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Eliciting mental models of science and risk for disaster communication: A scoping review of methodologies

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A B S T R A C T

We present a scoping review of methods used to elicit individuals' mental models of science or risk. Developing a shared understanding of the science related to risk is crucial for diverse individuals to collaboratively manage disaster consequences. Mental models, or people's psychological representation of how the 'world works', present a valuable tool to achieve this. Potential applications range from developing effective risk communication for use in short-warning situations to community co-development of future communication protocols for the co-management of risk. A diverse range of tools, in diverse fields, have thus been developed to elicit these mental models.

Forty-four articles were selected via inclusion criteria from 561 found through a systematic search. We identified a wide range of direct and indirect elicitation techniques (concept, cognitive, flow, information world, knowledge, mind, and fuzzy cognitive maps, and decision influence diagrams) and interview-based techniques. Many used multiple elicitation techniques such as free-drawing, interviews, free-listing, sorting tasks, attitudinal surveys, photograph elicitation, metaphor analysis, and mapping software. We identify several challenges when designing elicitation methods, including researcher influence, the importance of external visualization, a lack of evaluation, the role of 'experts', and ethical considerations due to the influence of the process itself. We present a preliminary typology for elicitation and analysis and suggest future research should explore methods to assess the evolution of mental models to understand how conceptualisations change through time, experience, or public education programs. These lessons have the potential to benefit both science and disaster risk communication activities, given best practice calls for mutually constructed understanding.

1. Introduction

Recent natural hazard events, such as the Whakaari White Island eruption (2019) [1] and Canterbury earthquake sequence (2010-) [2] in Aotearoa New Zealand, as well as the continuously evolving Covid-19 public health and climate crises, demonstrate the vital importance of effectively communicating science advice to enable and support appropriate individual and organisational decision making. An understanding of science, and risk, plays critical roles in decision making throughout all phases of disasters and emergencies. This includes interpreting scientific analysis of rapidly evolving novel hazards during a high-pressure response (e.g., as during Covid-19) [3,4] through to understanding the science represented within longer term risk assessments required for longer-term recovery decision making (e.g., demarcation of 'red zone' properties in Christchurch due to future liquefaction risk following the

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Canterbury earthquakes [5]).

The management of disasters involves all sectors of society, from individuals and households through to local, regional, national, and international agencies, as well as all appropriate disciplinary sectors for that crisis, such as emergency managers, planners, engineers, scientists, public health, and the public(s). Thus, how the science of disasters is accessed, interpreted and used by diverse stakeholders, each operating within their own world views and understanding of science knowledge and processes, is important.

These varying perceptions of how science of the natural world works can result in significant variations in how people interpret new information about hazards, such as warnings. This variability cannot simply be managed by sharing *more* information, which could overwhelm individuals [6]. In addition, communication problems can arise if a message appears to contradict, or fails to address, people's existing perceptions of science itself, a common problem given the complexity of response environments and diversity of information sources [e.g. Refs. [7–10]]. Thus, it becomes important to both understand people's perceptions of science, the scientific process, and the essential (and unavoidable) role that uncertainty plays within science and science communication, such that they can be taken into account in messaging.

These prior perceptions of science advice and risk phenomena can be encapsulated by people's *mental models* of how they think the world works [11–15]. They can encompass an individual's understanding of physical systems, how we produce knowledge, as well as cultural, philosophical, socio-political, educational, and organisational influences on understanding [see also [11,14,15]]. Such mental models are a set of simplified causal beliefs and epistemic values people use to interpret events. They can thus underpin the epistemic differences that exist between disciplines and organisations [8,16], and the various influences upon them also add to the communication challenge.

People may thus reference their 'science model' [17] to interpret a communication (including assumptions about underlying hypotheses, subjectivity, etc.), which then affects how credible they perceive the science (or the scientists) as being. Previous research has qualitatively explored the mental models that people hold about hazardous processes and other phenomena (e.g., climate change [18], lunar eclipse [19]), to enhance science education [12,20–22], and to understand hypothesis formation [23,24]. Comparisons of expert and lay mental models of phenomena [15,18,25,26] have also been used to inform and enhance risk and hazard communication (e.g., hurricane forecasts, Morss et al., [26]; Bostrom et al. [27]).

Thus, mental models provide an invaluable tool to help us begin understanding the differing perspectives within a risk domain. Mental models have potential to be used not just to enhance science and risk communication of hazards, but also to enhance our public education campaigns. They can also be used to advance shared understanding during participatory co-development of a risk assessment and mitigation plan with communities and individuals [28–33]. While much research has considered the application of this method for understanding natural hazards *phenomena* to advance risk communication [e.g. Refs. [25,27,34]], there is now a need to identify appropriate methods to elicit the mental models that describe perspectives of *science*. This is particularly important if we are to enhance our communications of scientific uncertainty in a manner that accounts for different world views and philosophies [see Refs. [8,35]].

A wide array of approaches have been developed to elicit mental models [see e. g, Refs. [34,36,37]], ranging from the fields of science education, to risk communication, and technology and team training, with a recent Web of Science search returning >6000 papers that refer to mental models. Data collection methods and techniques for eliciting mental models also vary widely within these approaches, ranging from free-drawing [e.g. Frerichs et al. [38]] to interviews [e.g. Cobern et al. [39]] and card-sorting [e.g. Hagemann et al. [40]]. There is an immediate need to draw lessons from across this body of research and identify core design considerations that can inform the development of appropriate elicitation methods. We thus present a scoping literature review to address the research question "***Which cognitive mapping tools, and other quantitative and qualitative methods, exist in the literature to map mental models of science, and the science related to risk?***".

Effective science communication is intrinsic to effective disaster risk assessment, management, and communication. Due to the recognised parallels between current best practice in both science communication and risk communication [see review Doyle & Becker in [41]], and the growth of participatory science processes within disaster risk management, the goal of this review is thus to provide recommendations for the application of these methods to the field of disaster risk management, with clear relevance to science communication. It is also recognised that both risk and science communication require models of mutually constructed understanding [33,42] to achieve the goals of a democratic, two-way, citizen focused engagement [28–30,43–45] as reviewed in Doyle & Becker [41]. Thus, such mental model methods have great potential to contribute to the achievement of this goal and benefit both science and risk communication. However, we note the scope of the lessons we draw here are focused on disasters due to the contextual specifics of natural hazard and disaster science compared to other scientific domains, such as astronomy or health science, and given the socio-political and economic factors that will influence mental models of disaster risk.

We next describe our method, followed by a descriptive summary of the identified elicitation and analysis approaches. We then close with a discussion of the key challenges and critiques identified across the literature that should be considered in future design of such methods.

2. Method

We adopt a methodological scoping review approach [46–48] to conduct a "preliminary assessment of the scope of available literature" [49] (p. 85) on mental model elicitation methods. Such a review aims to identify the breadth of methods and approaches across the literature, rather than an extensive review and evaluation of each individual method. The goal is to provide a transparent method for mapping areas of research [50], and to provide "a broad picture of the state of research in a given topic area" [51] (p. 7). Through this we provide a brief narrative synthesis of these different methods, and crucially identify the key considerations,

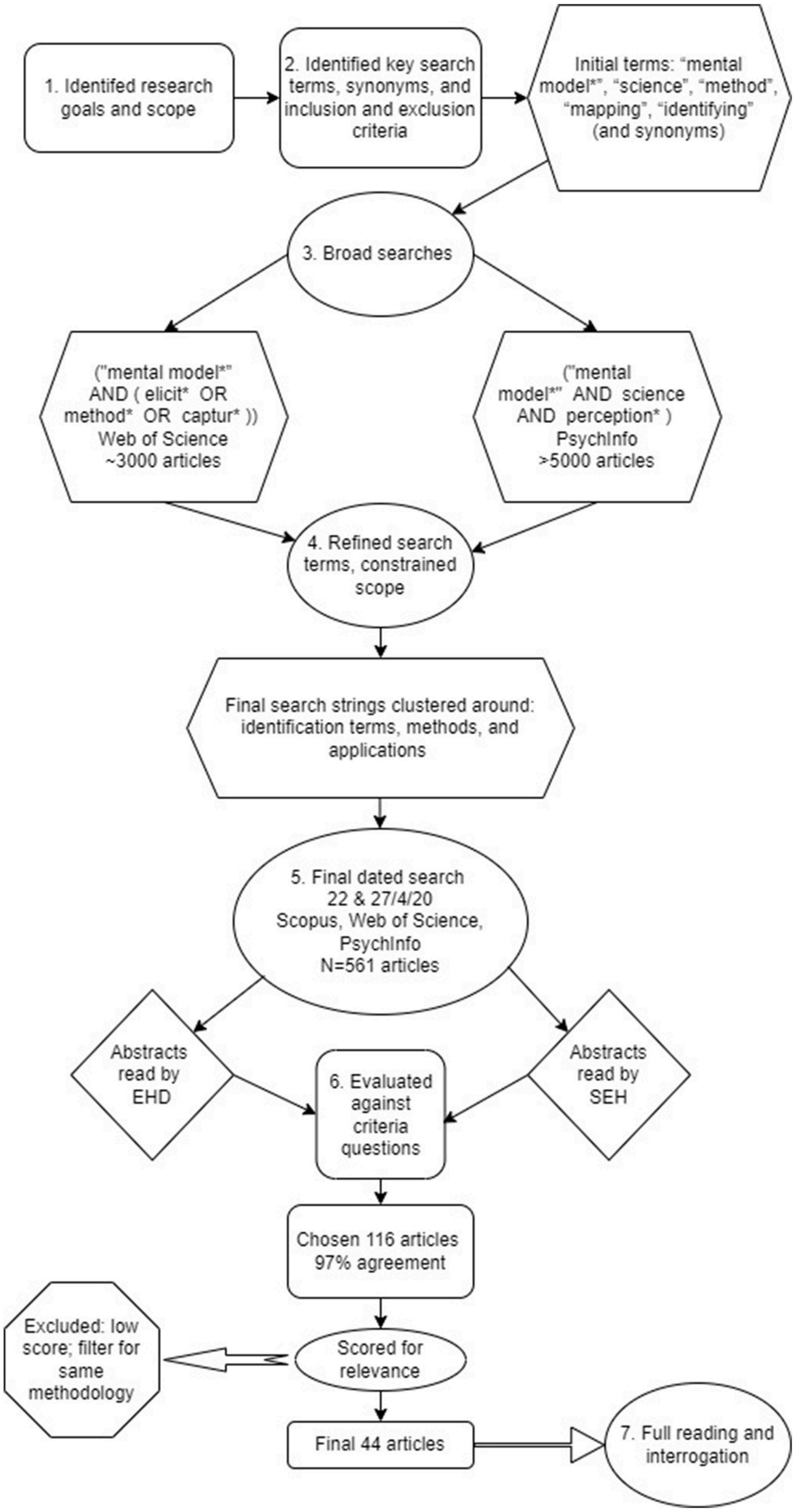

Fig. 1. Caption: The 7-step systematic search process [after [8,46,52]]. Databases searched included Scopus,[3] Web of Science,[4] and PsychInfo,[5] and searches were restricted to articles written in the English Language. The 97% agreement in step 6 refers to the agreement between SEH and EHD in selection of abstracts. Where there was disagreement, differences were discussed until consensus was reached on selection or not.

challenges, or research gaps of developing and applying these methods [47–49]. This paves the way for future systematic reviews of the best available research on individual approaches and identified issues [48,50]. Thus, we do not aim to produce an exhaustive comprehensive systematic review of methods. Where a cluster of linked articles describe a method, we include representative example articles from that group in our review to focus our efforts on reviewing the breadth of approaches being taken. Linked studies are thus referred to as secondary sources, including those where a methodology has been split across multiple articles.

