Communicating uncertain climate futures: Lessons from the literature

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Conflict of Interest

The authors report there are no competing interests to declare.

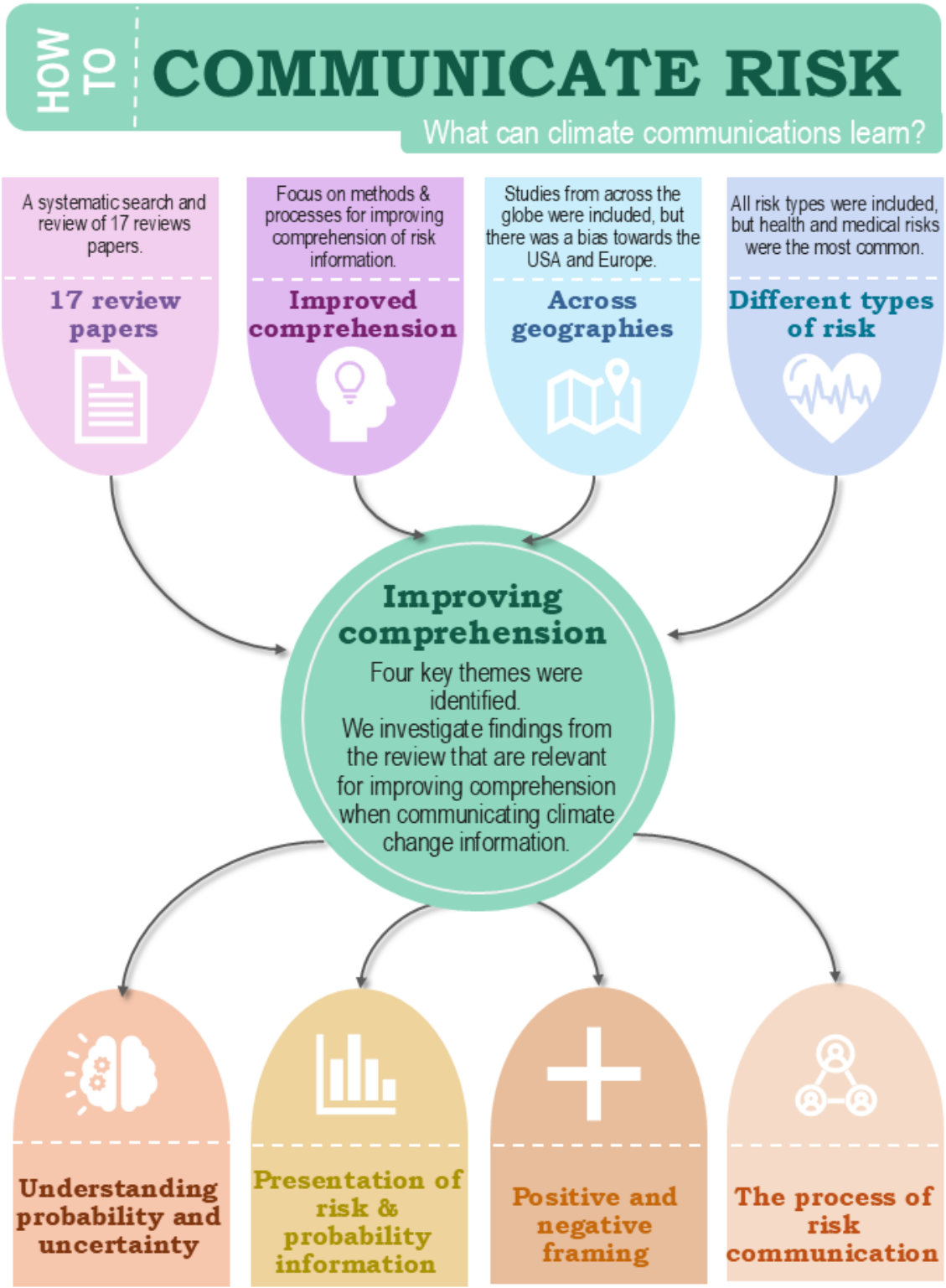
Abstract

There is increasing demand for information about future climate risk to inform climate change adaptation planning. However, climate change impacts are uncertain and complex, and climate information is often technical and challenging to communicate. To inform effective methods for communicating future climate information, we undertake a review of reviews of risk communication literature, with a focus on improving comprehension. We do not constrain our literature search by the type of risk or the geographical region to allow for interdisciplinary and geographical learning, but find that most reviews occur within health, and there is a bias towards North American and European studies. Four key themes were identified during the review: 1) understanding probability and uncertainty, 2) presentation of risk and probability information, 3) positive or negative framing of risk information, and 4) the process of risk communication. Understanding of probabilistic and uncertain information varies amongst not only the general public but also scientific experts, possibly due to differences in cognitive processes and familiarity with statistics. Icon arrays and bar charts were identified as improving comprehension of risk information, whilst qualitative descriptors of risk were deemed less effective than quantitative descriptions, though a combination of the two may be most optimal. Common methods of communicating climate projections (box plots and plume plots) have not been widely reviewed. Health risks have different characteristics to climate change risks and as such

we identify lessons that are relevant to climate, and areas where further research is needed to inform effective climate risk communication.

Graphical/Visual Abstract and Caption

Caption: This article reviews 17 risk communications review articles, with a focus on improving comprehension, to identify effective communication methods and what can be applied to communication uncertain climate futures.


HOW TO
COMMUNICATE RISK
What can climate communications learn?
A systematic search and review of 17 reviews papers.
17 review papers
Focus on methods & processes for improving comprehension of risk information.
Improved comprehension
Studies from across the globe were included, but there was a bias towards the USA and Europe.
Across geographies
All risk types were included, but health and medical risks were the most common.
Different types of risk
Improving comprehension
Four key themes were identified.
We investigate findings from the review that are relevant for improving comprehension when communicating climate change information.
Understanding probability and uncertainty
Presentation of risk & probability information
Positive and negative framing
The process of risk communication

Introduction

There are increasing efforts by countries, companies and individuals to adapt to the changing climate. Although climate services have made progress in building shared understanding of climate risks between climate experts and decision-makers (Steynor et al. 2016), communicating about future climate remains a challenge. It can be difficult for decision-makers to understand how climate change might affect their context and, due to the complex nature of climate adaptation, there are many factors beyond climate influencing decision-making, as well as factors such as local economy and technological development that interact with climate (Tall et al., 2018). Whilst there is unequivocal evidence about climate change at a global scale, there are large uncertainties in how global warming will affect regional and local scale climate (James et al., 2014; Shepherd, 2014). Innovative approaches are applied within the field of climate services to communicate uncertain climate futures, but the efficacy of these approaches is not often assessed systematically. Meanwhile, there is great potential to learn from risk communication research in other domains that have systematically assessed the efficacy of communicating risks. This review of reviews brings together empirical research findings and recommendations from across the broader field of risk communication to identify conclusions that are relevant for communicating uncertain climate change. We focus specifically on comprehension of information, noting that comprehension of future climate risk is a necessary but by no means a sufficient condition for effective adaptation decisions.

