seeking behaviour to clarify issues, and poorer communication practice?

We thus suggest future research should explore relationships between an individual’s degree of cognitive uncertainty and the different ways scientific uncertainty is communicated for several natural hazard scenarios. This should consider participants with different philosophical models of science. This could also explore their levels of motivation to reduce any uncertainty, and their potential communication behaviours. Insights may provide lessons for more effective communication within, and from, multi-disciplinary advisory groups (as found for Science Advisory Groups (SAGs), such as the NZ Volcanic and Aotearoa Earthquake Science Advisory Panels⁷) and across community groups with different levels of trust in science, and the scientific process.

If we have a deeper understanding of how an individuals’ tolerance of uncertainty relates to their mental models of science, science advice communication can be tailored to support their uncertainty reduction behaviour (after e.g., Ref. [140]). Recent research has shown that *intolerance* of uncertainty does not link strongly to conspiracy theory beliefs [141], suggesting that future research could explore the levels of uncertainty that can be effectively communicated to those who may have anti-science, anti-authority, or conspiracy theory views. Matt et al. [142] also found that tolerance of uncertainty was negatively associated with concern for COVID-19, and suggested that communications and interventions should focus on encouraging people to become more concerned such that they take actions. We note this is similar to the motivational anxiety associated with earthquake aftershock forecasts and discussed in Doyle et al. [143] and Becker et al [144], but also note that, as discussed therein, that too much anxiety can become de-motivational.

Our research and the literature indicates that this cognitive, and thus communication, uncertainty can arise due to several factors, as follows: 1) The ways in which experience with science impacts articulation of scientific concepts and the language available to understand and conceptualise science; 2) How time pressures, discipline, and culture can influence participant understanding of process, particularly with regards to what they consider credible evidence for a hypothesis, what drives science, and what evolution of knowledge or science means; and 3) Whether individuals view science as an endeavour belonging to individuals, as a body of knowledge and practice, or as part of a community of science, and how that influences their judgments and understanding of findings and advice. We next discuss each of these in turn, followed by a summary of lessons for effective communication.

4.1. Having a structured language for articulation

When asked to describe what the scientific method meant to them, all participants described a broadly similar empirical method, with the main difference being that the Lay Public group felt they could not initially answer the question, possibly due to a lack of confidence, experience, language, and lack of regular use of science (section 3.1.1). All participants highlighted how the scientific method, and any associated scientific training and experience, provided a structured way to move from a question to a discovery, creating an ordered process in an environment of uncertainty. Such training also provides a language to articulate observations, scientific ideas, and understanding of uncertainty; but the way of describing and thinking about uncertainty may vary depending on the type of training (see also [23]). Interestingly, the current participants indicated that people *should* have these different ways of thinking to broaden their own, and society’s, scientific research and understanding of science (Section 3.1.2).

We interpret from this that having a range of science experiences offers advantages as they provide a wider language to articulate complex problems as well as providing more structural approaches to choose from when exploring scientific questions. The additional ways of viewing a problem can help shift a block or impasse to solve them, and thus potentially provide a tool to address uncertainty

⁶ We note this cognitive uncertainty relates to uncertainty about beliefs and attitudes of others and is not the same as the cognitive uncertainty used to describe uncertainty in decision-making and as found in the field of economics.

⁷ Within many SAG processes, differences in understanding the scientific issue can arise due to the disciplinary, and thus epistemological and ontological, differences of the members of the group. However, such multi-disciplinary membership is vital to ensure a breadth of expertise can be drawn upon to provide appropriate advice [62].

[145–148]. We also note that, as discussed in section 3.1.1, many participants' high-level descriptions of the scientific process broadly aligned with a hypothetico-deductive method (see e.g., Ref. [126]). While the narrowness of their description may have arisen due to limitations on the scope of the interview questions, it may also reflect the core understanding they developed through their schooling, even if they have had further scientific training since. This supports the more modern school curricula that includes exposure to multiple scientific methods of inquiry.⁸ This in turn may increase understanding of different worldviews and approaches to science and enhance communication *about* natural hazard science – particularly if knowledge of those differences increases a beneficial form of communication uncertainty (section 4), encouraging information seeking and clarification behaviours, both hallmarks of effective two-way communication (see review in Ref. [26]; see also [149,150]).

Multi- and trans-disciplinary science collaborations are vital when working to address natural hazard risk, particularly as participatory science and community approaches to risk assessment and management have been identified as most appropriate, ethical, and likely to have success [1,3,151–155]. However, while these different ways of articulating and structuring natural hazards science provides a distinct advantage by allowing multiple ways of approaching a problem, they can also present conditions for a detrimental form of communication uncertainty if individuals are not clear about the language and method they are using. This can damage trust and relationships, particularly when communicating with scientists from other disciplines, which is an inherent part of managing natural hazard risk. In addition, while some of the Lay Public understand structured methods of scientific enquiry, they may not have the formal protocols to undertake them or the language to articulate them (section 3.2, see also Doyle et al. [23]). Thus, they may articulate concepts differently to those trained in science. However, that does not mean they do not understand those concepts. Thus, much like recommended calls to move beyond the 'knowledge deficit model' for natural hazard risk and science communication (see review in Ref. [26]), communication from science agencies could be improved by first recognising an audience's prior understanding, and second including a clarification of terminology and language to support an audience's mental articulation of the scientific concepts and findings (see also [23]).

4.2. Time pressures, discipline, culture

Across our interviews, participants also shared perspectives around what they perceived as influences on the scientific process, their understanding of the process of natural hazards science, and their understanding of the development of knowledge. This included how time pressures on the science, particularly during natural hazard crises, and the scientific discipline and culture associated with that science, influence their understanding of the scientific method being used (section 3.1). This was further influenced by their own scientific experience and training, including how they judged that science and its findings or advice. This framed what they understood as constituting 'proof' or evidence (section 3.2), what drives science, and how the evolution of knowledge or science occurs.

Participants highlighted how science has its own culture of practice (section 3.1.4), including its culture of peer review, ethical and moral principles, with some variety between disciplines. However, they saw this culture of practice as distinct from other cultural knowledge and worldviews and highlighted the importance of having such different ways of viewing and knowing things to advance scientific enquiry (section 3.1.2). They also acknowledged how society's priorities influenced science, including what science and society were curious about, what government set as priorities, what was funded, and what was 'needed' (Section 3.1.1; [22]). Participants thus discussed how the impacts of a recent natural hazard event might lead to an over-prioritisation of some science topics, at the detriment of others equally important. This can thus create a knowledge uncertainty [22].