This structured search followed the process outlined in Fig. 1 [after [8,46,52]]. Broad searches (step 3) identified many articles out of scope; thus scope was constrained to papers that presented methodologies and considered models of, or applied to, phenomena, hazard, risk, education, science, the scientific method, and scientific and organisational processes. Further methods were identified, such as: repertory grids, concept mapping, mental model diagramming, mind mapping, influence diagrams, semantic web analysis, belief networks, and fuzzy mapping [see e.g. Refs. [34,36]].

Through this preliminary search process [52], search terms were organised into three core clusters: 1) *identification* terms (identify, map, elicit, etc), 2) *methods* (concept map, mapping tools, etc), and 3) *applications* (science: scientific, research, etc; phenomena: hazard, risk, etc). Seven final search string terms were defined as shown in Table 1, using the approach of Davy [52], where multiple search combinations are required to ensure appropriate articles were captured. A diverse range of topics were covered in the resultant 561 articles (minus duplicates), including science education, perception, and understanding (physics, astronomy, chemistry); risk (from risk communication to perceptions and assessments); health science (incl. food safety); hazards (floods, geological hazards, chemical, food, ocean); climate change; ecology and environmental management; biodiversity, sustainability, and conservation; and science, technology, and society.

Each abstract was read independently by the two lead authors (EHD & SEH) and included or excluded depending on the criteria questions: *Does it consider science, uncertainty, hazard, or risk? Is the mental models method adequately described?* Fifty-one papers that focused on quantitative computational mental models were excluded as being beyond methodological scope. The selected 116 articles were scored in their expected ability to meet our research goals (1 (most, n = 56) to 3 (least, n = 17)), see Fig. 1. Of the highest scores, 31 described the same methodological 'mental models of risk approach' [15], and were filtered to 19 to reduce repetition. A final 44 articles were thus chosen for full reading against the interrogation questions (Table 2).

The above search process was confined to science, hazard, uncertainty, and risk, as differences across broader domains will influence the formation and elicitation of mental models. The 'problem domain' of mental model investigations often influences the structure and design of the elicitation task. Thus, we anticipate method design and analysis to differ between subject areas, necessitating this search restriction such that findings remain contextually relevant. Context also affects an individual's mental model, due to the influence of economics, politics and power dynamics, social structure and agency, and cultural worldviews [53–55]. Accordingly, mental model approaches used in broader contexts, such as organisational operations, business, human resources, and education beyond science, were not considered as their contextual differences could moderate the application and design of the mental models approach beyond the scope of application here.

3. Results

3.1. Paper characteristics

The 44 articles identified cover a diverse range of topic areas, including risk management (n = 11), climate change (n = 7), and science education (n = 6), as described in Table 3. Publication years range from 1993 to 2020, with seven pre-2000 and 32 from 2010 onwards. Considering the article's lead author location, most articles originate from the USA (n = 21), followed by the UK, Australia (both n = 5), and Denmark (n = 3) with representation from a range of other countries (e.g., Israel, Italy, Germany, Taiwan, Israel, see Appendix A.1) based on Lead Author location. The most highly cited are Ruiz-Primo & Shavelson [37] (n = 1115), Thompson & Mintzes [56] (n = 212), and de Bruin & Bostrom [57] (n = 199) (Appendix A.1; Scopus citations as of April 27, 2020). These in turn describe challenges of using concept maps for student assessment, the relationship between knowledge concept maps and an attitude inventory, and using mental models to assess what to include in science communication.

A preliminary classification of methodologies described by the abstracts identified that the most dominant method is what we term the 'mental models approach' (MMA; or mental models of risk approach: MMRA, see Table 4). This cluster of approaches are based upon or adapted from the Carnegie-Mellon/Morgan approach [15] and outlined by Bruine de Bruin & Bostrom [57]. Many mental

Table 1
Search strings and results found for each database, on 22nd & 27th April 2020.

Search String	Scopus	Web of Science	PsycInfo
("Repertory grid method*" OR "Concept map*" OR "mental model*" OR "Mind map*" OR "knowledge map*" OR "influence diagram*" OR "belief network*" OR "cognitive map*") AND elicit* AND science	95	186	95
"mental model*" AND "understanding of science"	4	8	3
"elicit*" AND "mental model*" AND "science"	65	82	85
"public perception*" AND science AND ("Repertory grid method*" OR "Concept map*" OR "conceptual model*" OR "mental model*" OR "Mind map*" OR "knowledge map*" OR "influence diagram*" OR "belief network*")	7	27	4
"mental model*" AND science AND perception*	148	127	249
"elicit*" AND "mental model*" AND ("risk" OR "disaster" OR "hazard" OR "climate change")	40	44	16
"mental model*" AND elicit* AND scientific		18	

Table 2
The interrogation questions and assessment criteria.

Paper Overview	Type of paper (study, review paper, etc.). Case study/Application. Good mental model review section (Y/N)? Do they compare methods? If so, which ones? How? What did they find? Citations.
Methodology	What is the approach used? Is the approach novel? (i.e. did this paper create it?) (Y/N) - If not, whose approach did they use? What are the limitations? What are the benefits? Data Collection Tool(s). Elicitation: Direct, Indirect, or Both? Analysis Methods. Brief comment on whether or not there is enough information in the manuscript to follow it as a how-to guide or recipe (or do they reference another article?). How-to. Does the paper include the rubric/interview guide/questionnaire? (Y/N)
Key Findings and Conclusions	Key findings with respect to the understanding of science and the scientific method. Is uncertainty discussed? If so, what is said? What future research questions do they identify with regards to the methods? (Y/N) Does it talk about the future research of understanding science? Other notes.

Table 3
Study topic areas, and journal discipline of the 44 articles.

Study Topic Area/Application	Count	Journal Discipline	Count
Risk Management and Communication	11	Science Education and Teaching	12
Climate change	7	Risk Management and Analysis	7
Science Education and Teaching	6	Enviromental Management	6
Environmental Management	5	Land Use and Land Management	3
Conceptualisation	4	Natural hazards	2
Land use and land management	2	Research Methods	2
Natural Resource Management	2	Water/Marine Science	2
Clinical science	1	Climate change	1
Cognitive Science	1	Cognitive science	1
Human Resource Development	1	Environmental Modelling	1
Information science	1	Human Resource Development	1
Knowledge Engineering	1	Information Science	1
Science Communication	1	Knowledge Engineering	1
Systems Sciences	1	Marketing	1
		Science Education and Teaching	1
		Psychology	1
		Systems Sciences	1

models elicitation techniques include cognitive mapping, concept mapping, influence diagrams and network analysis, repertory grids, and rich elicitation, several of which are integrated into the MMRA approach and use techniques such as think-aloud protocols to document and analyse people's decision making processes (see also Jones et al. [58], Grenier & Dudzinska-Przesmitzki [59], Levine et al. [60], & Greyson et al. [61] for other applications of a think-aloud approach).

The range of data collection methods used within the different papers are described in Appendices A.2 & A.3, including the steps involved in elicitation. After first clarifying key terminology, we next provide a descriptive summary of the selected elicitation methods [47] followed by a critical discussion of key challenges, advantages and disadvantages of methods.

3.2. *Clarifying terminology: direct and indirect methods, tasks constraints and structure*

Many methods can be identified as involving either *direct* or *indirect* elicitation, or both [14,34,62]. As reviewed by Wood et al. [34] diagram-based representations can be elicited directly from respondents, derived from their discussions, inferred from their decisions and actions, or from across these different data collection and analysis approaches. These have various advantages and disadvantages, but key is how the different elicitation approaches may capture what people describe as the thinking process that they *think* they followed to inform decisions, versus the elicitation capturing the thinking process that they *actually* followed to inform those decisions. Diagrammatic approaches that participants directly create, or participate collaboratively on, can help individuals reason, make inferences, and facilitate an understanding of group perspectives [34].

Thus LaMere et al. [62] defined *direct* elicitation as having participants create and define the structure of their models themselves, sometimes assisted by a facilitator or visualization tools, and enabling immediate verification of the models by participants. In contrast, *indirect* elicitation relies upon the interpretation of an analyst to determine the structure of the participants' mental models,

Table 4
The broad categorisation of elicitation approaches, and associated articles from those reviewed. See Section 3.3 and Appendices A.2 and A.3 for more details.

Overarching approach	Description	Articles
Mapping	An approach that is dominated by mapping activities or tasks, such as concept mapping, cognitive mapping, fuzzy cognitive mapping, flow mapping, information world mapping, mind maps, and knowledge maps.	Concept mapping [37,39,56,58,66–71]; cognitive mapping [72–76]; fuzzy cognitive mapping [77]; flow mapping, information world mapping, mind maps, and knowledge maps [38,61,63,84].
Mental Models Approach (including Mental Models of Risk Approach and Values Informed Mental Models)	An approach based upon or adapted from the Carnegie-Mellon/Morgan approach [15] which is dominated by the use of influence diagramming elicitation methods.	[15,26,27,40,57,76,86,88–93,95,98,99]
Non-specific multi-method approaches	An approach that used multiple methods or did not follow a specific design or approach from the categories above. If those techniques were present, they did not dominate the study as it was designed specifically to focus on a 'multi-method' approach, giving *equal prominence* to multiple data collection techniques or approaches.	[38,58–60,62,64,93,100–104]
Other elicitation techniques	These include repertory grids, laddering, and metaphor techniques that are highly structured and constrained tasks that seek to elicit and prioritise constructs with participants. Presented independently but could be used within other approaches.	[64,100,104]

based upon textual information such as interview transcripts or questionnaire data. LaMere et al. [62] highlighted challenges with both approaches, with the direct elicitations often being simplified compared to the verbal descriptions, while indirect elicitation reflects "the analyst's interpretation" of the mental model which may be "influenced by their own biases, beliefs, and values" (p. 2). They thus developed a combined 'rich elicitation approach', discussed further in section 3.3. We also note here that direct elicitation is not immune to researchers' biases, beliefs, and values due to the design of the prompts and guidance they provide (discussed further in section 4.1).