Insights from the broader field of risk communication have the potential to be of considerable use for informing climate change communications. The goals of risk communication can vary, but usually include promoting or influencing comprehension, perception, preference, behaviour and/or informed decision making. While the broader topic of climate risk perception has been widely studied (Conway, 2024; Pidgeon, 2012; Salas Reyes et al., 2021), existing research has largely focussed on beliefs and concerns about climate change, with fewer studies directly addressing the challenge of improving comprehension of future climate information. Additionally, there is a wealth of literature in environmental psychology, which has identified important lessons for communicating climate change to promote sustainable mitigation behaviours (Steg et al., 2012). While this latter body of work provides valuable insights for communicating in an adaptation context, it does not always focus on the

specific challenges of communicating technical, quantitative, and uncertain information to inform decision-making.

An understanding of climate projections and risks are required for an individual to access and evaluate future information, process the meaning of risk estimates and to make informed decisions (Pidgeon & Fischhoff, 2011). Failure to consider the uncertainties inherent in climate projections can result in poor understanding of this information, or even maladaptation (Schipper, 2020). Studies that have investigated comprehension of climate projections indicate that preference for specific communication formats does not always translate into better comprehension (Lorenz et al., 2015) and may in some cases result in overconfidence in understanding (J. D. Daron et al., 2015). Meanwhile, mapping climate model data in slightly different ways can lead to large differences in interpretations of precipitation change (J. Daron et al., 2021), highlighting the need for further research to better understand appropriate ways of visualising risk information.

Just as climate information users require information that is understandable, professionals working in climate science need guidance on how to communicate uncertain climate futures. Intergovernmental Panel on Climate Change (IPCC) authors have called for guidance on visual communications and communicating probabilistic information (Janzwood, 2020). Meanwhile a review of climate information websites found that the websites required a high level of technical capability and that those developing the websites overestimated how easy they were to use (Hewitson et al., 2017). Indeed, climate scientists' extensive familiarity with their area of expertise may hinder their ability to communicate information to non-specialists, due to disparity in experts' and users' consider as easy to understand (Pidgeon & Fischhoff, 2011; Porter & Dessai, 2017).

Based on existing empirical risk communications research, we investigate 1) what communication methods improve comprehension of risks and 2) how relevant these broader risks communication findings are to improving understanding of future climate change information? We undertake a review of reviews to synthesis the vast amount of existing risk communications literature to establish a consensus amongst findings and reflect on the relevance to climate change communications. This manuscript is structured with a review methodology, followed by the literature trends in the identified

review papers. A results section with four themes is discussed before the relevance of the findings to future climate information and risks are presented. The paper concludes with suggestions for future research and conclusions.

Methodology

A systematic search and review of reviews of peer-reviewed journal articles was undertaken (Grant & Booth, 2009) with a focus on the risk communications findings and frameworks in the context of improving comprehension, understanding or interpretation. Comprehension is an individual's ability to understand a concept or action and relies on a higher cognitive process that also relies on existing knowledge to make relations between concepts (Y. Wang & Gafurov, 2003). Whilst communication, understanding or interpretation are uniquely defined, we use them interchangeably depending on the terminology used in the studies being reviewed. As such the search strings were "(probabilit* OR uncertain* OR futur* OR Africa*) AND ("meta-analysis" OR "meta-analysis" OR "systematic review" OR "thematic review" OR "qualitative review") AND (understand* OR knowledge OR interpret* OR comprehen* OR decision) AND ("risk communication") NOT (child*) NOT (disability OR disabled) NOT ("mental* ill*") NOT (addict*) NOT (dementia)."

Projections of climate to 2050 and 2100 can be difficult to interpret and use in a decision context due to the uncertainties and probabilistic nature of projections. As such, literature that is focused on communicating in uncertain contexts were included in the search, alongside a specific search for African studies. Previous research has primarily focused on Western, Educated, Industrialised, Rich and Democratic (WEIRD) societies (Newson et al., 2018) leaving a gap in studies focused on much of the African context. Climate services in Africa are rapidly developing, alongside the already vast research and actions in climate adaptation and climate resilient development (Vincent et al., 2020; Vogel et al., 2019), and research on the best methods to communicate future climate information may assist in this effort.

An adapted PRISM search flow chart (Moher et al 2009) was used to guide the review using three stages: identification, screening, and eligibility (Figure 1). Peer reviewed journals were identified using

three databases: Web of Science, Scopus and PubMed. The two-stage screening phase included screening the title and then the abstract and were guided by an inclusion and exclusion criterion. To be included in the review, papers had to be: focused on improving understanding, interpretation or comprehension of a risk; available in full text; written in English; be a systematic, qualitative, meta or thematic review; and include adult participants. Review papers were excluded if they had included review papers in their review, as this would have resulted in a review of review of reviews. Additionally review papers that included child participants; participants specifically living with mental illness or physical and/or mental disabilities as they were not deemed to be the relevant context and tend not to provide findings on uncertainty communication that are potentially generalisable to the context of climate communication. There were no limitations on the year papers were published nor the study design or risks being researched. This was to allow cross disciplinary learning across fields with various risks and diverse methodological approaches.