Most participants acknowledged that bias exists in research findings due to the different cultures of practice, and the priorities and judgments made within them (section 3.1.2), for example questioning whether a study could ever be fully objective (section 3.1.3). Through this discussion, participants shared their intuitive understanding of epistemological and ontological differences between individuals, even if they did not formally describe these concepts with that language. They demonstrated an understanding of how different disciplines and cultures might explore different questions due to their understanding of what exists to be investigated (ontology), and their understanding of how we can answer our questions and what is possible to be answered (epistemology) (see Sections 1 & 2). Several participants discussed how whether there was one reality or real world to be measured would vary upon different cultural understandings, as it would be perceived differently by different people. They focused on the diverse perspectives people have about the world, discussing lived experiences, inclusive approaches, and variations in what is considered knowledge, what is 'enough' knowledge, and how knowledge evolves (sections 3.1.2 & 3.3). Even though most participants thought *themselves* there was only one reality, they still thought that what is reality would be perceived differently by different people, and thus had an inclusive approach to understanding what reality is.

However, for some participants their personal understanding of these concepts limited what they would identify and define as 'proof', particularly for natural hazards contexts where events can be one-off, unique, data scarce, and hard to replicate in lab settings (Section 3.2). This may then impact their trust in communication and collaboration with others. The Lay Public group discussed the need for proof the most, and both the Lay Public and Science Literate group discussed needing this proof to support science advice (Section 3.2). However, several Scientists also discussed how proof builds knowledge and science more generally, contributing to the wider science endeavour. Interestingly many of these discussions around 'proof' seemed to misunderstand that science can "provide falsification, but not 'proof'" ([50], p. 2). As discussed by Freudenburg et al [50] this perception can impact policy and decision-making on science advice, as individuals equate proof with certainty or what is known, and may then finalise decisions due to an 'absence of

⁸ See e.g., the 'Investigating in science' strand of the NZ Curriculum (<https://www.sciencelearn.org.nz/resources/418-the-investigating-in-science-strand>, last accessed 2/4/2025).

proof (p. 4). Thus, when decisions are being made in the wider environment of uncertain and data-poor natural hazards science, perceptions that there is a lack of proof in science advice may be interpreted as a further lack of scientific certainty and used to justify action or inaction. Further research is also needed to understand the implication this may have for the communication of expert elicitation processes, which are often conducted when model assessments and primary data are limited or unavailable [131–133].

Reflecting on the challenges for science communication, while most participants appeared to be comfortable with changing science, their view of how and why it changes are different. This in turn can create potential miscommunications, communication uncertainty, and can harm collaboration, due to the mismatch in expectations of why natural hazards science advice might change and the reasons for associated uncertainty in scientific findings. To address this, it becomes important to be transparent not just about assumptions made in the scientific process but also about the *process and causes of any changes* in science advice. In particular, participants thought that it is the *evolution and dissemination* of research that creates the debate and evaluation necessary for new ideas to be developed and for more research to be conducted (section 3.1.4). As stated by the Scientist Beta “*The more we disagree, the more arguments we’re going to build, and better justifications we need to find, the better evidence we need to build, and the better evidence, the more information we will have, the more knowledge. And the more knowledge, the more science*” (see Appendix 2, ‘What evidence is there?’ code).

This also raises several future research questions: are participants more accommodating of this evolution of knowledge in lower pressure, scoping, research environments, versus high pressure natural hazard event decision contexts? How does this vary depending upon the amount of overall information they need to assess, from other sources beyond science, and the concept of information overload [156]? How is this further influenced by the high pressures due to time, political, and public demands characteristic of events (see Ref. [62])? How is this further affected by their perception of the political orientation of the scientists, which has previously been shown to impact information seeking behaviour [43]. This is particularly relevant when considered alongside what participants’ consider to be ‘enough’ knowledge discussed above. In addition, do individuals who have a worldview more aligned with objective realism, or who regard there to be a single point of scientific truth, have less ability to accept and accommodate others’ interpretations of different realities, ‘truths’, and appropriate epistemological methods? Research should explore how such perspectives might impact natural hazard science communication, particularly when uncertainty is present, and when time and resources limit the amount of research that can be conducted and evidence that can be collated. Through this lessons should be identified to overcome associated communication challenges for audiences with these different worldviews.

It is also important to understand the cultural context of where this research is conducted. Our study is rooted in the Aotearoa NZ science context, within which there has been considerable effort by Māori, government, and funding organisations over more than 20 years to bring awareness to, and incorporate, Mātauranga Māori⁹ into the practice of science [37,40,157]. In Aotearoa NZ, natural hazard science is commonly seen as sitting within a Western European Science epistemology [39,41]. However, over recent decades the above initiatives have sought to grow a more bicultural approach to science, that recognises the value of both Mātauranga Māori and Western European approaches to science [37,38,158–160]. Thus, the breadth of understanding, acknowledgement, and respect for the different approaches to, and cultures of, natural hazards scientific practice and enquiry that was demonstrated by our participants (see e.g., section 3.1.2) may be a reflection of these past, and current, efforts to integrate Mātauranga Māori not just into scientific practice but across Aotearoa NZ culture generally. We thus suggest future research should explore our research questions in other cultural, and global, contexts. In particular, lessons may be identified for communicating natural hazards science across and with diverse groups that can be applied into other international contexts that also seek to weave indigenous and locally sourced knowledges with dominant, or colonial, science paradigms.

4.3. Perceiving science as an individualistic or collective endeavour

Finally, related to the role of science communication across epistemological and ontological worldviews in the advancement of science, discussed above, several participants had different perspectives on whether science is an individualistic or collective endeavour. This affected their expectations of natural hazards science information and advice. Participants discussed how collaboration across scientists was important as it influenced, shifted, and advanced thinking (Section 3.1.2). In particular, the scientists group saw value in drawing across other knowledge bases, such as ‘citizen’ and local knowledge, to integrate across the different perspectives and develop more holistic and integrated understanding of the world (see García & Mendez-Fajury [161] for an effective example this participatory and community informed approach to volcanic risk communication). Participant discussions thus included recognition of the value of multi- and trans-disciplinary approaches, including when stakeholders are involved in co-created question formulation or scientific studies, how different cultural understandings of the world would require different approaches to be brought together, and how natural hazard science advice may incorporate advice from agencies and organisations beyond the academic university settings.