Within the direct mapping methods, Ruiz-Primo et al.'s [37] work in education further characterised direct methods as having a *task* that elicits evidence of a student's knowledge structure, a *format* for a participant's response, and a *scoring* system for evaluating accuracy and consistency against a 'correct' map. *Task demands* relate to what the student is asked to do, such as filling in a skeleton map vs. constructing a concept map from scratch or writing an essay vs. responding to interview questions. *Task constraints* relate to the restrictiveness of the task, such as being asked to construct a *hierarchical* or *network* map or being provided with the concept terms to use in the task, labels for concept links, or the allowance to use more than one link or move concepts around on the map. The need for justification of responses, definition of terms, or collective construction of maps, are also identified as constraints. Finally*, content structure* relates to the type of map (spider, hierarchic, chain, etc), which Ruiz-Primo et al. [37] stated does not need to be imposed as it will reflect the structure of the subject domain.

3.3. A descriptive summary of the spectrum of elicitation approaches and methods

Many techniques and elicitation methods and tools can be identified within a range of umbrella approaches (some of which can be identified as distinct methodologies). As described in Table 4 and Appendix A.2, these can be broadly categorised into **mapping, mental models or mental models of risk, non-specific multi-method approaches**, and **other elicitation techniques**. The selected papers in this review were classified into these four overarching methodological categories to guide identification of key lessons. These categories emerged after grouping similar methodologies together, identifying the **dominant** approach for a particular paper, and identifying common themes across papers.

The mapping category thus encompasses those papers whose primary focus involved mapping data collection tools and analytical methods, such as "Cognitive Structure Flow-Map" [e.g., 63] or "Concept Mapping" [e.g., 39] (See Table 4 & Appendix A.2 for more). The Mental Models or Mental Models of Risk category includes all papers that specifically followed or adapted the Carnegie-Mellon/Morgan approach [15], and heavily use influence diagramming elicitation methods. The non-specific multi-method category includes approaches that used multiple methods and either did not follow, or were not dominated by, one of the above specific methodological designs or approaches. Finally, the other elicitation techniques category includes those papers outside of these three categories, and include distinct elicitation techniques such as repertory grids, laddering, and metaphor techniques [e.g., ZMET, 64].

Some papers could have been classified in multiple categories (e.g., Grenier & Dudzinska-Przesmitzki's Multi-method Mental Model Elicitation (MMME) [59] which used 20 statement tests, interviews, and concept mapping). However, the focus for categorisation herein was the dominant or primary data collection for their study. Thus, non-specific multi-method was chosen when other tools were used with equal or greater prominence, or when the authors' focus was on specifically designing a multi-method *approach*. Similarly, a paper classified as mapping or MMRA may include some supporting data collection techniques (e.g., MMRA can include surveys, interviews, card sorting, or other mapping approaches), but they were not assigned as 'non-specific multi-method' due to the prominence of the core method and approach design.

We observed a complex overlap of techniques and elicitation methods across these approaches, unclear terminology, and a conflation of techniques with approaches (or methods with methodologies), suggesting the need for a typology or framework of approaches (discussed further in section 4.6). The degree of imposed task structure and constraint also varies within and between these approaches, and many can be applied in both direct or indirect ways, depending on researcher design preference, as described in Table 5, and discussed next.

3.3.1. Mapping

Ruiz-Primo et al. [37] defined a **concept map** as a "*graph consisting of nodes representing concepts and labelled lines denoting the relation between a pair of nodes*" (p. 569), which they interpret as representing important aspects of concept organization/cognitive structure in a participant's memory. We note this is similar to a semantic network [see Ref. [65]]. Nine articles described the generation of these 'concept maps' (Appendices A.2 & A.3), with two employing **indirect** methods [39,66], five employing **direct** methods [56,67–70], and two reviewing the different methodologies and their application in education [37,71]. These studies use concept maps to assess participant understanding either independent of or during an education course, aiming to assess perceptions and misperceptions, as well as the influence of delivered educational materials and learning objectives within a student cohort [56,67,68]. Alternatively, they can be used to compare changes in concept map structure with expertise and level of training [69].

The different concept mapping methods identified in this literature review are summarised in Appendices A.2 & A.3 and Fig. 2, and **often have high degrees of task constraint and map structure**. The **direct** approaches involve participant drawing of concept maps [56,67–70], meanwhile the **indirect** approaches use a combination of elicitation tools including photos, semi-structured interviews, sentence sorting, and questionnaires [39,66]. These are then subjected to content analysis [66], or grounded theory techniques [39], and often involve an iterative development approach [e.g. Refs. [69,70]]. Group approaches include that of Vink et al. [69] where a concept map is collectively developed until consensus is reached.

Cognitive mapping [72–74] is sometimes used as an alternative name for concept mapping but can also be interpreted as the broader overarching elicitation approach of which a concept map is an output. Cognitive mapping can be defined as "*depict[ing] a system as a network in which nodes represent concepts and edges represent directed causal effects*" [72] (p. 414), where the 'concepts' are any physical, social, or normative ideas the individual or group consider critical to the system. Alternatively, Romolini et al. [73] described cognitive maps as "*tangible expressions of implicit representations*" (p. 11) and state that two main elements central to any cognitive map include concepts and relations, where the concepts are used to represent "*tangible (i.e., objects, events, and facts) and intangible (i.e., emotions, sensations, and meanings) aspects of social reality*" (p. 11) while relations are not just restricted to causal effects but also association, equivalence, topology, structure, and chronology.

These cognitive mapping approaches generally involve elicitation techniques with **medium to high levels of task constraint, and commonly involve unstructured maps,** however some can have strict structure constraints**.** For example, Romolini et al.'s [73] direct approach follows the 'Conceptual Cognitive Concept Mapping' (3CM) of Kearney & Kaplan [75] via four stages: 1) knowledge elicitation from existing documents, open-ended interviews, questionnaires, and direct elicitation through mapping activities, 2) construction and refinement of concepts and relations; 3) relationship identification through qualitative and quantitative (incl. multivariate) analysis; and 4) aggregation of maps for comparison. However, in comparison, Moon & Adams [74] use an approach based upon influence diagrams (Abel et al. [76], discussed further below) to represent a mental map, thus applying a significant task constraint to the structure of the map [37] due to its focus on decision analysis-based mental models.

An additional **very structured, constrained, direct** elicitation approach includes those that employ '**Fuzzy cognitive mapping'** (FCM) (Levy et al. [72], Olazabal et al. [77], see also [37,67]), sometimes including the use of mapping software tools such as 'Mental Modeler Software' [see Ref. [78]]. Such FCM approaches were also employed by a range of other non-selected papers [including [79–83]], and are a form of semi-quantitative mind mapping process that can also be classified as a form of 'systems mapping method' to explore complex decision environments, and to integrate diverse knowledge bases to further understand and identify alternative

Table 5
The broad similarities and differences between approaches and methods, based upon whether elicitation is direct or indirect, the imposed map or output structure, and for direct approaches the level of task constraint. Due to the high degree of variance in the actual application of an approach, due to differing research philosophies, this table is a general simplification only. The nuance of these approaches is discussed in Section 3.3, and details can be found in Appendices A.2 & A.3.

Approach	Sub-approach or methods	Direct/Indirect?	Imposed map or output structure?	Level of task Constraint? (if direct)
Mapping	Concept mapping	Can be both	Structured	High
	Cognitive mapping	Can be both	Commonly unstructured; some structured	Usually semi-constrained, some highly constrained
	Fuzzy cognitive mapping	Direct	Very structured	Very high
	Flow mapping, information world mapping, mind maps, knowledge mapping	Can be both	Can be both	Can be both
Mental Models Approach	e.g., Mental models of risk approach; Influence diagrams, Values informed mental model	Can be both, mostly direct	Structured	Often very high
Non-specific multi-method	e.g., combination of interviews, card sorting, influence diagrams, mapping, free drawings, free-listing, sorting, attitudinal surveys	The goal is to triangulate through both, where adopting a multi-method design is a priority	Can be structured or unstructured	Can be high or low
Other elicitation	Repertory grid, Laddering	Direct	Structured	Constrained
	Metaphor elicitation techniques	Both	Unstructured	Unconstrained

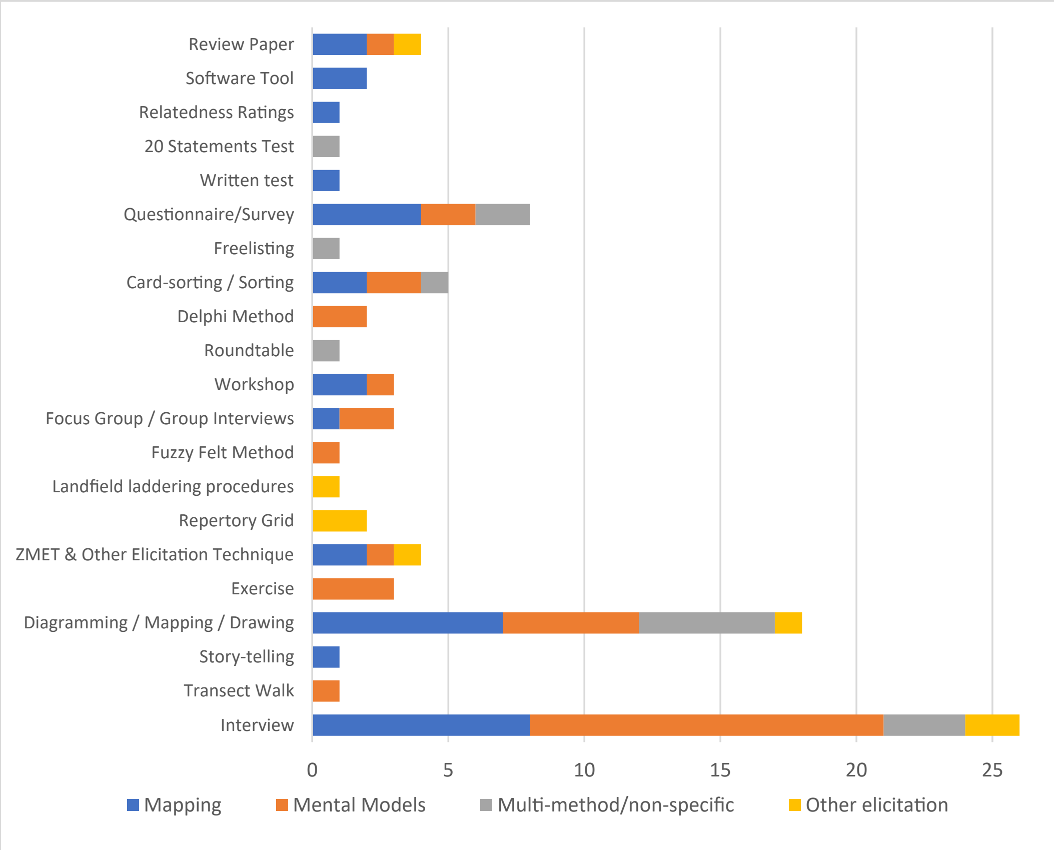

Fig. 2. The range of data collection techniques identified in the different approaches. (Interviews = individual, semi-structured, think-aloud, and reflection; Exercise = decision-making, group modelling. The mapping category includes cognitive, concept, fuzzy cognitive, flow, information, and mind mapping. Mental models refers to those that specifical categorise themselves as adopting a mental models approach (e.g., Mental Models of Risk).).

actions. These often use fuzzy-logic to numerically describe the 'truth' or 'uncertainty' of a relationship via a weighting variable between 0 and 1 (see review in by Olazabal et al. [77]). Unlike other techniques they can also be used to ellicit expertise from a range of researchers through a combination of group and individual interviews, or from existing documents or datasets. They usually incorporate 5 steps: 1) problem definition resulting in the question the participants must answer, 2) elicitation, 3) data treatment, 4) homogenisation, and 5) aggregation.

