Cognitive and psychological science insights to improve climate change data visualisation

Author information

Jordan Harold*

School of Psychology and Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, NR4 7TJ, UK.

Jordan.Harold@uea.ac.uk

Irene Lorenzoni

School of Environmental Sciences, Tyndall Centre for Climate Change Research, and Science, Society and Sustainability (3S) Research Group, University of East Anglia, Norwich, NR4 7TJ, UK.

I.Lorenzoni@uea.ac.uk

Thomas F. Shipley

Department of Psychology, Temple University, Philadelphia PA 19122, USA.

tshipley@temple.edu

Kenny R. Coventry*

School of Psychology, University of East Anglia, Norwich, NR4 7TJ, UK.

k.coventry@uea.ac.uk

Corresponding author

Correspondence to: Jordan Harold or Kenny R. Coventry

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Contributions

J.H. and K.R.C. outlined the scope of the review with input from T.F.S. and I.L. The manuscript was drafted and prepared by J.H. with critical feedback from K.R.C., I.L. and T.F.S. All authors contributed to editing of the final manuscript.

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Abstract

Visualisation of climate data plays an integral role in the communication of climate change findings to both expert and non-expert audiences. The cognitive and psychological sciences can provide valuable insights into how to improve visualisation of climate data based on knowledge of how the human brain processes visual and linguistic information. We review four key research areas to demonstrate their potential to make data more accessible to diverse audiences: directing visual attention; visual complexity; making inferences from visuals; and the mapping between visuals and language. We present evidence-informed guidelines to help climate scientists increase the accessibility of graphics to non-experts, and illustrate how the guidelines can work in practice in the context of IPCC graphics.

Limiting the risks of severe impacts from climate change will require substantial changes in society to mitigate greenhouse gas emissions and adapt to a changing world[1]. Scientific information is one factor among many that can influence decision-making to action change[2,3] and there is an increasing demand for accessible and relevant climate data by decision-makers[4]. Global assessments of climate change by the Intergovernmental Panel on Climate Change (IPCC) provide important policy-relevant information. While summaries of these assessments are primarily aimed at experts working in government, they have been criticised for being inaccessible to non-experts, with particular focus on the complexity of language used in Summaries for Policy Makers (SPMs)[5,6,7]. However, figures within SPMs (i.e. graphics of scientific information in the form of graphs, diagrams, thematic maps and other visuals), may also be inaccessible to non-experts (Fig. 1).

For example, viewers looking at graphics of climate model projections can confuse scenario uncertainty (i.e. unknown future societal choices) with model uncertainty[8]. There are challenges in visually synthesizing and representing uncertainty in climate knowledge, and diversity in normative judgements about the implications of such uncertainties[9]. Climate scientists may use different strategies to create meaning from climate science graphics than non-experts[10]. Furthermore, graphics of the same data represented in various styles have been shown to differentially influence judgements about future climate[11].

[insert Figure 1]

Figure 1. **a**. An example of a scientifically rigorous, policy-relevant IPCC graphic (caption below)[99]. **b**. Aspects that might limit the accessibility of the graphic to non-expert audiences.

IPCC, AR5, Working Group 1, Figure SPM.5. Radiative forcing estimates in 2011 relative to 1750 and aggregated uncertainties for the main drivers of climate change. Values are global average radiative forcing (RF[14]), partitioned according to the emitted compounds or processes that result in a combination of drivers. The best estimates of the net radiative forcing are shown as black diamonds with corresponding uncertainty intervals; the numerical values are provided on the right of the figure, together with the confidence level in the net forcing (VH – *very high*, H – *high*, M – *medium*, L – *low*, VL – *very low*). Albedo forcing due to black carbon on snow and ice is included in the black carbon aerosol bar. Small forcings due to contrails (0.05 W m^{-2}, including contrail induced cirrus), and HFCs, PFCs and SF_6 (total 0.03 W m^{-2}) are not shown. Concentration-based RFs for gases can be obtained by summing the like-coloured bars. Volcanic forcing is not included as its episodic nature makes is difficult to compare to other forcing mechanisms. Total anthropogenic radiative forcing is provided for three different years relative to 1750.