However, other participants focused their discussions more on the role of individuals, particularly when considering how knowledge evolves (Section 3.3). They raised the concept of innovators, and how they develop knowledge, or how individual scientists’ theories can be seen as an outlier and disregarded, but may be subsequently found to have value. The rarity of natural hazard events may create more opportunities for these innovators to emerge, including through increasing research funding and prioritisation, or alternatively there may be a *perception* that there are more innovators due to the type of media framing after such events. As reviewed by Charney [162], popular reporting of scientific achievements tends to devalue the collective sharing and collaborative work, and focus their framing instead upon a competitive academic race to the “finish line”.

⁹ Mātauranga Māori represents the indigenous Māori knowledge and encompasses traditions and values as well as philosophies, world views, and scientific lines of enquiry.

Considering the discussions of consensus and collectivism (section 3.3), the Lay Public appeared to place more emphasis on consensus to progress knowledge than the Science Literate or Scientist groups. Research in team decision-making has indicated how groups can have both positive and negative behaviours when evaluating and assessing information. On the one hand, a group can provide the diversity of thinking discussed in section 4.2 and provide value to the process by pooling information and knowledge, and stimulating new interpretations with each other [145–148,163,164]. However, such a group can also experience several negative social and cognitive influences (see review in Ref. [165]), including the well-known ‘groupthink’ that may arise in cohesive groups or those with a strong collective goal [166–168]. This is a particular peril for science advisory groups operating during natural hazard scenarios that are asked to provide advice with a strong human impact [62]. Careful facilitation and leadership are thus required to overcome these challenges. We also note that consensus amongst a science advisory group could be erroneously viewed internally, and externally, as correctness due to such issues (see Ref. [108,169]). This can also cloud their views about different solutions or interpretations, and lead to a resistance to incorporating a different view, or to outsiders and their interpretations. Thus, for our participants, their perceptions of the scientific process and their judgments of natural hazards science advice would have been influenced by their assumptions about the efficacy of collaborative science groups and consensus building versus the efficacy of individual scientists’ processes.

In this work we are not endeavouring to judge whether individual or collective science endeavours are more, or less, appropriate. Rather, our research highlights that individuals have prior assumptions about whether such science has been done individually or collectively, and may have biases towards one approach or the other, with different levels of trust in the associated outcomes and advice (Section 3.2.1). This influences their judgment and use of that science. If an individual is more likely to trust the collective approach to science, for example through multi-disciplinary collaboration, they may disregard advice from a scientist they perceive to be speaking as an individual, about an opinion or novel information. They may also disregard advice from someone they perceive is too passionate to be open to other interpretations, or due to a distrust of their reputation. In turn, others may disregard advice from a group of scientists, due to their perception of the presence of the team challenges discussed above, or believe the group lacks incorporation of other perspectives (see Ref. [42,108,169]). This may cause individuals to discount the science advice and rely on prior knowledge. Osaka & Bellamy [93] found that when faced with divergent science advice on the relationship between drought and climate change, lay people reverted to their prior beliefs to manage this uncertainty, doubting the science and the scientists, and reinforcing their existing views. To interpret unfamiliar science, individuals may also incorporate tacit knowledge, such as their intuitive feel of ‘how the weather should normally be’ [23,92]. In uncertain contexts, such as disagreements amongst scientists, unclear consensus and advisory group mechanisms, and lack of clarity around timeframes of advice, such prior beliefs, tacit knowledge, or knowledge about other contextual factors can thus be superimposed onto, or influence interpretation of, official information (see also [84]). Disagreements, or incivility between scientists, has also been demonstrated to increase the mistrust of scientists and scientific methods [170].

For communication practice, this further highlights the need to communicate not just the natural hazards science and science advice, but also the process with which the science has been created, particularly how decisions are made, and disagreements resolved or acknowledged, when multiple scientists are involved ([170]; see reviews in Ref. [8,62]). We add to this that further research is needed to understand how to effectively communicate when additional scientists or others comment externally to a SAG process, whether they are credible or whether they are perceived as ‘maverick’ [171–173]. In rapidly evolving, highly uncertain, natural hazard events it is still unclear how best to consider, address, or correct these views in official SAG or agency communications, however recent research has highlighted the value of ‘weight-of-evidence’ statements to convey scientific consensus and overcome the false-balance reporting of isolated contrarian messages [173].

This raises a future research question: if individuals have very different views of science, being either an individualistic endeavour, a body of knowledge and practice, or a collective endeavour as part of the science society, how do we communicate advice from SAGs in a manner that most effectively integrates with these diverse views? How do we communicate consensus and dissensus to such a variety of perspectives? (see also [10,108,169]). Similarly, how does an individual’s trust in, and use of, natural hazards science differ depending on whether it was produced in a transdisciplinary way, or not? Secondly, how do we effectively communicate *within* such advisory groups when there are different epistemological and ontological assumptions and worldviews present within them? How do we identify how much variety in group assumptions, values, and uncertainty should be communicated externally for it to strengthen trust in the information and its source? This is particularly important as it relates to the management and communication of uncertainty around disciplinary and methodological bias, of which individuals will have numerous prior assumptions [22].

4.4. Limitations

Numerous future research questions have been raised by the findings we present here, as discussed above. The number of questions arises through a limitation of this study, in that it represents only one part of a multi-part interview and represents the exploratory phase of the study that sought to explore how participants thought natural hazards science is produced. Our findings demonstrate that there are indeed several lines of enquiry that warrant further investigation, such that we can understand how an individual’s philosophy or model of science is influencing how they interpret, respond to, and use science advice from individuals, organisations, and advisory groups. Thus, future research should seek to explore the themes raised here in greater depth than was possible in this study.

As outlined in the studies of the other components of this interview study assumptions [22,23], several other limitations exist, including: a) the Covid-19 restrictions at the time of interviews that limited our ability to explore these topics through broader public interviewing and engagement, while also likely limiting the full breadth of participants who chose to respond to the interview advertisements, b) that lessons may have been learnt through a deeper consideration in the interview of participants’ prior experience

with scientific agencies, and c) the need to consider how these findings might be reflected in other cultural and geographical contexts. In addition, while the qualitative methodology enables a deep exploration of ideas, nuance, and meaning, the inherent and associated small numbers of participants mean our findings can not be generalised beyond these participants. We thus suggest a mixed method approach, combining this deep exploration of understanding and a broader quantitative exploration of the questions raised herein, may provide important lessons for effective communication more broadly.

5. Conclusions

While much research has explored hazard, risk, and science understanding and perceptions, little research has explored how individuals understand the scientific process itself. This process shapes the science undertaken within the many disciplines, from geology to hydrology and economics to social science, that each inform the natural hazards science advice they receive, interpret, and use. Thus, it is important to explore people's scientific 'worldviews', and how they understand scientific processes. This enables more appropriate science advice communication, which is vital as effective risk management depends upon individuals correctly interpreting and acting upon related advice, whether for themselves or for their organisational role.