Similar to concept and cognitive mapping, a cluster of approaches variously described as '**flow mapping**', '**information world mapping**', '**mind maps**', or '**knowledge mapping**' were also identified. These include the **direct** elicitation approaches of Frerichs et al. [38] and Greyson et al. [61], and **indirect** elicitation approaches of Anderson & Demetrius [63] and Owen et al. [84] (described further in Appendices A.2 & A.3). Greyson et al. [61] identified a key benefit of information world mapping approaches is their ability to centre the voice and views of marginalised groups more than other interview approaches, due to the participatory approach to data collection which is centred around participants' own perspectives on information practices. Other benefits include the ability to strengthen understanding of how conceptualisation shifts over time [38], such as that explored by Frerichs et al. [38] in their **direct** iterative mind mapping technique. This also elicited perceptions of concepts in combination with group model-building approaches (Vennix & Forrester [85]), and using other additional semi-constrained diagramming tasks (e.g., graphs, causal loop diagrams). This approach can also be combined with unstructured and unconstrained tasks, such as the use of free drawn mind maps (Frerichs et al. [38]) and interactive drawing-based interviews (Greyson et al. [61]). Thus, participants can produce a range of map types, such as the directional, mind, and symbolic maps that Greyson et al.'s participants produced when instructed to "put themselves on this page" ([61], p. 151). Such an approach is similar to the 3CM approach discussed above [73,75] and Grenier & Dudzinska- Przesmitzki [59], discussed below.

In comparison, the **indirect** approach of Anderson & Demetrius [63] has a more structured flow-map outcome, developed from interview data. Through this their goal was to develop a representation of *sequential* and multi-relational thought processes that preserves the order and cross-linkage of ideas within a narrative, and minimises intrusion by the interviewer. Finally, the knowledge mapping approach of Owen et al. [84] utilises a highly structured and constrained **direct** elicitation through influence diagrams, discussed further next.

3.3.2. Mental models approach or mental models of risk approach

The 'mental models approach' or '**mental models of risk approach**' (MMRA) is fundamentally designed around the use of influence diagrams in the elicitation method(s), and developed as a way to design effective risk communications [15,57,86]. These influence diagrams are decision analysis-based mental model tools [34] that represents beliefs about "*influences on decisions and their outcomes"* including *"structural constraints stemming from decision analysis*" (p. 1335). As discussed above, Moon & Adams [74] interpreted them as representing a cognitive map where the interrelationships define a system, stating *"that an influence diagram is not a mental model per se, but an external representation of an internal model in the mind."* (p. 345).

In reviewing the work of influence diagrams since the 1970s, Howard & Matheson [87] described influence diagrams as a single representation that displays *"both the sequential and informational structure of decisions*" (p. 144). Influence diagrams can be considered as a diagrammatic decision analysis-based mental model tool [34]. The various approaches to influence diagrams were classified by Hurt [88] as a construction of either 'relational schemas' mapping interrelationships, 'numerical schemas' mapping probabilities or utility functions with a focus on solving problems, and 'functional schemas' consisting of algorithms by which particular courses of action are determined. Each of the different approaches to influence diagrams can thus represent an imposed *task constraint* [37] and illustrated the high level of structure in this method (section 3.2).

Building on the work of Abel et al. [76], who **indirectly** developed mental models based upon quantitative coding analysis of interview transcripts to identify differences and commonalities across groups, influence diagrams have become one of the most common methods applied within MMRA. This was born out of research built on the mental models approach of Morgan et al. [15]. As reviewed by Boase et al. [86], over 100 articles refer to MMRA (or "MMARC"), adopting approaches similar to Morgan's which involves: 1) generating an expert mental model of decision processes and goals, built from expert interviews and literature, 2) generating target audience (often public) models through interviews for comparison, 3) conducting wider population surveys to assess prevalence and variability of views, 4) using this to inform new design of a risk communication, and 5) evaluating the efficacy of the new communication [see also [57]]. Influence diagrams, as a representation of a type of decision model [see also [74]] can thus be used to **directly** elicit the **expert** model in step (1) via techniques such as Morgan's assembly or scenario method ([15]; see Appendix A.3) and to **indirectly** elicit the **target audience or lay people's** mental models in step (2). This can be done through a range of approaches from analysing photo elicitations and card-sorting activities accompanied by think-aloud methods, surveys, phone or in-person interviews, focus groups and workshops, and wider population surveys to confirm prevalence [15,40,57,89].

We can see that there are two distinct approaches to how the expert and lay phases relate. Hagemann et al. [40,89] utilised the expert model from phase 1 to inform the design of the rubric of the lay model interviews, while Bruine de Bruin & Bostrom [57] and Skarlatidou et al. [90] utilised the expert model codes to inform the analysis of lay interviews. In contrast, others focused primarily on the generation of a base 'expert' model of the decisions that a risk communication seeks to inform, usually constructed from a range of diverse disciplinary experts or expert groups (e.g., decision modelers, scientists, behavioural scientists). The comparison of these expert and lay perspectives thus informs the generation of appropriate risk communications [26,27,91–93] (see Appendices A.2 & A.3 for more). As discussed by Lazrus et al. [94], differences in causal beliefs about hazards between expert and lay groups correspond to "*important differences in perceptions of risks and the effectiveness of responses to them*" (p. 423), with conceptual connections differing from those made by professionals. These may limit people's ability to make appropriate protective decisions, and thus it is vital to understand them further to enhance risk communication.

The importance of capturing the social context is raised by Cassidy & Maule [95], who adapted the Morgan et al. [15] MMRA approach by integrating it with techniques to assess social representations of collective risk knowledge [96, cited within] to account for the social construction of risk and how risk knowledge is built, held, and communicated *collectively* [97, cited within]. Bessette et al. [98] further highlighted the roles of values as well as beliefs by developing an elicitation approach to develop a (researcher-drawn) stakeholder **Values Informed Mental Model** (ViMM). They highlighted that eliciting people's values related to risk and risk management, as well as what they know about risk, has greater potential to enhance communication. However, they acknowledged that values gaps may arise depending upon stakeholder representation and thus researchers must ensure a diverse range of participants [see also 26,93]. Mayer et al. [99] built on and adapted the work of Besette [98] by instead asking directly about ethical (e.g. fairness, welfare) and epistemic (e.g., robustness, reliability, consistency) values. They highlighted that a ViMM can: "*(i) enable insights that can inform the design of new computational models and (ii) make value judgments explicit and more inclusive of relevant values*" (p. 107).

3.3.3. Non-specific multi-method approaches

Many of the reviewed approaches utilise a range of methods (interviews, card sorting, influence diagrams) each of which attempts to elicit and understand mental models in novel ways [59,100,101], and they are thus collectively classified as 'non-specific multi-method approaches'. As discussed by Pezzullo & Filippo [100] adopting a mixed method approach to elicitation can offer better representation of a participant's mental model (see more below). Wood et al. [34] also highlighted that elicitation frameworks should be developed that integrate across different mental model diagramming processes to provide complementary information about the mental models of interest, such as decision-analysis modelling providing information about processes and contexts, concept mapping providing information about relatedness and importance of aspects within that process, and semantic web diagrams providing detail about relationship quality within the decision models.

Six of our reviewed papers adopted such a multi-method approach. Grenier & Dudzinska-Przesmitzki [59] highlighted that combining methods enables the limitations of each to be addressed, such as the over-reliance on interviewer interpretation in verbal elicitation or the 'circuitous' nature of graphical methods. A hybrid approach also allows a researcher to triangulate the data and identify inconsistencies in participants' responses, and develop a more holistic representation with deeper understanding.

As discussed by Frerichs et al. [38] different elicitation methods result in varying levels of 'distortion' in conceptual representations, thus there is a need to mitigate for these distortions by adopting multiple methods. LaMere et al. [62] also advocated for a **combined direct and indirect elicitation** to identify mental models as it produces in depth and richer models, however they highlight that such a mixed approach can risk overcomplicating the research, resulting in a daunting amount of 'messy' data than can be hard to analyse. Pan & Liu [102] and Levine et al. [60] combined free drawings, interviews, freelisting, sorting tasks, and attitudinal scales, which Levin proposes enables the formation of "aggregate mental models" of tacit beliefs when findings are integrated across these tools. Jones et al. [58] and Panagiotaki et al. [103] explicitly compared methods to identify suitable multi-method approaches. They found no significant difference between oral and diagrammatic-oral interviews [58] and that drawing and open questions increased incidences of 'naïve' scientifically incorrect mental models in school children compared to 3D models and forced choice responses [103] (see also discussion section 4.1). Given the goal is to triangulate through a range of direct and indirect approaches, these methods encompass structured and unstructured approaches, with varying levels of task constraint.

3.3.4. *Other elicitation techniques*

Other available tools include the repertory grid and laddering techniques, which are **highly structured and constrained** tasks that seek to elicit and prioritise constructs with participants via comparative and sorting tasks, as adopted by Pezzullo & Filippo [100] and Ben-Zvi Assaraf et al. [104], and combined with less structured approaches such as free drawing [104] (see Appendices A.2 & A.3, see also [105–107]). Finally, **direct** and **indirect** metaphor elicitation techniques can also be used (via photographs and other media), such as the "Zaltman Metaphor Elicitation technique" or "ZMET" [64]. This assumes that the analysis of metaphors can elicit hidden knowledge due to their central role in structuring knowledge, discussed further in section 4.2 (see also the use of photograph elicitation and other metaphor elicitation techniques in e.g., Morgan et al. [15]). The use of analogies and metaphors by participants in interviews about risks is also discussed extensively by Bostrom [108] [see also 94], where variations in metaphor (or analogy) use relate to the multiple models people use to explain phenomena where the metaphors are "*coherent systems, derived from our physical and cultural experiences of the world*" (p. 100). Thus, understanding the use of such metaphors as they are volunteered by target audiences in mental models interviews can also be used to directly enhance the design of risk communications [see also Heath and O'Hair [109]].