Visually representing climate data to inform decision-making can be challenging due to the multi-dimensionality of data, the diversity in users' needs across different stakeholder groups, and challenges and limitations in the use of software and tools to create graphics[12]. However, graphics can, in principle, support thinking[13] and support narratives when communicating with stakeholders[14]. Creating graphics of climate change data that overcome comprehension difficulties and avoid misconceptions has the potential to enhance climate change communications.

How can scientific graphics about climate change be made more accessible, while retaining their scientific integrity? This question has been posed by the IPCC as they look ahead to the Sixth IPCC Assessment Report[15]. In this review we consider research from the cognitive and psychological sciences to help answer this question. One of the goals of these disciplines is to understand how people comprehend written and visual information. We provide an overview of how people create meaning from graphical representations of data and highlight that intuitive design may not always correspond to best practice informed by evidence. We then consider four key areas: directing visual attention; reducing visual complexity; supporting inference-making; and integrating text with graphics. We present evidence-informed guidelines to support climate scientists in developing more accessible graphics, show how the guidelines can be applied in practice, and provide recommendations on how the IPCC might utilise these guidelines in the development of future reports.

We argue that improving accessibility to graphics of climate change data does not necessitate reducing or simplifying the *content* of the graphics per se (which might come with a risk of diluting the science), but can be achieved by supporting cognitive processing of the visual information.

Creating meaning from a scientific graphic

Graphics are often an effective way to communicate climate data - not only can they store and organise data efficiently, but they enable us to think about the data using visual perception[13]. Representing data visually can create patterns that the human visual system can easily process (e.g. the iconic ‘hockey-stick’ graph). However, graphics are not direct representations of reality; the meaning of the data they represent must be interpreted by the viewer. Therefore, prior to identifying how graphics of climate data might be made more accessible, we outline how the human brain creates meaning from a graphic.

First, sensory processes direct the eyes to specific features of the graphic. Visual attention determines which features of the graphic the viewer looks at. Features that are visually salient (e.g. by virtue of their colour, shape, size) can draw the attention of the viewer – known as *bottom-up* visual processing. Conversely, the viewer’s expectations, driven by prior knowledge (their previous experience of the world, and their goal or reason for looking at the graphic), can also direct visual attention – *top-down* visual processing (Fig. 2a)[16]. As visual information is perceived from the features of the graphic, a mental representation of the information is created in memory. The nature of the mental representation is influenced by prior knowledge and goals and is constantly updated as the viewer visually explores the graphic[13].

These cognitive processes are cyclical in nature; perceived and mentally represented information acts on expectations, which in turn direct further exploration of the graphic[17]. The human brain is thought to support cognition by constantly trying to match incoming sensory information against predictions of what to expect[18]. When perceived information matches our expectations, then comprehension is easy. Accessibility of a graphic can therefore be improved by matching visual features and prior knowledge (Fig. 2b).

[insert Figure 2]

Figure 2: Conceptual overview of the process of graphic comprehension and approaches to improving accessibility.

Intuitive design ≠ improved accessibility

Advances in computing and software technologies have enabled climate scientists to create a wide-range of visual representations of scientific data[12]. In addition, such representations may offer the viewer flexibility in how the data are displayed via interaction with the graphic. Such advances offer the potential to better match graphic parameters to viewer parameters to improve accessibility. However, these advances also place demands on creators and viewers of graphics in terms of their competence in selecting effective visual representations of the data for the task at hand[19].

Evidence suggests there may be limits to experts' self-awareness (metacognition) for creating or choosing effective visual representations of data. For example, some experts, as well as non-experts, show preferences for graphic features that can actually impair comprehension, such as realistic features[20], 3D features[21] and extraneous variables in data[22]. Consequently, intuitions about good design practices may not always match best practice informed by cognitive principles, and viewer preferences may not always be predictive of ease of comprehension. Conversely, designing graphics with cognitive principles in mind, and testing them with viewers, offers an empirical approach to improving the visual communication of climate science data.