In this research we: a) explored how diverse stakeholders understand how science used to manage natural hazards is produced and the operation of the scientific endeavour, and b) investigated how this understanding of the scientific process relates to their ontological, epistemological, and philosophical views of science. Our findings highlight broad agreement in the high-level fundamental steps of the scientific process, aligning mostly with a hypothetico-deductive process. However, most participants acknowledged that there are multiple ways of thinking and approaching science, and that people may have different perspectives on truth and reality, informed by their experiences, training, culture, and philosophy. Participants identified different disciplinary choices and biases as shaping the scientific processes, as well as recognising that science itself has its own culture of practice. This creates an interesting communication challenge: how to effectively communicate science insights from the many disciplines collaboratively involved in natural hazards research, given audiences expect each to have their own cultural practices, standards, and biases. Participants also acknowledged that science has limitations, and that levels of trust in the science, its processes and rigour, and the scientists themselves, helps them either manage and accommodate those limitations, or discount the science. Finally, across our cohort, participants recognised the evolution of scientific knowledge over time. However, while some were accepting of this evolution and saw it as integral to the process of science, others viewed that evolution critically, seeing changes in scientific advice as a negative.

From these findings we discuss the concept of 'communication uncertainty'. This arises when individuals recognise that others may have different perspectives on the philosophy of science and what constitutes appropriate scientific process, but might not know what those others' perspectives are. While this might seem too nuanced an understanding to be necessary for a simple natural hazards science communication, in more complex crisis environments when uncertainty is high, the information is complex and evolving, and pressures exist, such differences or a lack of mutual understanding of each other's scientific beliefs can result in an ineffective communication.

This communication uncertainty can also arise due to differences in language used to articulate the natural hazards science, the influence of time or disciplinary and cultural perspectives, and individual beliefs such as whether science is conducted individualistically or collectively and what that means for advice, such as that from advisory group mechanisms (such as the Volcanic or Earthquake Science Advisory Panels). We suggest that future research should experimentally explore how an individual's philosophy of science might affect their awareness, and acknowledgement, of others' perspectives on science; and whether that awareness does indeed create communication uncertainty, and create any associated cognitive uncertainty, and what that means for information seeking behaviour. If tested, this could provide greater understanding of how to effectively communicate between individuals with different scientific worldviews, particularly during high pressure natural hazard crisis scenarios. Understanding such differences is essential for effective communication.

We conclude by highlighting three key lessons for the practice of natural hazards science communication: 1) be transparent about the processes and causes of change in science advice, to support people's understanding of the evolution of that science and facilitate trust; 2) communicate both as trusted individuals as well as through SAG systems, given participants have varied trust in individualistic and collectivistic science, while also being transparent about how consensus opinions and advice are formed; and 3) provide an accessible structure and language to help lay people articulate the natural hazard scientific processes they often already understand, as apparent confusion may be due to a lack of technical language rather than a lack of understanding. We thus encourage adopting a principle where one moves away from a top down 'simplifying' approach to communicating natural hazards science, and towards an approach where one communicates science as if to peers of a different language and recognises the knowledge they hold, seeking to support them in understanding the science rather than 'telling' them the science. We encourage further research to explore the efficacy of these different approaches through experiments that explore the attitudes towards, and decision-making efficacy upon, science advice communication crafted in each way.

CRedit authorship contribution statement

Emma E. H. Doyle: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jessica Thompson:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Stephen R. Hill:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Matt Williams:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Douglas Paton:** Writing – original draft,

Methodology, Conceptualization. **Sara E. Harrison:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Ann Bostrom:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Julia S. Becker:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Emma E H Doyle reports financial support was provided by the National Science Challenges: Resilience to Nature's Challenges Kia manawaroa – Ngā Ākina o Te Ao Tūroa 2019–2024. If there are other authors, they 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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We dedicate this article in memoriam to Distinguished Professor David Johnston, who suddenly passed away on January 19, 2025 walking his beloved Te Araroa trail. David was the Director, and founder, of the Joint Centre for Disaster Research (JCDR) within the School of Psychology in Massey University's College of Humanities and Social Sciences. His vision and passion for a multi-disciplinary approach to disaster risk reduction, and to serving communities to build our collective resilience for the future, was an inspiration to all of us fortunate to work with him. He will be greatly missed, as we carry his vision forward. Further tributes can be found at <https://www.massey.ac.nz/about/news/colleagues-pay-tribute-to-distinguished-professor-david-johnston/>

We also dedicate this article to the memory of our dear co-author Professor Douglas Paton who sadly passed away during this research, on April 24, 2023. He will be missed by many, and we are forever grateful for the invaluable insights and laughter Douglas shared with us as a friend and colleague. Tributes can be shared at <https://www.forevermissed.com/profdouglas-paton/about>.

Appendix 1. – Interview protocol

Included below is an abridged version of the full interview protocol. General prompts not shown here were also used to follow up on topics raised by participants to elicit richer interview responses.

After an initial introduction and discussion to ensure participant is comfortable with the project (project description, ethics, consent, demographic questions), proceed to icebreaker questions:

Background / Warm up

- Tell me about your name
- Before we start, can you explain to me what your occupation and role is?
- (if appropriate) Can you briefly explain your level of experience in formal science training? E.g. school / post grad / practicing scientist.
- (if not a scientist) If you use scientific information in your job, how often do you use it?
 - What do you use?
 - Where, or who, from?
 - How do you use (or apply) it?

Part 1: Initial free response questions

Throughout this interview we will be focusing on natural hazards science. Natural hazard science is the science about hazards like volcanoes, severe weather, tsunamis, landslides, and earthquakes, and is used to prepare for and respond to disasters that could arise. So, please keep this context in mind when responding to the following questions.

Results reported in Doyle et al (2023, 2024)

- (If needs be remind them: Please also remember there are no right or wrong answers to my questions, and I am interested in your own perspectives)

- In your own words, can you talk to me about how scientists develop the science used for informing their advice about hazards?
- In your own words, can you tell me what “uncertainty” means to you?
- In your own words, can you talk to me about uncertainty associated with scientific advice?

Results reported in Doyle et al (2023, 2024)

Part 2: Mental mapping activity (direct elicitation)

First, I would like you to consider the question

- Thinking about natural hazards science, where do you think uncertainty comes from?