3.4. *A descriptive review of analysis methods adopted*

There is an equally diverse range of analysis methods, as depicted in Fig. 3. These broadly fall into three categories: methods to analyse directly elicited maps, methods to analyse the data used to inform indirect map construction (e.g. from interviews), and methods to analyse those indirectly elicited maps.

3.4.1. *Directly elicited mental models*

Much of the *directly* elicited map analysis is quantitative. These range from '**scoring approaches**' (as highlighted by Ruiz-Primo et al. [37]), where maps are scored against either expert teacher maps [67] using relatedness ratings of concepts, or for structural complexity and propositional validity [56] to produce scores for statistical comparison with other measures such as attitudinal data. Pan & Liu [102] visually scored drawings based on levels of evidence along three factors: the structure, the relations to natural environment, and the relations to built environment. A principal component analysis was then conducted of these three factor scores, with a descriptive and correlation analysis across the open-ended qualitative data and attitudinal variables. Panagiotaki et al. [103] scored drawings, questionnaires, and 3D model building for accuracy, followed by a chi-square comparison of scores between elicitation methodology groups. Vink et al. [69] considered a framework of 'concept map features' for analysis, considering concepts (clinal, basic science), organization (umbrella, problem-specific), and integration (clusters, hierarchies, links). Similarly, Levy et al. [72] focused on the complexity of the map's network structure and the prevalence of 'six fundamental causal patterns', or "motifs" related to cognitive theory.

Content analysis was also common [e.g. Refs. [67,70,73,84]] (see Fig. 3). This considered the transcribed interviews, photographs of maps, and results of any related activities to produce cross cutting 'constructs' to characterize response item groups. Meanwhile, Jones et al. [58] assessed the "number of functional linkages" as well as the 'mental model density', that is, the ratio of relationships to concepts [after [110]] as a way of representing the complexity of the maps. Interrogated coding analysis utilised generalized linear models to explore the effect of different interview procedures on the number of concepts elicited. Moon & Adams [74] conducted a similarity analysis of content, structure, and complexity, utilising social networking software to investigate the variables in the map (treating them as nouns/pseudo-people). Analysis of the interview data alongside maps also included qualitative approaches such as narrative analysis [68], thematic analysis [61,74], and a mixture of deductive coding and content analysis [38]. The latter was used to identify paired factors for network analysis of relationships between factors and concepts.

3.4.2. *Indirectly elicited mental models*

For *indirectly* elicited maps, the (often qualitative) analysis of the interview data is fundamental to the map construction process, as discussed in sections 3.3 & 3.4. Approaches include grounded theory techniques [39], qualitative content analysis [66], quantitative analysis of 'concept codes' to assess prevalence across interviewees [26,76] including a focus on pairs of codes to explore direct causal connections, and a combined content and thematic (interpretive) analysis of images alongside transcripts [95] to inform comparative analysis between groups. Bessette et al. [98] utilised thematic analysis to develop a final set of codes used to develop the Values Informed Mental Models for groups and individuals, considering: modelling decisions, systems, strategies, ethical values, and epistemic values.

Quantitative analysis of coded topics included combined network and content analysis approaches to infer the MMRA consumer decision-analysis influence diagrams and enable comparison with directly elicited expert diagrams [40,57,89]. Analysis across these groups also considered prevalence of structure elements, such as: misconceptions, peripheral, indiscriminate, and background beliefs,

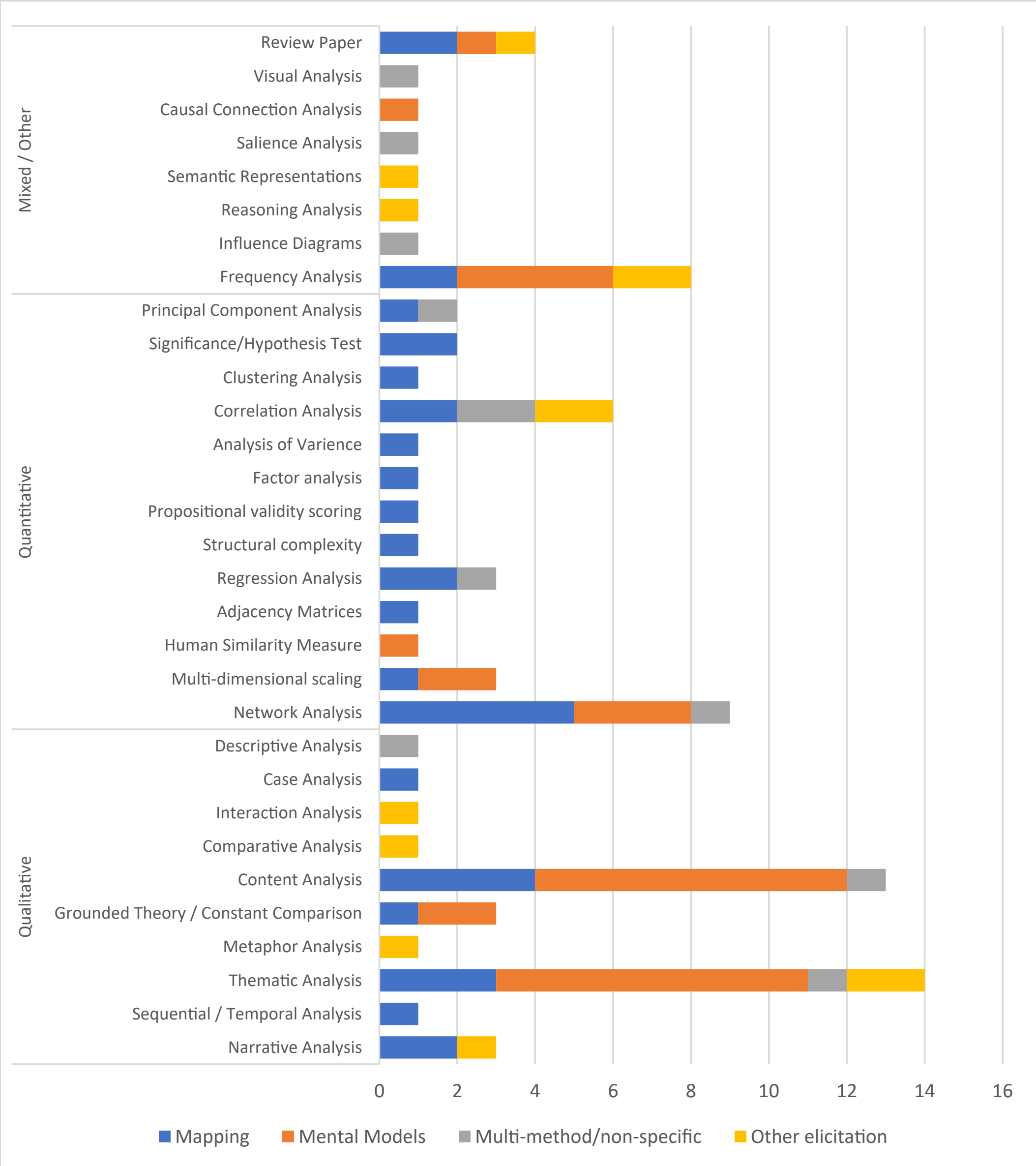

Fig. 3. The range of analysis methods identified in the different approaches. (The mapping category includes cognitive, concept, fuzzy cognitive, flow, information, and mind mapping. Mental models refers to those that specifical categorise themselves as adopting a mental models approach (e.g., Mental Models of Risk).).

and valuations [84]. Alternatively, salience analysis topics identified by Levine et al. [60] (using ANTHROPAC software [111]), then informed a network analysis to produce an aggregate model (using the method of Gephi [112]).

Reflecting further on the MMRA approaches, often the consumer or end-user mental models are elicited via a network and content analysis of codes found either deductively (drawn from expert's models) or inductively, and depend upon direct comparisons to experts through interview design or analysis. However, Cassidy & Maule [95] highlighted that these approaches 'privilege' the expert mental model and expert perspectives on risk over those of the lay public (discussed further in section 4.4), and thus adapted the Morgan et al. [15] MMRA approach to account for different social representations of risk.

Not all indirectly inferred mental models actually produced a 'map'. Kuonen et al. [91,92] analysed interviews via grounded theory, but chose to "*build a holistic understanding of risk knowledge through a non-hierarchical structure, rather than drawing distinctions that improved communications*" [92] (p. 436). Their goal was thus to develop a "*narrative to learn about the risks, uncertainties, and decision-making*" [91] (p. 56) rather than creating a generalizable conceptual model. Similarly, researchers' depictions of their own mental models of a system, developed when analysing interview data via mind mapping processes, can be considered a form of indirectly elicited mental model (see methodology recently described by Fearnley [113]).

3.4.3. Mixed direct and indirect elicitation

Analysis of broader activities, such as card-sorting, included consideration of semantic representations, ordering of concepts, and frequency and correlational analysis for identified constructs and dependencies [100]. Alternatively, comparative thematic analysis can be conducted across the full suite of data: interviews, images, and elicited constructs, to identify 'metaphor categories' [64]. Meanwhile Ben-Zvi Assaraf et al. [104] focused on the richness of models and components via an inductive categorisation of drawings, frequency and statistical analysis of categories, reasoning and comparative analysis of the repertory grid, and 'interaction analysis' which involved a comparative team reflection on individual themes of the interviews [after [114]].

It is clear from this summary, and Fig. 3, that there is an extremely diverse range of analysis approaches for both directly elicited maps and the data collected to support these, or to inform indirectly elicited maps, and for the final analysis of those. Some of these also use a range of software tools for network and salience analysis, or model building ([78,111,112], see also [115,116]). The lack of consistency across analytical approaches, or a critical evaluation of approaches, has thus been identified by a number of researchers as a significant challenge to address [38,61,62,74] discussed further in section 4.3.

4. Discussion: Key challenges identified across this research

A number of key themes relating to design considerations, advantages, disadvantages, and challenges were identified in the 44 articles reviewed. They include the need to distinguish more clearly between approaches and methods (discussed above), the importance of considering potential bias due to prompts or researcher influence, the advantage of moving beyond language to elicit mental models, the need for an evaluation of analysis approaches, a critique of the privileging of expert opinion, and being aware of the ethical issues that may arise due to the elicitation process actively influencing worldviews. These are each now discussed in turn, after which we conclude with a set of design considerations to guide future elicitations.