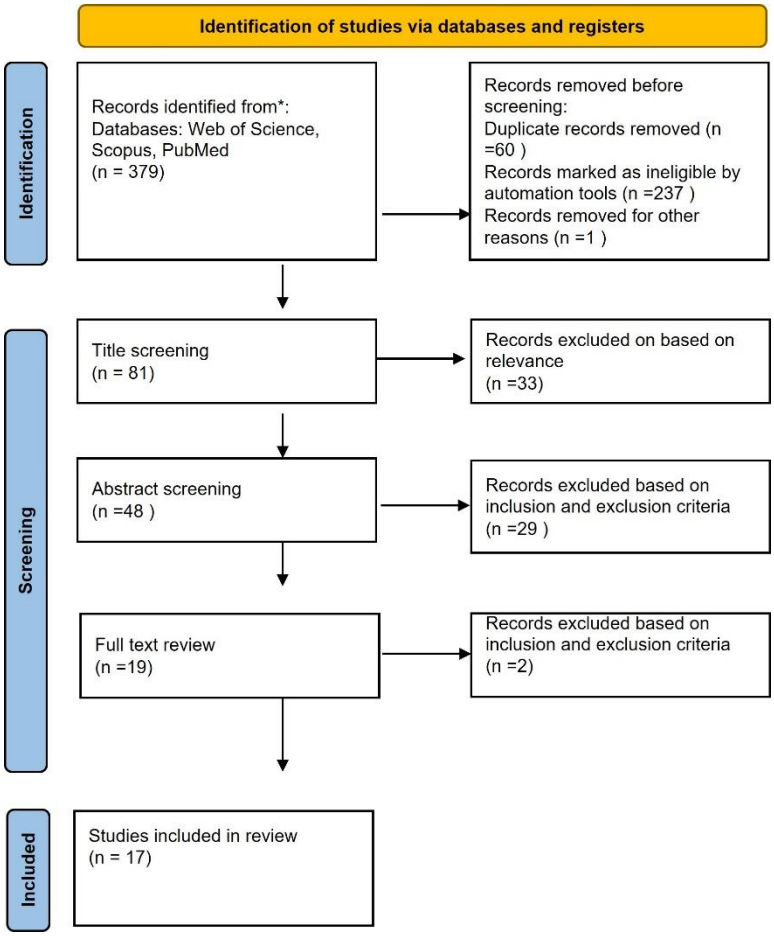


Figure 1. PRISM search flow chart adapted from Moher et al (2009)

The abstract screening was carried out independently by two researchers who then compared their decisions and discussed any variation in the decisions. The inter-rater reliability was measured using the Cohen's kappa coefficient, which measured at 0.43 (fair agreement). During the full text screening, two papers were removed as they were not relevant. Specifically, one included systematic review in their study and the other was not focused on understanding. The systematic review was not preregistered, however, the search strategy and codes for each database are available for replication in the Supplementary Materials.

Papers were analysed using a narrative synthesis using textual descriptions and tabulation (Rodgers et al., 2009). During the analysis, all the papers were read, notes were taken about the papers and information linked were entered in a table. Information in the table included: journal; authors; first author country; first author's institution; review method; databases used for search; geographical focus; years included in the review; number of studies included; methodology type; participant group; risk ; use of a theoretical or conceptual framework; main objective; main outcome summary of findings; research suggestions; intervention; exclusion criteria; inclusion criteria; effect size and effect size method (Supplementary Materials Table 1). The paper is ordered by the study designs that were included in the review: RCT, RCT and non-RCT, Quantitative and Mixed Method (Table 1). Due to the study design heterogeneity, meta-analysis could not be conducted and instead a narrative summary of papers occurs in each of the four identified themes using a thematic analysis of the objectives and summary of findings, before an overall summary of findings is provided (Rodgers et al., 2009).

Results

This section will outline the literature characteristics from the 17 papers included in this review of reviews, before providing the results of the findings from the papers which are presented by themes.

*Table 1 Final list of the 17 systematic review studies that were included in the review of reviews. *- Harrison et al., (2014) is one study which include a rapid narrative review and a systematic review*

Title	Authors	Number of studies included	Participant group	Risk Type	Methods included	Main objective	Summary of findings
Visualizing risks in cancer communication: A systematic review of computer-supported visual aids	Stellamanns *et al.,* (2017)	13	Lay people or patients	Health /medical	RCT (Randomised Control Trial)	Review literature on computer supported visual aids for behaviour, comprehension and preference	Static graphs (icon arrays, bar charts and pie charts) show some "promising results" on behaviour intentions, comprehension, accuracy and preference compared to written text. Some studies found no or moderate effects. Dynamic/interactive graphs research is lacking and more research is needed before conclusions are made.
The effectiveness of one-to-one risks-communication interventions in health care: A systematic review	Edwards *et al.,* (2000)	96 (effect size based on n=82)	Not stated	Health /medical	RCT and non-RCT	Review literature on the effectiveness of clinical intervention to change patients knowledge and perception. Identify potential effect modifiers on risk communication	Risk communication interventions were generally associated with positive (beneficial) effects. Interventions using individual risk estimates were associated with larger effects than were those using more general risk information. Outcome variables included perception, behaviour, anxiety and knowledge.
A systematic review of risk communication in clinical trials: How does it influence decisions to participate and what are the best methods to improve understanding in a trial context?	Coyle and Gillies (2020)	7	Hypothetical and real potential clinical trial volunteers.	Health /medical	RCT and non-RCT	Review evidence on methods for communicating risk to potential trial participants during the informed consent process	No clear method for improving understanding of clinical trial risks. Risk framing and influence on understanding had mixed results. Quantitative formats, particularly frequency formats and some visual aids appear to have promise, but more research is required.
Imprecision and Preferences in Interpretation of Verbal Probabilities	Andreadis *et al.,* (2021)	33	Lay people	Health /medical	RCT and non-RCT	Assess patient interpretation of and preferences for verbal probability information	Interpretation of qualitative probability terms are variable, overlapping and do not link with the quantitative probabilities assigned by experts. Suggests quantitative probabilities are used.