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(continued)

Please brainstorm ideas, phrases, and terms, that come to mind when you think of that question, writing them on the (virtual) post it notes. I have started some with what we discussed previously.

o What might increase or decrease uncertainty associated with science advice about hazards

Thank you for brainstorming all those items. Now we have this pile of items on post-it notes, we are going to conduct a mapping task.

- Can you please arrange these groups into clusters?
- Can you explain these clusters? Why have you grouped these items like this?
- How are these clusters related? Can you draw on different relationships?
- Please explain why for each decision...

Please talk aloud / explain as you go.

That is this activity completed for now. Before we proceed to our other interview questions, are there any other elements or relationships you would like to add?

Part 3: Semi-structured interview protocol

Results reported in current paper.

- Is there one real world that scientists are measuring?
- OR: Do you think what we measure reflects a single reality?
- Can scientific questions have more than one correct answer? Please explain.
- How do we confirm a scientific theory?
- What do you think causes shifts in scientific thinking: individually or collectively?
- Can you explain what “the scientific method” means to you?
- Do you think the scientific method is the only way to determine what is true or false about the world?
- What are your thoughts on the statement “Science is just one way of looking at the world”?
- How do you think a scientist’s values and beliefs relate to the science they do?
- Why do you think scientists disagree? What do you see as the reasons/ causes?
- What would you want to know if a scientist was uncertain?
 - o (If they are scientist – frame as other scientists they relate to)

Reflection and wrap up

Results reported in Doyle et al (2023, 2024)

Thank you for all your responses so far. We have entered the final stage of this interview, and I just have a few final questions to ask you.

- Reflecting back on your item map, and thinking about discussion, do you have any further comments on [Figure 1](#)?
- Thank you, we have come to the end of my questions, is there anything else you would like to add or discuss?

Appendix 2. – Themes, codes, and example quotes

Table A2.1

Theme “Science is a way of seeing the world”. Note there is some overlap in codes between sub-themes.

| Sub-theme | Code | Code description | Lay Public | Science Literate | Scientists |
|----------------------|-----------------------------|--|--|---|---|
| A scientific process | What is science | How do we do science, understand science | I guess doing our own research to just gather data about what’s happening and then trying to create patterns and theories as to why those things happen - Kappa | Yeah the proving and the process and like the physical field work research and everything - Omega | There must be overall in the science system a degree to which we lurch towards a more kind of reliable understanding. We must do this. And I suppose the science system is still working in that case - Eta |
| A scientific process | How data is gathered | What data, techniques, methods, technology, models | But anyway, I guess what scientists do, they look back and on the historical facts, and over time, I guess they’ve learned to make instruments through technology and science so that they can monitor a lot of what’s going on around the world - Fearn | I think it would boil down to slightly different ways of measuring and interpreting. And maybe what’s included and what’s not - Sigma | Again it would really depend on what scientific discipline you’re in. I don’t really know a lot about it because I’m not, I haven’t got that kind of training, but I guess it would be a process of having a hypothesis or an idea and trying to set out to do some kind of research, whether it’s going somewhere to gather something or whether it’s getting a dataset, or you know looking through a telescope or anything like that. Trying to crunch |

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Table A2.1 (continued)

| Sub-theme | Code | Code description | Lay Public | Science Literate | Scientists |
|----------------------|-------------------------|--|---|--|--|
| A scientific process | The scientific process | Method, methodology, rigor, inquiry | I think it means following like all scientific research follows the same process of coming up with a hypothesis or question, gathering information to answer that question, analysing the information, and then coming up with conclusions to answer the question or hypothesis - Kappa | So scientific method to me means like an empirical method of going about things, so having a hypothesis, testing a hypothesis, following a methodology so you can exclude or minimise confounding variables and things like that. So having a method than rather just an idea that you just throw out there and hope that people agree with without foundation - Phi | information into something that's meaningful and [that/it] will either prove or disprove the hypothesis - Nu So I guess I said that at the beginning, which was more that the scientific method is you have some evidence or you have, you may not have any evidence, you may go straight to an idea. You design an experiment to test that idea, hypothesis, you collect your data or your, some information somehow to help you, it might be a survey or whatever, to help test that idea or explore that particular idea to see whether it's got merit or not. You analyse that in some way and then you document that in some way that can be peer reviewed and assessed by other people. Other scientists. So that's the broad sort of general method that I would expect science to flow, to take - Upsilon |
| A scientific process | Science is empirical | Objective, positivist, rigid, western, credible | Because at the end of the day, the result, even the results, the results aren't even, shouldn't even be considered second. They shouldn't be considered the most important part. They shouldn't even be considered like the second most important thing. They should be considered like the third most important thing. The second most important thing of the scientific method is replication, right. So one is like all right get your formula, get your system down, okay you got it down, you can repeat it, but then if somebody else comes in and does that formula the same exact way, you should get the same results, and if you're not, then again the system's broken, fix the system - Delta | So scientific method to me means like an empirical method of going about things, so having a hypothesis, testing a hypothesis, following a methodology so you can exclude or minimise confounding variables and things like that. So having a method than rather just an idea that you just throw out there and hope that people agree with without foundation - Phi | I think that, say 50 years from now, before that scientific thinking was a bit more fluid than it is now. And I think it's become quite entrenched and established, at least in Western science, this kind of method of hypothesis and studies that indicate the accuracy and inaccuracy of that, that's a pretty universal kind of concept or idea of the way science works - Theta |
| A scientific process | How theory is developed | Multiple replications, getting the same results, it's a scientific thing | I guess a lot of experimentation or observation from multiple sources, getting different experts to give their opinions and then coming up with something that fits | This is going back quite a few years now. So in terms of a piece of scientific work and the conclusions that are made from it, it has to go through scientific peer review by independent | P: How do we confirm a scientific theory, ah. I think there's a lot in that word "confirm", because confirming implies that we basically believe it, but we just want to be 100 % sure, and there can be a lot |

(continued on next page)