4.1. To prompt or not to prompt? The issue of bias and researcher influence

Prompts are used to varying degrees across these studies, to help facilitate a direct elicitation drawing or mapping activity. They can guide the participant, help them complete what can often be a challenging task, while also stimulating thought. However, the number of prompts, type of prompts, and their influence on the final output is debated across this body of literature (see section 3.3). At the heart of this debate is the degree to which researcher instructions and guidance is needed to facilitate the elicitation versus the degree to which that influence may bias the final output and results, and thus reflect the task more than the individual's mental model [37,72,73,103]. Further, the researcher will need to consider the participants' knowledge of, and experience with, the topic and the method or technique being used, which may also variously influence their degree of direction and influence. As highlighted by Levy et al. [72] "*mental models are not a simple reflection of the content of one's mind, but are also a product of the manner in which they are elicited*" (p. 418).

Panagiotaki et al. [103] concluded that children's interpretations and responses were easily influenced by the elicitation methods used, and that drawing and open questions increased incidence of 'naïve' mental models, while 3D models and forced choice questions elicited more scientifically correct responses. However, we note here that while these elicited models may be perceived as 'naïve' when used in educational settings or for forms of assessment, in other contexts it is not a problem to elicit 'naïve' models from participants, as understanding such perspectives is a vital component in designing risk communication campaigns (see section 4.4). While the Panagiotaki et al. [103] study considered more impressionable children compared to adults [see e.g. Ref. [117]], similar issues were highlighted by Romolini et al. [73] in their critique of 'nomothetic' approaches. These are approaches where a researcher provides predefined concepts for structural interpretation, which Romolini et al. [73] stated are often meaningless to participants and result in maps that are an artefact of the method used to elicit them.

Both these critiques relate to the influence on the elicited data of the *task constraint* and *task demands*, as classified by Ruiz-Primo & Shavelson [37] (see section 3.2). In addition, often with the structured or constrained mapping tasks, a degree of participant training is required first, or a facilitated practice mapping session is conducted [e.g. Refs. [38,56,62,70]]. It can be argued that this training may result in further researcher influence and bias in the results. Additionally, extremely structured and constrained techniques like the Fuzzy Cognitive Mapping approach were highlighted by Olazabal et al. [77] as having problems with regards to transparency and reproducibility and researcher bias, particularly regarding the initial map-building elicitation process (and data treatment).

Romolini et al. [73] thus used the 3CM approach of Kearney and Kaplan [75] which aims to fully reflect the respondents' conception of a topic by encouraging them to display their thoughts in a graphical representation of their choosing, resulting in an individualised and rich response with hierarchies, systems, relationships, and groups to draw out the most salient understanding. By directly generating an (unconstrained) cognitive map in an interview, Romolini et al. [73] consider that the participants have more 'ownership' of the product, leading to the production of rich answers through a less invasive process than a structured querying interview or prescribed mapping approach, positing that this approach thus reduces researcher bias. Similarly, Jones et al. [58] utilised drawing activities with a less structured approach such that participants can use words, pictures, or a combination of both to represent their knowledge structures. However, this elicitation also occurs within a contextual domain [see 118] that presents a 'scaffolding' structure, such that even a method that may be viewed as an 'unstructured' elicitation is still influenced by the structure of the context within which it is elicited and the domain under consideration. This also arises as the elicited mental model represents both the building of a knowledge structure (knowledge in the model) as well as a process component (operations performed on that knowledge) [118].

A further challenge arises due to the highly variable performance of an unconstrained and unstructured drawing task, with some very rich and detailed responses, and others sparse with only labels [95]. This creates 'messy' data [62] that can be hard to analyse (see section 3.4). In addition, some participants produced very little in their response. Cassidy & Maule [95] thus addressed this by introducing seed or 'prompt icons' based upon common themes and items identified from their pilot phase. To stimulate thinking and provide more structure and constraint, participants were instructed to arrange these and add further elements. Similarly, Greyson et al. [61] provided a list of verbal and written prompts that participants might choose to include in their information world maps; Hurt [88] provided a list of domain elements to guide participants construction of influence diagrams; and Frerichs et al. [38] provided 'seed' diagrams for development and evaluation. The alternative approach of Grenier & Dudzinska-Przesmitzki [59] involved a pre-interview 'test' (involving 20 incomplete statements for completion), followed by a semi-structured interview to further understand statement responses. Analysis of both of these guided the structure of a final concept mapping interview and informed prompts (on post-it notes) for the participants to rearrange and build upon. Grenier & Dudzinska-Przesmitzki [59] felt this triangulation strengthened the credibility of findings and was more likely to capture all elements of a participant's mental model.

Clearly there is a spectrum of researcher influence in the design of the model, and while the open unstructured approaches have minimal influence, they present challenges for the participants to complete and researchers to analyse. Thus, prompts, structure, constraint, and seeded topics are often required to ensure successful task completion. However, as stated by Bostrom et al. [119] it is important to design elicitation to reduce the chance of reported beliefs being a "function of how they are elicited" (p. 960). Thus Bostrom et al. [119] utilised standardized open-ended questions to address this while also enabling a more uniform replicable task [see also 90].

We can also draw lessons from other fields, such as cognitive psychology and memory research, to understand some of the challenges of, and influences upon, the elicitation process. The elicitation itself can be viewed as a form of construction of a mental model within the particular social and physical environment of elicitation [120]. Thus it is to be expected that the elicitation process will be influenced by the researcher given that under some circumstances this process can have varying levels of 'co-construction'. The mental model produced can also be described more as a 'transactive memory system' [120], rather than an 'output' of a static unbiased model that resides within an individual. It is thus unlikely that the role of the researcher can be 'removed' from this process, rather these influences should be documented and acknowledged (as is fundamental to many qualitative research methods [e.g. Ref. [121]]).

It is important to also recognise that mental models may change at different elicitation times, and under different social and environmental conditions, as they represent a snapshot in time containing factors most relevant to the participant in that situation. We thus suggest that if time permits, prompts that are informed by earlier phases of data collection from the participant(s) themselves may produce maps that are more representative of the broader mental model constructs of an individual than prompts, constraints, or imposed map structures introduced from a researcher's perspective or from within the same interview session.

4.2. Moving beyond language as a medium for elicitation

A number of the selected studies highlighted the importance of moving beyond language to identify people's mental models, identifying that a wide range of elicitation methods (drawings, card-sorting, photo elicitation) enable different ways of identifying knowledge structures. Concept mapping activities (section 3.3) can provide 'visual pictures' of knowledge structures that are equal in effectiveness to more time-consuming interviews [68]. They can also enhance cognitive and meta-cognitive processes, facilitate meaningful learning [71], and help organise information and promote higher-level thinking [68]. Similarly, Wood et al. [34] discuss how diagrammatic representations used to elicit mental models can assist individuals "when reasoning and making inferences" (p. 1335).

Similarly, Cassidy & Maule [95] discuss how the creative process of visual elicitation helps participants reflect more deeply on topics, where drawing helps people structure and organise thoughts systematically (e.g., via concept maps), with less researcher influence (section 4.1) and increased participant ownership of the research. Levine et al. [60] posit that the tactile nature of freelisting, sorting, and drawing tasks enabled people to access their implicit knowledge, proposing this recombination of techniques enables the formation of "aggregate mental models" of tacit beliefs. Anghelcev et al. [64] asked participants to select and bring an image to the interview that represents their thoughts and feelings about a topic, and identified that using visuals in this manner allows participants to utilise a broader method of communication beyond the verbal, indicating deeper knowledge and understanding. They thus concluded that their visual metaphor ZMET method is advantageous over surveys, focus groups, and interviews because "*language is limited when it comes to conveying complex thoughts or emotions*" (p. 60), while thoughts "*occur as images, rather than words*" evoking deeper elements of human consciousness.

Similarly, Ben-Zvi Assaraf et al. [104] stated that drawing enables participants to more holistically convey their way of thinking and, referring to the work of Paivio [122], argued that "*perception and imagery are at least as fundamental as language*" [104] (p. 456). The use of these broader elicitation techniques also enables 'externalization' of participants knowledge and their representation of the issue at hand [123]. Cognitive research into problem solving and the use of external representations has demonstrated how by interacting with different media external to ourselves (such as via these different elicitation techniques), additional stimuli is provided for thinking beyond acting only as simple memory aids [123]. This thus enables us to see new patterns of meaning [see Refs. [124, 125]].

Not all studies support the use of visual or diagrammatic elicitation over interview or language-based approaches. A direct comparison of oral-based and diagrammatic-oral based elicitation by Jones et al. [58] found that there was no significant differences in content produced (number of concepts, number of functional linkages, density of mental model (linkages/concepts), specificity of concept terms), while the location where the interview and elicitation occurred *did* have a significant influence. Content analysis indicated that situated interviews produced more concepts, while non-situated interviews were dense and had more (cause & effect) linkages. Similarly, Rye & Rubba [67] found that interviews that contained a mapping exercise did not significantly differ from interviews without. They attributed a pre-interview "quiet time" as having a greater influence than the concept mapping itself for constructing thoughts.

The ambiguity of drawing activities, in terms of task-instruction and output analysis was also identified as challenging [37,64,103]. Panagiotaki et al. [103] found drawing with open ended questions more ambiguous than 3D model building and forced choice questions. For their participant group (primary school children), the open design was harder to understand and recall knowledge. Similarly, Cassidy & Maule [95] found that prompts delivered through 'Fuzzy Felt' icons[1] took the pressure off participants to creatively draw from scratch. Considering analysis of drawings and visual elicitation approaches, Anghelcev et al. [64] criticised the non-generalisability of the results, while Ruiz-Primo et al. [37] raised a number of key questions around validity and reliability. However, we note that the weight of this criticism depends upon the epistemological stance of the researcher and that many qualitative researchers do not seek generalisability [e.g. Ref. [121]]. Ruiz-Primo et al. [37] questions included: whether students can produce similar maps on different occasions; how large a sample of concept maps is needed to assess knowledge within a domain; if map scores are sensitive to the sampling of supplied concept terms; if the terms are representative of the subject domain; and whether equivalent concept maps and cognitive structures would have been identified from other techniques.

There appear to be limitations to using only drawing, due to ambiguity, validity, credibility, and repeatability (herein acknowledging that the concept of which varies depending upon the researcher's paradigm), and to using only language due to its limited ability to tap into our knowledge structures compared to other techniques such as drawing, topic sorting, image elicitation, and metaphors. This thus reflects critically on those approaches that indirectly infer mental models, influence diagrams, or concept identification from an analysis of interview or survey data only, and lends credibility to the mixed method elicitation approaches that use direct and indirect approaches [as advocated for by 62]. As stated by Anghelcev et al. [64] "*research methods which rely exclusively on consumers' words to infer their views on a topic could overlook important components of the consumers' mindsets*" (p. 60) (see also Kastens et al. [126] for a relevant discussion of how 'epistemic actions' to facilitate cognition are recognised in geological model drawing and sketch maps).