Title	Authors	Number of studies included	Participant group	Risk Type	Methods included	Main objective	Summary of findings
in Health: a Systematic Review							Quantitative probability estimates for verbal terms were higher than their actual assigned probabilities.
Evidence-based risk communication: A systematic review	Zipkin *et al.,* (2014)	84	Patients or healthy volunteers	Health /medical	Quantitative	Review methods of communicating probabilistic information to patients and the effect on their cognitive and behavioural outcomes.	Visual aids (icon arrays and bar graphs) improved patients' understanding. Accuracy was lower and risk perception higher for qualitative descriptors compared to natural frequencies or icon arrays. Denominator neglect and effect of natural frequencies was heterogenous.
Translating evidence-based information into effective risk communication: Current challenges and opportunities	Ghosh and Ghosh (2005)	52	Physicians, patients and students	Health /medical	Quantitative and qualitative	Physicians' understanding of probability statistics and terms, identify the modes and their effectiveness of how risk is communicated to patients	Physicians and medical students overestimating specific probabilistic statistics. Physicians have widely varying understanding of probability terms. Patients vary in their ability to grasp information about risk presented as numbers and percentages. Decision aids had an improved understanding but there is a lack of consensus of how to best communicate medical risk. Pictorial (infographics) may be an effective method to communicate risk.
Design Features of Graphs in Health Risk Communication: A Systematic Review	Ancker *et al.,* 2006	24	Patients	Health /medical	Quantitative and qualitative	Effect of graphics on quantitative reasoning, behaviour change and preferences	For good quantitative judgements: graphical element should be proportional to the number it portrays. Graphs emphasising numerator of a risk ratio more likely to promote behaviour change. Bar charts, risk ladders, scales and sequentially arranged icons can help patients understand individual risk. Graphical features that improve quantitative reasoning are different to the ones that induce behaviour change. Features that viewers may like may not improve quantitative reasoning or behaviour change.

Title	Authors	Number of studies included	Participant group	Risk Type	Methods included	Main objective	Summary of findings
Perception and Communication of Flood Risks: A Systematic Review of Empirical Research	Kellens *et al.,* 2013	57	Not stated	Flood	Quantitative and qualitative	Explore literature on flood risk perceptions and flood risk communication	A lack of research and limited theoretical background on flood-risk communication. Hard to compare across studies due to difference in methodology and frameworks. Almost an absence of true risk communications research on flood risk & all such recommendations are vague.
Risk as an attribute in discrete choice experiments: A systematic review of the literature*	Harrison *et al.,* (2014) (Systematic review)	117	Patients, healthcare staff	Health /medical	Quantitative and qualitative	Identify healthcare discrete choice experiments that incorporate risk and evaluate methods to present risk attributes	Risk attributes mostly communicated quantitatively (frequencies, percentages or combination of both). Denominators are presented differently (not always in natural frequencies). 22% studies communicated using both qualitative and quantitative probability descriptors. Risk was most often communicated as a point estimates without a range. Risk was framed negatively in 87% of studies. No consensus of a consistent approach to communicating or framing risk information for better understanding.
	Harrison *et al.,* (2014) (Rapid narrative review	99*	Patients, healthcare staff	Health /medical	Quantitative and qualitative	Review approaches to healthcare risk communication	Some studies reported qualitative probability descriptors did not aid understanding of information and was one of the least successful communication tool. No clear consensus but more general support for communicating risk through graphical or pictorial images, icon arrays and risk ladders.

Title	Authors	Number of studies included	Participant group	Risk Type	Methods included	Main objective	Summary of findings
Evaluating the Mental Models Approach to Developing a Risk Communication: A Scoping Review of the Evidence	Boase *et al.,* 2017	12	Various	Various (technology, disaster and health)	Quantitative and qualitative	Review studies that have evaluated communications using the Mental Models Approach to Risk Communication (MMARC)	Using MMARC had a positive effect on some (if not all) of the measured outcomes where knowledge was the most frequently used outcome (n=11). Most reported a significant improvement in participant knowledge following exposure to MMARC. MMARC maybe a useful framework for risk communications. No consensus on risk communication format or length is superior as all methods improved knowledge.
Communicating Environmental Health Risks with Indigenous Populations: A Systematic Literature Review of Current Research and Recommendations for Future Studies	Boyd and Furgal (2019)	13	Indigenous populations	Environmental health	Quantitative and qualitative	Review the focus of environmental health risks to indigenous populations, effective communications & identify gaps and recommendations	Almost all studies successful communication strategy involves the affected population in design and delivery. Developing communication processes that engage with and include Indigenous populations in message design, using trusted spokespeople, create communications that are understandable to affected population.
The effectiveness of Direct to Healthcare Professional Communication (DHPC) – A systematic review of communication factor studies	Møllebæk *et al.,* (2019)	16	Healthcare providers (HCP)	Health/medical	Quantitative and qualitative	Review, systematically appraise and assess the effectiveness of DHPC studies which report on the communication factors.	HCP found DHPCs lacked clarity (only by Americans HCP). HCP had different demands for the DHPCs as some want specific recommendations and others want facts or data that patients and HCP can use to make decisions. User knows best - risk communications starts and ends with the recipient. HCPs adapt communication based on patient literacy to improve understanding.
Communicating uncertainty during public health	Sopory *et al.,* (2019)	46	Public	Emergency	Quantitative and qualitative	Identify effective ways to communicate uncertainties to public audiences, at-risk	Communicating explicit information about uncertainty is required and generally agreed but it must be consistent, noncontradictory, clear and easy to

Title	Authors	Number of studies included	Participant group	Risk Type	Methods included	Main objective	Summary of findings
emergency events: A systematic review				public health		communities, and stakeholders.	understand. Some studies highlight the negative impact of communicating uncertainty as public cannot understand and/or conceptualise scientific uncertainty. Uncertainty information is prone to misinterpretation by both public and scientists. Quantitative interpretation of qualitative probability descriptors is not completely accurate. Public health emergencies have a chain of decisions and information flows where uncertainty can propagate. Different public health emergency stakeholders understand and experience uncertainty differently and may make suboptimal decisions.
A systematic review of health risk communication about Electro-Magnetic Fields (EMFs) from wireless technologies	Boehmert *et al.,* (2020)	28	Not stated	Health /medical	Quantitative and qualitative	Reviews risk communications literature in relation to Radio-Frequency (RF) -EMF mobile communication technologies risk	Less technical and simplified communications were better understood. Presence vs. absence of an uncertainty sentence did not have influence the assessment of scientific knowledge.
Communicating treatment risks and benefits to cancer patients: a systematic review of communication methods	van de Water *et al.,* (2020)	28	Cancer patients, healthy volunteers and HCP	Health /medical	Quantitative and qualitative	Summarise literature on methods of communicating probabilistic information for cognitive, attitudinal and behavioural outcomes	Less information at one time may improve understanding, but heterogeneity in cognitive results. Precise, defined risk (in percentage/frequency formats) about side effects were better understood compared to qualitative information. Potential source of recall bias in this result. Inconclusive results about most effective graphic type. Results were quite mixed and various methodologies are a barrier to making further conclusions.