Table A2.1 (continued)

| Sub-theme | Code | Code description | Lay Public | Science Literate | Scientists |
|---|---|---|---|---|---|
| | | | with most people's understanding, guess - Beith | reviewers. And I guess it gets put out there into the scientific community for, and scientists are very, they're not shy in holding back in terms of if they think something is rubbish they're going to challenge it. But I mean that goes back to that whole thing of making sure that scientific research always identifies the limitations and the assumptions that are made. So if it's a test study, it's like "we used this many people, but maybe we need to expand that". So, yeah, I think it's about, I guess the scientific community itself kind of has those, are the ones that have the checks and balances around scientific methodology and ensuring that no bold conclusions are made from research that needs to be developed more or whatever, yeah. - Iota | invested in that confirming because you've already gone down a particular path already. So sometimes I think do we go looking for disconfirming evidence, things that tell us where the boundaries of what we already suspect are true are actually true? - Eta |
| A scientific process | The benefit of science | When beneficial, when not | By, I guess, [creating? getting?] as much evidence as you can that supports that theory. So there's always going to be evidence that disproves a theory or produces doubt in a theory, and so you want to produce as much evidence as possible - Omega | P: Yes and no. [Laughs] For the most part, yes, but I guess there are some things that are just I guess the way they are. You know, might be difficult to prove using a scientific process - Omi | You see that quite often, you see it in the medical world where they're quite often criticising the way the experiment of who was given what drug and how that was set up and they come up with these results and they're actually not and it's false, there's too much bias in the system. So certainly there's bad science and bad untruthful results, or incorrect results that come out. So science can equally-well produce stuff that isn't the truth at all. - Upsilon |
| There are different ways of thinking | There are different ways of thinking | Different ways, influence of culture, scientists have different ways of thinking, should have different ways, changing thinking | Because I think if you look at the different ... I'm not a scientist [addict/at it?] by any means, but if you look at the people examining the universe, they look at things from a much different, I don't know what you'd call it, out of the box thinking than if you look at like string theory and all those random things, that's a lot different from the physical science that's here and now when they're looking at actual physical science on Earth. I think that those are quite different realms of thinking and realms of | And yet that's the Western approach to it. If you look at the Eastern approach, so if you go to China, they look at things in terms of a system and where the context is an important part of that, whereas we have a rules based society here in the West - Alpha | I feel like science is important, and especially for like understanding what's happening, but I feel like you've got to consider lots of other perspectives - Pi Absolutely. And suddenly it's not all about seismic wave velocities and rock density. It's like there's another way of interpreting and viewing the world that has perhaps been lost too, like certain cultures - Zeta |

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Table A2.1 (continued)

| Sub-theme | Code | Code description | Lay Public | Science Literate | Scientists |
|---|---|---|---|---|---|
| There are different ways of thinking | Different disciplines exploring together | Collegiality, scientists from different disciplines, pooling knowledge, collaborating | science than from each other, yeah - Alif I would say through research. Observation, through learnings, worldwide events, I would think there'd be a lot of sharing of information, perhaps between countries. And I guess, certain people would specialize perhaps in certain areas. And then I would imagine there are societies and things like that, that people in that field would associate with to share scientific information - Coll | Ooh, that's a very good question because I'm not 100 % sure of the answer. From what I understand is that there's a team of academic scientists that do research projects and that research project generally lasts over years, or like can be months or years or X, Y and Z, and then they pool their knowledge, produce papers which then goes to educate non-scientists in those fields. Yes, so like if you wanted to find out natural disasters you might team up with the Geology Department or the Volcanology Department and do it that way. It's how I would, so yeah, that's how I think it happens - Omega | I guess if someone is asking a different research question, or perhaps linking up other I guess disciplines or fields of science. I think there's a real power in people from different disciplines exploring something together in groups, rather than getting a whole lot of people with the same background and expertise working on a problem. I think that comes from that, but again it's also informed by events and things that occur in the natural world and observing those things and factoring them in - Rho |
| There are different ways of thinking | How data is interpreted/evaluated in science | Drawing conclusions | Yeah, and especially when you're gathering data. There's so many ways that data can be interpreted as well, so. Yeah, no, definitely not one way - Lamda | Yeah. So if you're saying okay what is the likelihood of that volcano erupting, you can have an answer that then gets interpreted based upon the person listening to it - Omega | We do sometimes disagree on forecasts as well, it's not just, so we have it in a situation here to. A lot of what it comes down to is interpretation of, for instance, model output or interpreting a situation is, we all have the same ... - Psi |
| There are different ways of thinking | You can get information from so many different sources | The internet, media | Particularly for natural hazards? I think the climate would have something to do with it, and the way that it's changing. And I guess the freedom that people have to write whatever they want on the internet can also have an impact on that sort of thing. So you can kind of get information from so many different sources that it can create more variation than there actually is, and what's actually being studied - Kappa | And then I think that's created the uncertainty around was the lockdown the right thing, is Covid a bad thing, is it not, is it allowed? And then if you get that view from the media and then you start going Googling down a thing, you will always find what you want - Mu | Yes, and it's still surprisingly open, and actually getting increasingly more open because of the internet - Eta |
| There are different ways of thinking | Truth and understanding | True or false, more than 1 truth, more than 1 way to understand the world | It's tricky, because I think a lot of people think that science is what's true in the world, but it's more just what we observe or know right now. And I think that there, personally, I think there should be a lot more room for intuition and definitely for more, like native knowledge - Beith | For me true or false means what their observation, what their experience actually is to be honest. I've sat in enough times to hear "these flood maps are false", and I was like no that's your observation of the maps, and this is your view of the world. For me, they probably represent a greater level of trueness because you | So like on one hand, we want to disagree with each other, because science is about the truth, and you don't get to the truth by saying "let's all agree with each other about objective reality." But it's objective reality so, one interpretation will be closer to the truth, and we're going to, the discussion is really like a series of agreements and |

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Table A2.1 (continued)