Accessibility ≠ loss of scientific rigour

The role of visual attention

To understand the details of a graphic we use our central vision, afforded by the fovea centralis, which provides greater acuity than our peripheral vision. The visual field of the fovea centralis is approximately two degrees of visual angle in diameter[23], meaning that when viewing an image from a distance of 60 cm (such as on a computer screen at about arm's length), our central vision covers an area approximately 2 cm wide. At any one moment in time our central vision can only focus on a limited area of a graphic. Therefore, we move our eye gaze to sample information from different spatial locations (Fig. 3a), and to build a detailed representation of the graphic as a whole we encode and retain information from these different spatial locations in memory.

Limited cognitive resources mean that only a fraction of the rich visual information entering the eyes at any given point in time is meaningfully processed and encoded to our internal representation in memory[24]. Where to look, and what information to process, is directed by visual attention. Consequently, if important details in a graphic are not captured by our attention, they will not be processed by the brain and will not be drawn on to help comprehend and interpret the data in the graphic (Fig. 3b). Directing visual attention to important details can therefore make graphics more accessible by supporting viewers to look at aspects of the graphic that afford understanding.

[insert Figure 3]

Figure 3. Example of visual attention for an IPCC figure for a non-expert viewer trying to interpret the graphic (measured using eye tracking: first 15 seconds of data shown). **a**: eye gaze shown as individual fixations and connections between fixations; **b**: areas receiving visual attention; computed from the locations of the fixations, weighted by the duration of each fixation. If visual features are not visually salient, they may not be attended to. In this

example, the graphic's legend receives little visual attention and some parts of the legend receive no visual attention at all.

Figure shown is IPCC, AR5, Working Group 1, Figure SPM.6.[99] Comparison of observed and simulated climate change based on three large-scale indicators in the atmosphere, the cryosphere and the ocean: change in continental land surface air temperatures (yellow panels), Arctic and Antarctic September sea ice extent (white panels), and upper ocean heat content in the major ocean basins (blue panels). Global average changes are also given. Anomalies are given relative to 1880–1919 for surface temperatures, 1960–1980 for ocean heat content and 1979–1999 for sea ice. All time-series are decadal averages, plotted at the centre of the decade. For temperature panels, observations are dashed lines if the spatial coverage of areas being examined is below 50%. For ocean heat content and sea ice panels the solid line is where the coverage of data is good and higher in quality, and the dashed line is where the data coverage is only adequate, and thus, uncertainty is larger. Model results shown are Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble ranges, with shaded bands indicating the 5 to 95% confidence intervals.

Directing attention by visual design

Visual properties that can capture attention by acting on bottom-up perceptual processing include colour, motion, orientation and size[25]. In addition, there are well-documented 'Gestalt' principles governing how individual elements in a graphic are grouped together psychologically into meaningful entities[26]. When elements of a graphic show a large degree of contrast in these properties, the contrasting visual information is automatically captured by attention and appears to 'pop-out' from the display (Fig. 4b-4d).

Another way to direct attention is through the use of arrows. Arrows are the symbolic visual equivalent of pointing gestures, which have a widely accepted meaning of 'look here' and are thought to direct attention automatically[27]. They can therefore be particularly efficient visual cues to establish joint attention between the author and the viewer for specific features in a graphic (Fig. 4e). Of course arrows also have other uses – such as denoting motion or temporal change – and one has to be careful not to use arrows to denote different operations within the same graphic.

Using these properties in the visual design of climate science graphics can therefore help guide attention. Particular visual properties (or combinations of these properties) to direct attention may be more suited than others, depending on the context in which they are used.