Title	Authors	Number of studies included	Participant group	Risk Type	Methods included	Main objective	Summary of findings
Cardiovascular risk communication strategies in primary prevention. A systematic review with narrative synthesis	Schulberg *et al.,* (2022)	31	individuals without known cardiovascular disease	Health/medical	Quantitative and qualitative	Evaluate effectiveness of cardiovascular risk communication strategies for improved understanding and to promote risk changes	Heterogeneity in outcomes and study design. Nine different categories of cardiovascular risk communication strategies were identified. Cardiovascular heart imaging and heart age (health of heart) were most effective at communicating risk, and bar charts, percentages and infographics were less effective. Conclusions for improving understanding are absent.
Communicating Probability Information in Weather Forecasts: Findings and Recommendations from a Living Systematic Review of the Research Literature	Ripberger *et al.,* (2022)	29	Not stated	Various (weather, disaster and health)	Quantitative and qualitative	Review literature on effective ways to communicate probability information and the evidence for various practises of risk communication	Better understanding when probabilistic forecasts are communicated compared to deterministic forecasts. Public can understand forecast probabilities but explanation of the forecast's events is required. Severity of communication, directionality, word choice are factors in the interpretation of probabilities. No general consensus on how to communicate probabilities in the numeric form (%, frequencies or odds) for comprehension, and likely depends on the context. Including probability information in weather forecasts improves comprehension but there is no consensus on the best way to do this.

Literature characteristics

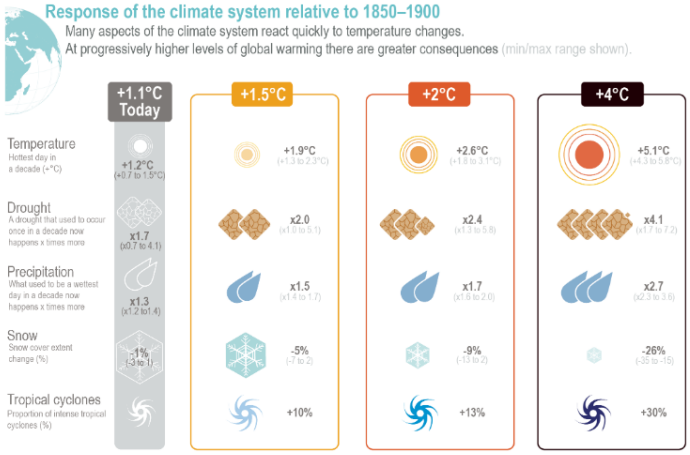
The 17 review papers included in this review of reviews were published between 2000-2023 meanwhile, the review papers reviewed studies that were published from 1966-2020. The lead authors were based in the USA (n=7) and Europe (n=10). The review papers were published in an array of journals (Supplementary Materials Table 1), but the most common were health or medical journals (n=10). As such, most of the papers were also focused on health risks (n=12). A mixture of risks was included by two papers, with one including weather, disaster and health risks (Ripberger et al., 2022) and another technology, disaster and health risks (Boase et al., 2017). Other risks included: flood, environmental health and broad emergency public health. Therefore, even in papers that were not concretely focused on health risks, there was an element of health in the risks which highlights the tendency towards health when considering risks. The geographic coverage of the studies included in the reviews were not outlined by 10 of the papers. Of the 7 reviews that did outline the coverage, the reviews included studies from North America (n=7), Europe (n=6), Asia (n=4), Oceania (n=4) Central & South America (n=2) and Africa (n=2). However, within the studies there was a bias towards Europe and North America. For example, although Boyd and Furgal's (2019)'s review included studies from North America, Asia and Central America, 7 studies covered the USA and 5 studies focused on Canada, meanwhile Guatemala, India and Bolivia were represented by only one study each. As such, the research in this review is skewed towards North America and Europe, and as such does not well represent other regions.

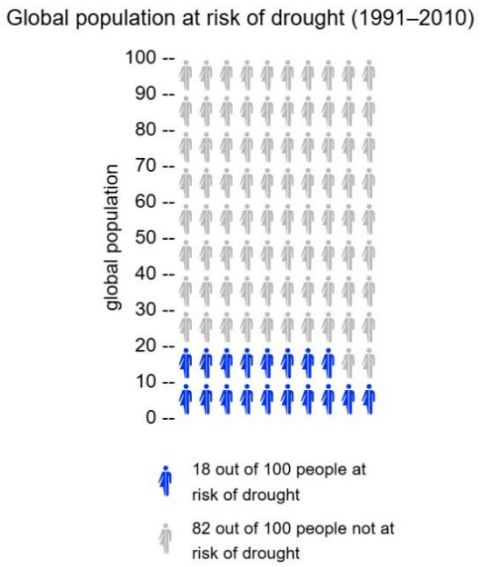
Systematic reviews were conducted by most papers (n=16) with only one paper presenting a scoping review. A rapid narrative review was conducted alongside a systematic review in one paper (Harrison et al., 2014). The methodologies included in the review papers were diverse and only 1 paper solely reviewed RCT studies (Stellamanns et al., 2017). Three papers included both RCT and non-randomised control trials and two papers included quantitative studies of any kind. A mixture of quantitative and qualitative methodologies were included in 12 papers. As such the estimated effects of the interventions on understanding was only stated for one study (Edwards et al., 2000) and similarly, one paper conducted a meta-analysis (Andreadis et al., 2021).

Findings

The results from the review are outlined in Table 1 (and Supplementary Materials Table 1), with 4 themes identified: 1) understanding probability and uncertainty, 2) presentation of risk and probability information, 3) framing of risk information, and 4) the process of risk communication. Some of the terms used in this review may not be as widely used in climate change research and as such examples of the terms are provided in Table 2.

Table 2. Examples of key statistical terms, visuals and graphs.