| Sub-theme | Code | Code description | Lay Public | Science Literate | Scientists |
|--|---|---|--|--|---|
| | | | | [haven't?] experienced that event. So for me true and false [is/if] someone is very much driven by what has been their life experience and observation of the [?] - Mu | disagreements about various aspects of that - Zeta |
| Disciplinary Choices and Biases; There are different ways of thinking | Is there one reality? | One real world, what is reality | Um, yes. I feel like we're getting a little bit more holistic about things like that and taking into account a little bit more of the cultural and social aspects towards those things as well - Kappa | Yeah, I just think there is, I don't think it's absolute, but I think that, yeah, I think there is one kind of reality but that reality is dictated, not dictated but it is influenced somewhat by the decisions and choices that are made by scientists in this context - Iota | No, not at all. No. Yeah, and I think I said I don't necessarily believe that everything we can measure with an instrument or with our eyes or with a computer is everything that goes on in the world. People have different ways of relating to reality that are completely different to how I might see the world, how you might see the world. And science has come from a very distinctive place - Nu |
| Disciplinary Choices and Biases; There are different ways of thinking | How do we understand the world? | How do we science, understand or see the world | It's tricky, because I think a lot of people think that science is what's true in the world, but it's more just what we observe or know right now. And I think that there, personally, I think there should be a lot more room for intuition and definitely for more, like native knowledge. And the things that, you know, they say, well, animals can navigate the globe with magnets, but we can't do that. Well, maybe we can, but we just don't, I don't know. I think there is a lot of innate understanding of the world that we have lost, because science is what's right. And the maybe that's just a cultural thing, because I'm sure in a lot of different cultures, they don't believe that - Beith | No, because even within that scientific process, that scientific process was taught to me by one person who has one world view, which is a European world view, but, um ... I think humans are naturally are scientists and through different cultures we've developed different ways of answering questions. We are probably one of the only species that is endlessly questioning things and endlessly wanting to change things, whereas your average ant or elephant is quite happy to plod about their day - Chi | I think there are some things that we cannot deny that is originating from the observations of the people from single concept, for example, if right now it begins raining, so no one can say no it's not raining, so it's raining. But in terms of the way that the people try to find answers for these phenomena, these concepts, so there would be amongst that the different answers and different points of view comes into play, so it is exactly there that we can see so many difference - Gamma |
| Science has its own culture | Rigour of scientific publication is really important | Publishing, peer review, journals, debate, disagreeing, evaluate research | I personally have a lot of trust in science, so I believe that they're always doing the best for what they're passionate about, so I always feel like they're looking for enough information and then doing the right thing in order to get the right conclusions, I guess. So I, yeah, if something is proven and peer reviewed in a journal then I kind of feel as though it's trusted advice - Kappa | This is going back quite a few years now. So in terms of a piece of scientific work and the conclusions that are made from it, it has to go through scientific peer review by independent reviewers. And I guess it gets put out there into the scientific community for, and scientists are very, they're not shy in holding back in terms of if they think something is rubbish they're going to challenge it. But I mean that goes back to that whole thing of making sure that scientific | The other thing I'd say about it is that science still has a lot of scrutiny and it has a way in which knowledge is made public and is available and can be commented on and can be tested again by others and built on in the world. And the science project, the pursuit of science enables that form of knowledge building to happen because of all of the ways it's supported - through peer review and through open discourse and all of the rest of it - Eta |

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Table A2.1 (continued)

| Sub-theme | Code | Code description | Lay Public | Science Literate | Scientists |
|--|--------------------------------------|--|--|--|---|
| | | | | research always identifies the limitations and the assumptions that are made. So if it's a test study, it's like "we used this many people, but maybe we need to expand that". So, yeah, I think it's about, I guess the scientific community itself kind of has those, are the ones that have the checks and balances around scientific methodology and ensuring that no bold conclusions are made from research that needs to be developed more or whatever - Iota | |
| Science has its own culture; Disciplinary Choices and Biases | What scientists are passionate about | What influences them, different viewpoints, their interests, passion | Yeah, I mean, I guess everyone's got different motivations. For some it might be to protect human life or to protect the planet. For others, It might be financial, for others it might be status, you know, I'm the person who saved everybody. Yeah. I think every person does everything for their own motivation, right, whether it's science or otherwise, we wouldn't do it if we weren't motivated. I guess the biggest difference would be that that informs the question they're asking - Beith | Well, it influences the choice of what you research. It influences any ability you might have to bias the outcomes. If scientific training is there then you're aware of those things and you're trying to mitigate against them, but I think, first of all the choice of what to investigate is extremely hard to mitigate against because you're not going to be a very happy scientist if you go "oh, I'm not going to research that because I like it, I am going to go and research all the stuff I don't like because that's the stuff that's not getting attention." - Xi | I think some people, trying to keep it to the natural hazards area, they'll be very interested in natural hazards per se, there's just something about it that really interests them. The environmental, it's easy to find people that are really passionate about the environment, it's probably easy to find people who are passionate about human health. So there might be passion for that particular domain, so the specialisation that you're in. I think scientists probably would almost all have a very strong sense of curiosity - how the world works, and wanting to find out more about that and test it. I should think that all scientists are probably pretty keen on learning as well - Upsilon |

Table A2.2

Theme "Science has limitations". Note no sub-themes were found for this theme.

| Code | Code description | Lay Public | Science Literate | Scientists |
|--------------------|---|--|---|--|
| No one is unbiased | Bias in data, personal biases, personal lenses, open mindedness, what influences outcomes | I think scientists probably try to be unbiased and open but I think, I don't think you can help but bring your own thought into it -Alif | Yeah. And I think then within that then you've got your biases. Because I don't think there's anyone on the planet that's completely unbiased. Like that person is mythical - Omega | Yeah, and I think openness to that. Like not just expecting, I mean we see what we expect to see so I think that, and it's hard because we're all biased when anybody does this kind of thing, but just to try and be objective but also open and have the slower brain pattern stuff going on to notice things and take things in - Rho |
| Conservative risk | To reduce criticism or poor outcomes, moving slowly | None. | And when we get into that situation and we have risks of litigation and we have risks of being dragged through the media and we have risks of potential litigation, it is resulting in what I | None. |

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Table A2.2 (continued)