4.3. The need for an evaluation of analysis methods

As discussed in section 3.4, a wide range of approaches exist to analyse elicited maps both directly and indirectly, and to analyse other data collected from associated activities (e.g., interviews, card-sorting, etc). Reflecting across the elicitation methods (section 3.3) and the analysis methods (section 3.4) there appears to be a number of axes of variance to the design of these methodologies:

1) the degree of associated data analysis needed to construct the maps themselves (indirectly);
2) quantitative vs. qualitative analysis approaches to maps, interviews, and other data;
3) identifying the structure or complexity of a map, and its structural features, vs. scoring a map against a 'correct' map;
4) analysis to identify novel concepts and new understanding of individual or group models vs. to confirm wider prevalence of concepts; and
5) whether the focus is on an individual (e.g. in education) vs. a group (e.g. mental models of risk).

The inconsistency in analysis approaches across studies was identified as a particular challenge by Moon & Adams [74] who called for the development and testing of more analysis methods to compare mental model diagrams. Similarly, Frierichs et al. [38] highlighted the lack of formal validation for mapping analysis processes, finding that the lack of imposed *task structure* [37] in their elicitation process yielded such a wide variation in elicited maps that they were difficult to analyse, limiting the ability to measure constructs. A standardized approach to eliciting mental models via the influence diagramming software 'M-Tool'[2] aims to address this particular challenge [115,116] while also enhancing accessibility across literacy levels. LaMere et al. [62] also identified that future research should identify and explore additional analysis methods like frequency analysis, suggesting that fuzzy cognitive mapping may help smooth the aggregation of mental models. Finally, Greyson et al. [61] also identified the need to develop an appropriate map-analysis methodology, suggesting options could be drawn from semiotic analysis, situational discourse analysis, and hermeneutics (see citations within).

It appears that the more quantitative approaches to analysing mental models throughout these papers are driven by a desire to understand the complexity and structure of these models, to facilitate a comparison between individual models, or to aggregate models across groups and individuals. However, the more qualitative approaches are more exploratory and focused on identifying new holistic ways of understanding people's beliefs and values (e.g. Kuonen et al. [91,92], or the values-informed mental model approaches [VIMM, 98,99]). However, Pezzullo & Filippo [100] highlighted that a mixed method analysis approach provided better representation of mental models.

The inconsistency in analysis also makes comparison across studies particularly challenging, as identifying limitations and assumptions across studies becomes an almost impossible task. Thus, we further the call of Moon & Adams [74], Frierichs et al. [38],

[1] Fuzzy felt icons are pre-cut felt shapes that can be repositioned on a textured board to create larger scene pictures. In Cassidy & Maule's [95] study these included icons of food chain elements (e.g., food items, factory, transport, elements of nature, etc.), and they relate the use of Fuzzy Felt to Gauntlett's [170] use of LegoTM figures to encourage 'playlike' creative interactions.

[2] https://www.m-tool.org/ last accessed 21/04/22.

[3] https://www.scopus.com/.

[4] https://webofknowledge.com/.

[5] https://www.apa.org/pubs/databases/psycinfo.

Greyson et al. [61], and LaMere et al. [62], and propose that we not only need to identify appropriate techniques and validate those existing, but that we need to systematically categorise the different approaches and evaluate their suitability, such that their appropriate applications and limitations can be clearly identified.

We thus suggest the following characteristics could be used as a starting point to classify the various map analysis approaches: *scoring* for accuracy; *structural* analysis or complexity; *concept* analysis; *construct* and concept identification; *causal* chains; and *knowledge* assessment. Analysis approaches for data from other activities, such as interviews and card-sorting could be tentatively classified by its *approach* (e.g., thematic; content; salience; network; etc) and its *goals* (concept or construct identification; confirming prevalence; indirectly constructing mental models; identifying values; etc.).

4.4. The role of the expert model

Many of the elicitation processes compare expert and lay mental models of a process or risk. In some contexts, such as education, the presence of an expert (scientifically 'correct') model to which a public or student model is compared is fundamental to the goal of assessing effective learning. However, in risk contexts, where there are social and cultural influences of what is perceived as a risk, Cassidy & Maule [95] highlighted that some of these approaches 'privilege' the expert mental model and expert perspectives on risk over those of the lay public or target audiences. As discussed in section 3.3, the role of the 'expert' model varies across different MMRA approaches. For example, Hageman et al. [40,89] utilised the expert model to inform the design of lay model interviews, while Bruine De Bruin & Bostrom [57] and Skarlatido et al. [90] utilised expert model analysis codes to inform analysis of lay interviews. Meanwhile other studies generated a base expert decision-analysis model to which lay perspectives are compared to inform risk communication [26,27,91–94].

As reviewed in Doyle & Becker [41] risk communication has shifted over time from risk education in the 1970s towards risk consultation in the early 2000s [30], including a spectrum of approaches that ranged from 'one-way' to 'two-way' communications, also defined as 'informing' vs. 'empowering', or 'technical' vs. 'democratic' [28–33]. The earlier models were often grounded in a 'deficit' model of communication [see also [127]] which viewed the public as lacking experts' understanding of risk and science and aimed to rectify those knowledge gaps. Later approaches recognised the importance of integrating and understanding values in the risk communication process [see e.g. Refs. [43,128]], particularly where risks can become politically contested or disputed [129], aiming to include audience concerns in the risk assessment itself [29] and restore trust [see also [130]]. Since then, risk communication practice has evolved further to include more social perspectives around risk and decision making [e.g. Refs. [131–133]]. Similarly, science communication has shifted from a 'science literacy' approach through to a 'science and society' approach that recognises citizens' roles in the construction of science itself [41,44,45]. People's values and group identity can be stronger predictors of their risk judgments than scientific literacy and numeracy [30,134–136]. Accordingly, Cassidy & Maule's [95] adaptation of the Morgan et al. [15] MMRA approach by integrating it with techniques that enable social representations of risk knowledge to be incorporated into the models (see section 3.3 above, and Breakwell [96]), appears to be aiming to adopt these latter 'science and society' science or 'democratic' risk communication approaches such that the socially constructed nature of risk can be accounted for.

Reflecting on Cassidy & Maule [95] and the range of different mental model elicitation methodologies and communication practices reviewed here, we propose that if researchers are using mental models to inform risk or science communication then researchers should carefully consider how they would compare 'expert' and 'public' models in a study design. Ultimately the goal of these approaches is to identify the mental models of each and focus communication campaigns on where they differ [57]. This is particularly valuable during a crisis which may demand a rapid one-way dissemination of appropriate risk and science advice to large audiences.

In longer-term planning or in the recovery phases of a disaster, there may be sufficient available resources and time to effectively collaborate and develop more democratic, empowering, two-way risk communications [see e.g. Ref. [31]] or to co-develop the science and risk assessment in a participatory manner with communities [e.g. Ref. [131]]. The MMRA mental model process thus offers an invaluable tool not just to enhance rapid communications, but to assess the range of priorities and perspectives for the basis of any participatory work. In a manner similar to the scientific co-production of knowledge [e.g. Refs. [137–139]], participatory approaches to communication aim to identify users' or audiences' science priorities and needs rather than generating communications that might be formatted to meet a specific model of stakeholder decision making [8,140–144]. Thus, mental model elicitation techniques that identify values [98,99] can particularly enhance this participatory process.

Accordingly in collaborative co-production contexts, the use of the term 'expert' (rather than 'scientist' or 'risk assessor'), and the privileging of an 'expert' model as the 'correct' risk or science model, can become a barrier to effective development and uptake of the final risk communication products. Trust in the source, communication, and process may also be impacted if expert renditions do not reflect what is seen as important by users during the co-design. This is particularly true in environments where a pluralistic approach to science is adopted, which aims to respect equally the various epistemologies and philosophies of participants [145–149]. As discussed by Greyson et al. [61], a related advantage of direct mapping approaches is thus their ability to centre the voice and views of marginalised groups more so than other interview approaches.

Thus, future research should explore how the mental models of risk approach can be variously adapted for these different contexts, for example to either enhance democratic participatory approaches fundamental to community decision making, or to enhance mass risk communication campaigns that aim to alter individual behaviors. This includes exploring how the differences in mental models can be explored without privileging a particular group, and how to effectively elicit mental models from large and diverse population groups. As discussed in our method (section 2), contextual factors including cultural worldviews, economics, politics, and social structures [53–55] can influence perceptions and communication of risk and its associated science. Thus, while we do not consider any one method, design choice, or analytical approach to be more or well less suited to different subject areas, we do highlight that the contextual influences, assumptions, bias, and philosophical choice of the researcher should be considered in the evaluation of the method choice (such as the role of the expert model) and interpretation of associated findings (see section 5.1 for more). This also has ethical considerations, discussed next.

4.5. Ethics: how the process influences worldviews

An interesting, and unexpected, final theme concerns the ethics of eliciting mental models in general. Skarlatidou et al. [90] highlighted how a mental models methodology can be used to change participants' world views. While this might be a primary goal in education or risk communication contexts, in other contexts it presents an ethical concern. The methodology and the final product could be used to change views and influence opinions, and could mislead or misinform the final user to meet a developer's agenda, or to hide or simplify risks. Similarly, the elicitation process itself (not just the final communication product) can change mindsets due to its involved and creative nature (see also section 4.2). Hartmeyer et al. [71], Cassidy & Maule [95], and Tripto et al. [68] all identified that elicitation processes that use visual externalization can enhance cognitive processes, facilitate learning, help participants reflect more deeply, and help them organise and promote higher-level thinking (see sec 4.2). LaMere et al. [62] additionally highlighted that direct elicitation processes involve a deliberate articulation and visualization of knowledge which can also be a learning experience for participants. The potential for elicitation to change the way participants think is thus highlighted by Skarlatidou et al. [90] as an area of future concern, such that we need to ensure and safeguard the system's credibility and avoid its abuse. Accordingly, researchers must carefully reflect on any undue influence from the researcher during design and be aware of the potential to change mindsets. This is particularly important in disaster risk contexts where the socio-political landscape and history, and related power dynamics and imbalances will affect participatory processes [54,150], and impact the trust needed for effective communication and application of these methods. Thus, while no singular method or analytical approach can be prescribed for different subject areas and contexts, the researcher should reflect on these contextual factors and the ethical considerations of their selected method (discussed further in section 5.1).

Finally, an additional ethical consideration was raised by Greyson et al. [61], who highlighted the importance of gaining participant consent not just to participate in the study, but also to specifically obtain consent to retain any artistic output generated by participants through the elicitation process, such as from drawings, map construction, or photo elicitation. This is particularly important with participants who identify as artists or indigenous, where intellectual or cultural property may be shared by participants (see also Smith,[151]).