Risk communication terms	Description	Example
Qualitative probabilities	Communication of probability using qualitative (verbal) descriptors	"Likely", "Very likely"(Mastrandrea et al., 2011)
Quantitative probabilities	Communication of probability using quantitative (numerical) descriptors	"66-100% likelihood"(Mastrandrea et al., 2011)
Natural frequencies	Use of the same denominator value.	"1 in 10" and "5 in 10"
Infographic	Combination of data, diagrams, text, and images together to communicate complex, abstract or dense information (Dunlap & Lowenthal, 2016)	 For IPCC Climate Future infographic example see https://www.ipcc.ch/report/ar6/wg1/figures/technical-summary/ts-infographics-figure-1
Decision aids	Assist informed decision making by providing (often health related) information about the decision and options available.	For an see (BMJ, 2013)

	Outcomes of the decisions are also provided e.g benefits, harms, uncertainties. (BMJ, 2013)	
Positive (gain) framing	Messages framed with an emphasis on the positive outcomes of the problem or risk.	"By mitigating climate change, we can prevent further increases in winter floods in maritime regions and flash floods throughout Europe." (Spence and Pidgeon, 2010)
Negative (loss) framing	Messages framed with an emphasis on the negative outcomes of the problem or risk.	"Without mitigating climate change, we will see further increases in winter floods in maritime regions and flash floods throughout Europe."(Spence & Pidgeon, 2010)
Individual risk	Use of an individuals characteristics to calculate their personalised risk estimate	'Your personal risk of developing colon cancer in your lifetime is 9%' (Vromans et al., 2024)
Generic risk	Using the general population's characteristics to calculate a generic risk estimate	'The general risk of developing colon cancer in your lifetime is 9%' (Vromans et al., 2024)
Icon array	Visual communication of percentages using coloured icons. Each coloured icon represents a specific percentage (in the example in the next column each icon represents 1%) (Recchia et al., 2022)	 *(Created using Iconarray.com,* (T. Wang & Sun, 2023)

Understanding probability and uncertainty

Ten of the review papers directly assessed whether people understood probabilities, risk and/ or uncertainty information. Ghosh and Ghosh (2005) reviewed papers that tested medical physicians',

patients' and medical students' comprehension of probabilities related to diagnostic tests. There was a wide range in how probability statistics were understood within the three participant groups, and it was common for physicians and students to overestimate particular diagnostic test probabilities. The Ripberger *et al.*, (2022) study reviewed literature of various risks to identify ways to include probability information in communications and related it to weather forecasts. They found that confidence intervals and forecast periods were often misunderstood, as people interpreted the risk probability to be greatest at the end of the timeframe given. However, the review concluded that, with careful explanation, forecast probabilities can be understood by the general public. The focus of Møllebæk *et al.*, (2019) was the effective communication of drug risk information to healthcare providers (HCPs). The HCPs in the USA found the risk information they receive about drugs were lacking in clarity, however this was not reported in other countries. A study reviewed how Radiofrequency Electromagnetic Fields (RF-EMF) mobile communication risks are communicated (Boehmert et al., 2020). They could not calculate the effect size for comprehension in this study as the number of comprehension studies was too small, however they suggested that simplified messages with less technical language were better understood. Meanwhile in Andreadis *et al.*, (2021) they assessed how lay people interpret medical and health risks. They find that the way in which people interpret verbal probabilities (e.g "very likely") does not correspond to their numerical probabilities.

Three papers explored the "denominator neglect" which occurs when the reader gives insufficient focus given to the denominator and instead, more focus is given to the numerator and can result in misinterpretation of the probability (Mikušková, 2015). In Ancker *et al.*, (2006), they explored how graphics influence the quantitative reasoning of quantitative health risks amongst patients as well as patients' behaviour and preference. They established that patient comprehension is better when the ratio denominators are the same (also known as natural frequencies). For example, it is easier to compare 1 in 10 with 2 in 10 than to compare 1 in 10 with 1 in 5. Yet denominators are presented in many different ways in the healthcare context (Harrison et al., 2014). Finally, the denominator neglect findings were heterogenous in Zipkin *et al.*, (2014) review of communicating probabilistic health risks,however, the review found that natural frequencies were easier for people to understand, in line with Ancker *et al.,* (2006). As such there appears to be evidence that people find it easier to

understand risks when they are communicated using natural frequencies and may mitigate against the denominator neglect.

Of the 10 papers that reviewed understanding probability, 5 included understanding of uncertainty, though the conceptualisation of uncertainty varies slightly across the studies. Harrison *et al.*, (2014) reviewed studies that used discrete choice experiments to evaluate methods of presenting healthcare-related risks to patients and healthcare staff. They found that risk is most commonly presented as a point estimate with no inclusion of range or variability to signify the uncertainty, which influences the understanding of risk. In Boehmert *et al.*, (2020)"s RF-EMF review, scientific knowledge comprehension was not influenced by the presence or absence of an uncertainty statement. Meanwhile, Ripberger *et al.*, (2022) discovered that people can infer uncertainty when given a deterministic forecast but understanding can be improved by providing a probabilistic forecast that acknowledges uncertainty. However, as previously mentioned, people misinterpret confidence intervals, suggesting people's ability to grasp uncertainty and ranges may be limited. A review of effective cardiovascular risk communications to improve understanding was the focus of Schulberg *et al.*, (2022). They concluded that individuals' uncertainties of risk were reduced when people were provided with a direct and personal communication such as cardiovascular imaging. Finally, Sopory *et al.*, (2019)"s review was specifically focused on how to communicate the uncertainty of emergency public health risks to the general public, stakeholders and vulnerable groups. They outline that the general public often misinterpret uncertainty information and scientists and some members of society are unable to conceptualise or understand uncertainty. Despite this they conclude that the communication of uncertainty should be carried out in a clear and non-contradictory way.

Overall, the review of reviews highlights that the comprehension of probability and uncertainty information varies amongst both the general population and domain experts. Evidence reviewed in this body of literature demonstrates that the presentation of probabilistic information can be improved by reducing the cognitive effort people need to expend, for example by using natural frequencies that facilitate easy comparison. Additionally, people can infer uncertainty from deterministic information and providing uncertainty information can improve comprehension and judgement, though care must be taken in communicating uncertainty to ensure it is not confusing.

Presentation of risk and probability information

Twelve studies reviewed the alternative ways of presenting risk information and their impact on understanding. Namely studies focused on 1) visual or graphic aids such as icon arrays, graphs and infographics and/or 2) comparison of quantitative versus qualitative probability descriptors.