| Code | Code description | Lay Public | Science Literate | Scientists |
|---|---|---|--|---|
| | | | suspect is, we're starting in a conservative baseline, and most scientists' starting point at the moment is in a conservative view, but that's because we are in a world that if you're not, you get rewarded for being conservative, but you get smashed or you get taken to task if you're slightly less conservative or slightly wrong and a consequence results from that - Mu | |
| A funding perspective | What's funded and why, the impacts of what's funded and what's not funded | Well, about, I guess, the type of research they do, or how they go about doing it, because if you've got a lot of money, and you just go for it, and other people are inhibited, so there might be the science might be ... - Fearn | Yeah, I guess there's push and pull strategies so mine was a pull strategy - here's a risk analysis, here's the gaps in the information that we need, on the other side I'm well aware that there are scientists that have pet projects, pet interests, and they secure funding by various means, and some of them pump out probably really decent knowledge and you look at it and you think "mm, okay, so what?" and it's difficult, you don't, it's difficult to join up that knowledge versus people's needs I suppose. So sometimes you get that disconnect. - Alpha | I think they develop it primarily through a kind of intersection of what's going on in the world in that field, so what's going on in New Zealand, and what is fundable through various channels, so it's a kind of a mix of ... And the funding is to a certain extent shaped by what users might need - Eta |
| What evidence is there? | Proof, what evidence is there, need more evidence, need more studies, data, information | Like so they say they did this and this is the outcome they got, let's repeat what they've done and see if we get the same outcome and prove that it's correct or disprove that it was right - Alif | So there's [a lot] of like field work in some elements. And a lot of lab work. And a lot of like, I guess it's just finding the evidence. There's a lot of research going to find the evidence so it's not just the one size fits all. And there's a lot of hypotheses that, because what I believe [is/of?] science it's being disproven is as fair and as truthful as being proven in your hypothesis. Whatever your outcome is the right outcome, do you know what I mean? Because you use the evidence to come up with that so everything is right, [xx?] even if it's wrong to your hypothesis it's all right - Omega | Yes, for me. My conception and how I understand science. The more we disagree, the more arguments we're going to build, and better justifications we need to find, the better evidence we need to build, and the better evidence, the more information we will have, the more knowledge. And the more knowledge, the more science - Beta |
| I didn't understand what you were saying | What science is communicated, it is effective communication, can people understand it? | Um no, just Stuff or the Herald. Yeah, they might have links to some articles. And I have to admit that I'll start reading them. And then I'm like, it's over my head. So go back to the Herald or the Stuff article to read it. Yeah. - Nion | So I think if you have a scientist that has the ability to self-reflect that way, then I think the correct conversation and the correct penny drop moment, do you know what I mean? Like you know when someone words something in a way that you may have heard a thousand times from different people but that person just says it in that one way, causes that penny drop moment. I think you also have to be that ability to, 'cos I think some scientists get, especially depends on the field of science, get stuck in the science. - Omega | The way I think that should be done is to work from the perspective of people who are exposed to the hazards, and try to understand what kind of information is going to be most useful to them to mitigate the hazards. Then once you know that, you use that knowledge to create information based on what you know to communicate to these people in the most helpful possible way so that they can, if they need to do anything, they can do that - Theta |
| I have a lot of trust in science | Believe science or not, trust people, credibility | I don't trust the scientist, I trust the scientific community as a whole, to not let lunatics go running free. I trust that the scientific community is pretty strict in maintaining the scientific | Ah. I guess it's not trusting a scientist, it's trusting a body of knowledge which is continually tested and independently researched, and there's rigour to it - Chi | All sorts of things I guess. Their background. Their prior research. Their publication history. What other work that they've done that seems credible to me, if I'm familiar with it. Who |

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Table A2.2 (continued)

| Code | Code description | Lay Public | Science Literate | Scientists |
|------|------------------|--|------------------|---|
| | | process. Like I said, I don't know scientists, I just call it all science. science as a whole. And you're just a representative of science as a whole. And I don't know one science from another, but I put my trust in, I want to be able to put my trust in the scientific process as a whole - Luis | | they work with. Their methods that they've used, how well they've documented them - Upsilon |

Table A2.3

Theme "Knowledge evolves". Note no sub-themes were found for this theme.

| Code | Code description | Lay Public | Science Literate | Scientists |
|---|---|---|---|---|
| How knowledge develops | How knowledge develops or changes, new data or info | Because nothing is absolute, right, so just because you could scientifically do something it doesn't mean you can scientifically do it 100 % of the time. Like the fallacy in public perception of science is that oh science has been proven "wrong" before, and I put that "wrong" in air quotes, right, science has been proven "wrong" before so therefore it's not right, that's not what science is, science isn't there to tell you absolutes, science is there to give you answers to things that weren't there before and your answers are supposed to evolve with new information - Delta | The fact that we continue to develop and publish things that contradict previous things and learn and develop, I mean often you'll never be absolutely certain that something is finalised other than something that you can absolutely indisputably prove - Xi | I guess probably mostly comes back to some new data or some new, someone's had a new idea which they've tested which changes things - Upsilon |
| Those innovators who advance knowledge | Those who advance science or knowledge | Yeah. that's also a tricky one, because then you have people who've come up with scientific theories in the past, and they've been the odd one out, and then it turns out down the line, they were actually right - Beith | New data, and just keep doing experiments or different types of experiments. Sometimes you might have people that come along that have completely different ways of thinking about things, and just throw a curve-ball in there or something like that. - Omi | Yeah, what causes shifting in scientific thinking? Scientific revolutions. I guess I think of this in terms of change theory, and I suppose you always have innovators and those innovators might be in methodology, the way of developing knowledge or information, or they may be in simply applying the existing ways of studying in a new way. And those people are quite important, or those experiences of innovation are quite important. But it's then the people that follow next that is the really important one. Because if it's just one crazy outlier in a shed somewhere who has come up with an idea, that doesn't really change the world. It's the next level where people actually able to early adopt these new ideas and start pushing them again, even further. We need those kinds of, we need in our science both of those - the freedom to be innovative but also the capacity to follow that innovation - Eta |
| Knowledge changes over time | Over time, context | Because historically, when we think we're right, we find out 50 years down the line that we weren't - Beith | Well science in itself is trying to acquire new knowledge, so any time you've done any research, you've acquired new knowledge that will a) could confirm what you already know, or b) change it. But there's no one set end point, it's evolving - Chi | Within the environment of the time. Yeah. Or they are, like I think about science is, what we know from science is the most likely knowledge given the data, given what we understand of the constraints and the context at the time - Zeta |

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Table A2.3 (continued)

| Code | Code description | Lay Public | Science Literate | Scientists |
|---|---|--|---|---|
| What is knowledge | What is knowledge, how do we understand what knowledge is, knowledge is different to different people | Information should be celebrated, not shunned. Things that, studies that disprove a widely held belief or widely held fact shouldn't be disproven because it contradicts it, it should be tested and celebrated as like an advance of our understanding of the world - Delta | Yes, yes. We've always had these philosophical discussions about knowing what you know and knowing what you don't know, and not knowing what you don't know. [Laughter] - Sigma | We have to know. We must discover. It's a drive to discover and to know. I'd say that's a big part of it, and that's probably common to everyone who does research, probably wants to know something - Zeta |
| Is there a consensus of knowledge? | Is there one, one has been reached | It would be surprising If you had a group of scientists who were looking at the same data at the same information, you could expect that come to the same conclusion - Coll | I think when you have all scientists in the world working on different things and they all come up with very similar stuff, then you generally can kind of say that you're on somewhat of a right path - Iota | And I think that's the same with science, is that you need a degree of critical mass - Eta |
| We don't know everything | What we know now, don't have a definitive answer, need more info, is this helpful | the problem is, you know, you can't know everything - Luis | And the other is just limitations of understanding. And that's just natural that's going to exist - Mu | Within the environment of the time. Yeah. Or they are, like I think about science is, what we know from science is the most likely knowledge given the data, given what we understand of the constraints and the context at the time - Zeta |

Data availability

The data that has been used is confidential.

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