4.6. A preliminary typology for mental model elicitation and analysis techniques

This review demonstrates the wide variety of elicitation and appropriate analysis techniques to: a) indirectly develop and compare mental models, and b) directly assess the elicited maps. Considering the techniques within and across the identified approaches (Fig. 1, Table 5), those that are commonly used to **directly elicit mental models** (usually within an interview setting) include:

- **Structured and constrained drawing with prior training**, e.g. to create influence diagrams or concept maps [e.g. Refs. [27,56,70,94]], or for fuzzy cognitive mapping [e.g. Ref. [77]].
- **Unstructured semi-constrained drawing of concept maps**, which can be relational as well as causal [e.g. Refs. [73,75]], and can use other media (e.g., fuzzy felt method, Cassidy & Maule [95]).
- **Completely unstructured and unconstrained free drawing** of the topic [e.g. Refs. [61,102]].
- **Other mapping approaches** such as information world mapping, knowledge mapping, flow mapping, causal loop diagrams, and graphs [e.g. Refs. [38,61,63,84]].

In the above definitions, 'structure' herein defines the degree to which the mental model has researcher imposed rules on the organisation of its content, whether elicited directly or inferred directly. Thus, in an unstructured approach participants create and define the structure of the models themselves [62], whereas in a structured approach the researcher defines the structure of the content of the model (such as spider, hierarchic, chain, etc. [37]). 'Constraint' relates to the restrictiveness of the task, such as being asked to construct a hierarchical or network map [37] or being provided with concept terms to use, etc., and only applies to direct elicitation techniques. For further discussion and definitions see section 3.2.

These above techniques can be further categorised by their task demand and content structure [37]. The following techniques then aim to **directly elicit constructs to inform indirect development** of mental models:

- **Construct elicitation** through photo elicitation and seed topics [e.g. Refs. [15,64,104]].
- **Laddering techniques** (Landsfield Laddering) and Repertory Grid techniques [76,100,104,106,107,152,153].
- **Brainstorming**, including freelisting and sorting [e.g. Refs. [27,60,64,70,73,74,90,94,101,104]].
- **Sorting**: Card, topic, and photo sorting, including sorting into: positive/negative, themes, risks/benefits, relevance, clusters/links, seriousness/likelihood, similarities/differences, importance, etc. [e.g., above and [39,40,89]].
- **Word Association** [e.g. Ref. [104]].
- **Metaphor analysis**, including visual metaphors and photo elicitation [e.g. Ref. [64]].

Additional techniques can be used to supplement and provide deeper understanding across these mental model elicitation approaches:

- **Topic sentence completion** questions delivered ahead of interviews to inform concept map interview structure [e.g. Ref. [59]].
- **Attitudinal surveys** using inventories and measures [e.g. Ref. [56]].

- **Situational interviews** and mental model elicitation on-site [e.g. Ref. [76]].

Finally, there are those techniques used to **indirectly elicit mental models**, and often in combination with the techniques listed above:

- **Semi-structured interviews** which are then subjected to either thematic [e.g. Refs. [39,90,98,101]] or content [e.g. Refs. [27,66,70,76]] analysis, including techniques taken or adapted from grounded theory methodologies [39,91,92,99], network analysis [38,67,88] or salience analysis [60], or via the use of mapping software [76,115,116] (see section 3.4).
- **Focus groups and workshops** [e.g. Refs. [26,66,72,84,93]], or roundtables [101].
- **Questionnaires and Surveys** [e.g. Refs. [27,56,57,66,72,102,103,154]].

This supplements the list of Moon et al. [36] who identifies: interviews, drawings, repertory grids, a variety of mapping techniques including influence diagrams, cognitive maps, fuzzy cognitive maps, and Bayesian belief networks (see refs within; see also categorisations in Refs. [34,37,73]). However, our list above aims to be distinct in its classification of techniques and methods into direct and indirect approaches [62]. We note here that the overlap in terminology for techniques, tools, and approaches found across the literature presents a particular challenge when selecting, designing, and understanding an appropriate method. Thus, there is a need for more clarity, potentially through the development of a typology of these data collection methods and approaches.

5. Concluding remarks

Over the last two decades the processes of disaster risk assessment, management, and communication have shifted from top-down, one-way approaches towards more democratic shared assessment of risk, that recognises the social construction of risk [96,97,155] and the importance of working with communities to identify the risks, priorities, and needs [see review in Ref. [144]]. This has resulted in the development of a range of participatory, co-production, knowledge exchange, and engagement approaches [137,138,141,156,157]. These aim to involve stakeholders in the research process itself in a trusted ongoing relationship that works towards ensuring research is 'socially responsible' through a process that identifies decision relevant information for communication [140,144,158–160]. Such an approach is empowering [28–30,43,131] and moves from a 'deficit' informing approach to one of risk consultation, similar to the science to society movement ([44,45]; see section 4.4).

However, challenges can exist in identifying suitable tools with which to identify these perspectives, and to develop a shared understanding in a co-development or participatory process. This is particularly important when working with the diverse groups that collectively manage risk, including communities, scientists, engineers, non-governmental and government decision-makers, and beyond [159] who are each influenced by different individual, social, and cultural values in their assessment of risk [9].

We thus suggest that the elicitation of mental models presents a valuable tool to use within these settings, to enhance shared understanding of phenomena, process, beliefs, values, and needs. Thus the mental model approach can be applied not just in the development of disaster risk communication to inform education campaigns or effective warnings, but to enhance participatory and co-development approaches to risk by providing a useful tool within which to understand an audiences' 'structural understanding of risk' [161], to identify the audience concerns, goals, and relevant information [29,30,144], and to enhance a shared understanding [159] of risk that can develop trust [162] and ensure disaster science is 'useful, useable, and used' [163].

In recognition of the wider application of this mental model approach, we thus identify an initial typology for mental model elicitation (presented in section 4.6), to help guide the selection of the appropriate mental models approach for different disaster risk assessment, management, and communication contexts. We highlight that the approach chosen may vary depending upon the time and resources available and thus some may have less participatory engagement or co-development than others. In using this initial typology, researchers should reflect on their research philosophy and paradigm to identify where they sit on the spectrum of direct and indirect elicitation process, and their positionality with respect to the role of the expert model and the ethics of the elicitation process.

Through this review we have highlighted the range of approaches that sit within the mental model approach, and recognised challenges which include the degree of researcher influence for different elicitation and analysis approaches, the diversity and inconsistency of analysis approaches, the privileging of the 'expert' in some approaches, the powerful nature of external visualization to elicit these mental models, and the need for careful consideration of ethics due to the potential to change mindsets.

Future research could identify ways to incorporate participants into the analysis of these mental models [see also [95]], to increase validity and further develop the depths of these models, as well as to identify how the lessons identified in this review apply within group elicitation processes. Further, there is a need to explore how these mental models evolve and how conceptualisation shifts over time [see also 38] or through experience [76], and how to identify these changes to further our understanding of the efficacy of education, risk communication campaigns, and community based risk management initiatives.

5.1. Limitations and future research

The focus of this scoping review was to identify the breadth and range of themes in the literature selectively sampled through inclusion, exclusion, and relevance criteria (see section 2). Thus, our aim was not to capture and describe the entire body of literature describing the elicitation of mental models, nor to understand their use outside of the fields of communication, disasters, science, and education. As such, there are several limitations in our review.

First, we confined our scope to science, hazard, and risk (with a particular preference for those that discussed uncertain science or uncertain situations). Consequently, important and relevant texts may have been missed in our key word search or omitted through the relevance search and filtering process on abstracts. Contextual influences on mental models are expected to differ considerably between domains, due to economics, politics and power dynamics, social structure and agency, and cultural worldviews [53–55]. Thus, we did not consider approaches from broader contexts, such as organisational operations, business, and HR. It is unclear the degree to which these contextual influences would moderate the appropriate design of elicitation, its analysis, its findings, or all three. However, given the 'problem domain' is fundamental to the design of the elicitation exercises, we anticipate that there will be considerable variation across domains (e.g., focusing on influence diagrams in organisational networks vs. free drawing of scientific systems). We thus highlight that there is a need to identify robust frameworks for evaluation of these methods that considers contextual factors "*and the underlying frame that influences and is influenced by the research domain*", as developed elsewhere [164] (p. 1) and called for across DRR studies [165,166].

Second, review of these papers with a different application (e.g., education) may draw different conclusions from the literature regarding method challenges. Third, the dependence on abstracts for the first filtering is limited by the quality of the abstract, and its ability to accurately reflect the key messages and content of the associated article. Fourth, when a cluster of articles exist within a methodology or approach, we selected representative examples to focus on reviewing the breadth of different approaches rather than a comprehensive review of each method. Thus, linked articles not selected for review (and used instead as secondary sources) may have included elements of design methodology not captured in this review and its summary presentations. Similarly, as discussed in section 3.3, some papers could have been classified into different categories due to the subjectivity of deciding on the suitable category. Given the focus of this paper is on overall lessons, and the paper categorisation was developed to provide initial order to the large body of literature, this limitation has little impact on our identified challenges, themes, and lessons. However, it should be considered carefully in the ongoing development of typologies of techniques. Additional limitations include the time between the date of our literature search, and publication. As we are not aiming for an exhaustive review, any additional sources found after our search were introduced as 'secondary sources' for comparison of issues identified in the 'primary sources'.

Further, as noted across many other disciplines that investigate human behaviour and reasoning, most studies involve research participants drawn from WEIRD societies (Western, Educated, Industrialised, Rich, and Democratic [167,168]). When combined with our search restriction to English language studies, this results in a cultural bias in our reviewed studies. Some of our reviewed studies were conducted in non-WEIRD societies [e.g. Refs. [64,68,82,102,104]], suggesting these mental model methods are being applied more broadly. However, we anticipate that culture will add significant contextual factors to an individual's mental model, due to a range of influences including their worldviews, degree of collectivistic or individualistic thinking and its relation to perceptions of social systems, and the socio-political landscape within which the study problem is based. Thus, design, application, and interpretation of these methods will need to be understood through these different cultural lenses. This requires a systematic investigation and comparison of these methods across cultures, which was unfortunately beyond the scope of this current study. We recommend it be prioritised for future reviews and considered in the design of mental model research itself [168]. In particular future research should consider the appropriateness and adaptation of these methods for cultures that view knowledge as shared and collectively owned [151, 169], and where a longer co-designed consensus driven group mental model elicitation process should be considered and led by the needs and priorities of those communities (see also the Cassidy & Maule's [95] approach that considers collective social construction and communication of risk).

Future research is also recommended to conduct more comprehensive critical reviews of the key considerations identified in section 4, including: research into the influence of prompts and the consideration of researcher influence on elicitation processes; research that draws on cognitive science to understand the role of external visualisations; and research to identify effective evaluation approaches for elicitation approaches and their analysis. Further research is also needed to identify methods that assess the evolution of mental models, and how conceptualisations change through time and experience.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2022.103084.

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