Decision aids of various formats and media had a positive impact on patients understanding and pictorial communications show some promising results, however, there is a lack of consensus on the most effective way to communicate medical risks (Ghosh & Ghosh, 2005). In a number of studies, graphical or pictorial images were identified as effective methods for communicating risk, but study heterogeneity and mixed results made it difficult to draw conclusions (Coyle & Gillies, 2020; Ghosh & Ghosh, 2005; Harrison et al., 2014; Stellamanns et al., 2017; Zipkin et al., 2014). Icon arrays, in particular, were suggested as a valuable method for communicating risk as they convey gist, or compare the risk to other well-known risks (Ancker et al., 2006; Harrison et al., 2014; Ripberger et al., 2022; Stellamanns et al., 2017; Zipkin et al., 2014). Meanwhile, bar charts also showed promise as a communication method for improving understanding (Ancker et al., 2006; Stellamanns et al., 2017; Zipkin et al., 2014) as did risk ladders (Ancker et al., 2006; Harrison et al., 2014). However, Schulberg *et al.*, (2022) study of cardiovascular risk found bar charts and infographics were less successful at improving understanding compared to heart age and cardiovascular imaging and that generally, graphical formats had a mixed effect on understanding. However, this finding may be due to heart age and cardiovascular imaging communicating individual risk, whilst bar charts and infographics communicated generic risk. Meanwhile, reviews on flood risk communications (Kellens et al., 2013) and communicating probabilistic risk information about cancer treatment (van de Water et al., 2020) found such diverse results that no conclusion could be made.

The issue of complexity in risk information was raised by two studies. Whilst patients may prefer simple graphs, they are not always suitable for communicating complex information (Ancker et al., 2006). In the context of weather forecasts, Ripberger *et al.*, (2022), highlight the distinction between visualisations which emphasise the most likely outcome, versus visualisations which emphasise the potential for alternative possibilities (in the case of weather forecasts as in climate, this may include

showing individual model simulations with a range of outcomes). The latter approach has been found to be helpful for improving awareness of risk and possible options, but it may also distract from the most likely outcomes.

The comparison of quantitative and qualitative communication of probability information was conducted by 8 reviews. Qualitative descriptors of probability information were found to be less effective at improving understanding than quantitative methods (Andreadis et al., 2021; Harrison et al., 2014; van de Water et al., 2020; Zipkin et al., 2014). The qualitative descriptors of healthcare-related risks were one of the least successful ways to communicate risk in Harrison *et al.,* (2014) and patients had lower understanding of qualitative descriptors compared to natural frequencies, event rates (e.g. 63 deaths per 100 000 population) or icon arrays in Zipkin *et al.*, (2014). Similarly, percentage and frequency formats about the side effects of cancer treatments were better understood by cancer patients, healthy participants and HCPs than qualitative descriptors of probability information, although they highlight that the results may have been biased by the design of the studies due to recall bias (van de Water et al., 2020).

Qualitative descriptors of probability (e.g. “likely”) are usually associated with a quantitative estimate (e.g. 66-100% likelihood) by those generating risk information. However when given qualitative descriptors of probability, people can associate these with the incorrect the quantitative likelihood estimates or the interpretation of qualitative descriptors (e.g. “likely” and “very likely”) may overlap with one another (Andreadis et al., 2021; Sopory et al., 2019). In the case of the term “common” which, in this specific context, had an expert assigned numeric estimate of 58.7%, lay people gave estimates ranging between 10-100% (Andreadis et al., 2021). Whilst quantitative probabilities can sometimes improve understanding, they are still open to misinterpretations and qualitative descriptors were found to be effective at improving understanding of cardiovascular risk (Schulberg et al., 2022). Quantitative and qualitative descriptors of probability may be understood differently depending on the level of numeracy of the reader (Ripberger et al., 2022), and as such quantitative and qualitative descriptors may be best presented alongside each other (Andreadis et al., 2021; Ripberger et al., 2022).

The review of reviews has therefore identified key findings on how the presentation of risk influences understanding. Icon arrays and bar charts generally improve understanding of information, though further research is required for other types of graphics, and context is likely to play a role. Icon arrays, in particular, are health risk specific and often communicate the likelihood of people being affected. Meanwhile, presenting probability information in a quantitative way is more effective for improving understanding than using associated qualitative descriptors, due to ambiguity in how verbal probabilities are interpreted.

Framing of risk information

The way risk information is framed in communication and its effect on understanding was reviewed by 6 papers and include loss/gain or positive/negative framing, and individual versus generic risk framing (see Table 2 for examples). Framing gives some elements of a complex problem more emphasis to assist readers to understand the risks, why it matters and what should be done (Nisbet & Mooney, 2007). Harrison *et al.*, (2014) found that 87% of healthcare-related risks were framed negatively. The way a risk is framed was found to influence understanding, however the direction of this influence was inconclusive due to mixed results (Coyle & Gillies, 2020; Ripberger et al., 2022; van de Water et al., 2020). Meanwhile communicating that ‘an event will occur’ versus ‘an event will not occur’ has an impact on how people estimate the probability of the event. When the event is framed to occur, people overestimate the event probability. When the event is framed to not occur, people underestimate the probability.

The comparison of individual and generic risk communication was reviewed by two papers, focused on health risks. The sole review in this review of reviews that calculated the effect size explored health risks such as coronary heart disease, HIV, smoking and cancers. They calculated that the individual risk estimates had a larger effect than generic risk estimates. However, the outcome variables used to measure the effect size included perception, behaviour and anxiety as well as knowledge rather than knowledge alone (Edwards et al., 2000). Meanwhile in a review of cardiovascular disease risk communication, there was no conclusion on the influence of individual

cardiovascular risk on understanding (Schulberg et al., 2022). Overall, there is evidence that framing influences understanding but there is no consensus on the direction of this influence.

The process of risk communication

Five review papers explored processes that occur in developing risk communications. Boyd and Furgal (2019) reviewed literature on environmental health risk communications for Indigenous populations. They found that engaging with Indigenous populations to develop risk communications that had suitable message design, were tailored to the context, and used suitable, culturally sensitive language, were more likely to be understood by the population. Boase *et al.*, (2017) reviewed studies that have adopted the mental models approach to risk communication (MMARC). MMARC follows a five-step process which includes engagement with stakeholders to understand their mental models and evaluating communications with the target population (Morgan, 2002). MMARC acknowledges that people's views and knowledge are influenced by experiences, external information sources and complex information, some of which may not be accurate. An MMARC approach resulted in significant improvements in people's knowledge, and they conclude it is a useful framework for developing such communications.

In the healthcare setting, HCPs had different requirements for the types of drug risk communications they receive (Møllebæk et al., 2019). Whilst some wanted specific recommendations, others wanted facts that could be used to inform patients' decision making. HCPs adapt the risk communication they receive depending on their patient's literacy so that the information is better understood. Similarly, in public health emergencies it is highlighted that there is flow of information and decision making, within which uncertainty can propagate (Sopory et al., 2019). If this information flow is unclear, contradictory or inconsistent it can result in confusion and poor decisions. They also note that this flow of information can be hindered if experts and policymakers understand, and experience, uncertainty in different ways. Finally, in a review of probability information for cancer treatment risks, authors suggest that providing smaller amounts of information over a long period of time could improve understanding (van de Water et al., 2020).

Overall, consideration and interaction with the end user can improve their understanding of the risk and make an informed decision. The flow of information is also an important consideration as experts make decisions about how and when the information is passed along.

Discussion

We have reviewed 17 review papers to explore literature on risk communications for improved understanding. Based upon this study 5 key findings that are relevant for communicating future climate information will be discussed.

1. Lay people and scientists alike struggle to interpret probability information.

The review has found that many people, including experts and scientists, misinterpret probabilities and statistics. When communicating uncertain future climate information, it is important to try and to reduce the mental load of interpretation for all involved, including scientists. In a study with participants from climate adjacent UK organisations, 79% and 46% of participants described probability estimates as a feature that hindered their understanding of maps and graphs, respectively (Kause et al., 2020). When communicating climate projection probabilities and statistics (such as relative change or percentiles) care should be taken to explain them and not assume that they will be correctly interpreted by people, even those that are in the field of climate change.

2. Differences in interpretation of qualitative and quantitative probability descriptors.

Qualitative descriptors for probability (e.g. “very likely”) are not as well understood as quantitative descriptors (e.g. 90-100% likelihood). The IPCC has calibrated language and frameworks for likelihoods which include quantitative and qualitative descriptions (Mastrandrea et al., 2011). These have also been adopted beyond IPCC reports. Despite a calibrated framework, IPCC authors disagree on how to communicate probabilistic information (Janzwood, 2020).

3. Use natural frequencies when communicating ratios.

The review found that using a common denominator (e.g. 1 in 10 and 2 in 10, rather than 1 in 10 and 1 in 5) can improve people’s understanding. This may be relevant when talking about future risks such as floods and their return periods which are often communicates as a “1 in 100-year event” or “1 in 5-year event.” However, further research is required as people misinterpret the likelihood of a risk

when it is communicated as a return period, especially if that event has occurred recently ((Grounds et al., 2018).

4. Icon arrays can enhance comprehension.

Although such visualisations are not widely used for communicating climate projections icon arrays could be an effective and new method for climate communications. Similarly, infographics could provide aesthetic and well explained information about climate risk. Given IPCC graphics can be too complicated, icon arrays (Fischer et al., 2018; McMahon et al., 2015) might be a simpler option for future documents.

5. Interaction with information users and drip-feeding information can improve understanding.

This resonates well with experience in climate services, where working with decision-makers over a long period of time, and collaborating to co-produce information has been found to create shared understanding (Jack et al., 2020). Mental models could be a useful way to identify how people understand climate information and improve communications (Mayer et al., 2017).

Whilst there are key takeaways for communicating climate risk from this predominately health focused review of review, some findings are not as relevant. There are 3 areas including: timeframe of the risk; communicating individual risk instead of generic risk and the visualisations of risk information.
This study has found individual risks can be a more appropriate method for communicating risk compared to generic risk. Communication of individual risk in the context of climate risk is not common and the low spatial resolutions of climate projections make it challenging to provide personalised climate information (Smid & Costa, 2018). Regarding the timeframe of the risk, in a healthcare or emergency setting there may be less time to properly interpret probabilistic information and the risk are more imminent than climate risks. Although the time IPCC scientists have limited time to work on reports and assign confidence and likelihood estimates (Janzwood, 2020; Kause et al., 2022), it cannot be compared to the healthcare or emergency public health context in which some of these studies are placed. Finally, the health and climate disciplines use different visualisations. Line (plume) plots, box plots and maps are more common ways of visualising climate projections. Whilst bar charts are sometimes used in seasonal forecasts, they are not currently used within climate projections. Meanwhile decisions aids or support tools have different goals within healthcare and climate, with the former aiming to support individual patient decision making or changing behaviour.

Meanwhile, a decision aid, in the context of climate adaptation, may come in the form of a climate service and is likely to be developed specifically for a targeted sectoral decision makers within organisations and businesses (Vincent et al., 2018).

This review of reviews may have been limited by the focus on “risk communication”, there may be other studies on communicating uncertainties that were not identified. Furthermore, as this was a review of reviews, it was challenging to get a detailed understanding of all the methodologies used in the studies included in the review papers. It is also challenging to get a detailed view of the participants in each study, and how their experience, education and background might influence the findings. Where consensus could not be reached in the review studies, it may have been due to heterogeneity in methodology, study design and contexts. As such, it is challenging to assess whether uncertainties are due to genuine variation between people in how they interpret information, or due to differences in the methods or contexts. However, it is worth noting that 5 of the reviews highlighted a need for improved study designs. While the reviews covered here focus on the communication of risk and uncertainty, it should be noted that none fully considered the extent to which metacognition, recipients’ awareness and insights into their own reasoning, as well as motivational biases may affect how information is interpreted

Given risk communication and systematic reviews have their roots in the medical and health disciplines, it is no surprise that the studies in this review are dominated by health and medical risks. Nevertheless, the review has highlighted useful insights that could be applied in climate communications, as well as highlighting the need for risk communication research focusing on future climate information, for example to test common climate visualisations such as plume plots and maps. Finally, the countries included in the studies in this review, as well as lead authorship, is not representative of all regions. More research is urgently needed on regions outside of North America and Europe, as cross country and culture difference exist in the interpretation of risk information (Daron et al., 2015 and Kause 2020).

Conclusion

This review identified reviews which specifically focused on risk communications for improved understanding. Although all risk types were included, the majority were in the health discipline, and as such, may not be journals that climate researchers read. The study design, contexts and risk types were highly heterogenous, making it difficult to generalise, however, there are findings that are relevant to climate change. These include the effectiveness of bar charts and icon arrays; the varied comprehension of probabilistic information and uncertainty information, ineffectiveness of qualitative descriptors of probability information compared to quantitative descriptors and the improvement of understanding of risks when adopting a collaborative design of risk communication.

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