Informed by human behaviour and neuroscience, computational models of 'bottom-up' visual attention have been able to accurately predict which features of an image are most likely to be attended to[28]. Such models provide immediate assessments of visually salient features of a graphic, and might be useful to inform the design process[29]. To check viewers' actual visual attention for a graphic, eye-tracking can provide empirical evidence to inform visual design. For example, eye tracking has been used to observe differences in the eye movements of individuals who were successful or unsuccessful in solving a problem scenario depicted in a graphic; visual elements that supported problem solving could then be made more visually salient[30].

[insert Figure 4]

Figure 4. Schematic of properties known to direct visual attention that can be used in the design of graphics to help direct viewers' attention to important information.

Directing attention by informing expectation

The details that are looked at within a graphic can also be directed by expectations about the task at hand. For example, patterns of eye gaze are different when viewers search a graphic for a specific feature, compared to when they try to memorise the graphic as a whole[31], or when a map is studied to learn routes as opposed to the overall layout[32]. Explicitly stating the intended task for which the graphic was created can help guide viewers' visual attention to appropriate information. Furthermore, prior knowledge about the data, and prior knowledge about the format or type of graphic chosen to represent the data, can also influence a viewer's cognition[33,34].

Research on the comprehension of meteorological charts has shown that providing viewers with relevant knowledge can support attention by directing it towards task-relevant features and away from task-irrelevant features[35]. Furthermore, making task-relevant features visually salient by adapting visual design may enhance performance once appropriate knowledge is provided[35]. Hence the interaction between bottom-up perceptual processing and top-down attentional control should be considered when designing graphics, with particular consideration given to what knowledge the viewer needs to correctly interpret the data.

Handling complexity

Some climate science graphics are more visually complex than others. For example, ensemble datasets of climate models can be particularly complex and challenging to visualise[36]. What is visual complexity, and how can complexity be handled to enable graphics to be more accessible? Possible components that might contribute towards defining and measuring visual complexity include the number of variables and/or data points in a graphic[37], the degree of uniformity of relationships represented by the data[33], or the degree to which the data are organised to make relevant relationships in the data easier to identify[38]. However, while these components might be informative for simple graphics, they may not be easily applied across the diverse types of graphics used to communicate climate science, and may not always be predictive of comprehension. For example, in some instances an increasing number of data points might make patterns in the data more obvious.

An alternative proxy for visual complexity is 'visual clutter', where excess visual information, or a lack of organisation of that information, impairs cognition[39]. Excess visual clutter can increase the time it takes to search for an item[40], increase errors in judgments[41] and impair processing of language accompanying a graphic[42]. Computer models, based on principles of human cognition, can assess graphics for visual clutter and have been validated against viewers' actual performance when undertaking simple tasks with graphics, such as searching for a specific feature[39]. Although such models have yet to be established as offering diagnostic value in identifying comprehension problems with graphics, they can be useful to inform the design process by comparing different design options for a given graphic[29].

One approach to avoid unnecessary visual complexity is to only include information in a graphic that is absolutely needed for the intended purpose[43]. However, climate science graphics may need to contain a certain level of detail or information to maintain scientific integrity (i.e. to accurately represent the extent of, or limits to, scientific knowledge). Such graphics may still be visually complex in spite of only showing important information. While experts can integrate complex visual features into meaningful units of information (perceptual 'chunks'), non-experts may lack such skills[44]. Hence, segmenting information into chunks of appropriate size and difficulty, and guiding viewers' attention to connections between these components could make comprehension of the data easier[45]. However, such an approach should be taken with care. If the task expected of the viewer is to compare or contrast data represented in a graphic (known as 'integrative tasks'), then this may be more easily performed when the data to be compared share representational similarities, such as close spatial proximity, or the same colour[46].

Supporting inference-making

Comprehension of a graphic of climate data goes beyond just perceptual processing of visual features. For example, enabling viewers to make relevant and scientifically robust inferences from data might be preferable to merely stating intended inferences in the accompanying text of a graphic. Furthermore, graphics are not only used to impart information, they can also be used to support sense-making and guide decision-making. In the context of the science-policy interface, this is indeed one of the goals of science communication and aligns with the IPCC's remit of being policy-relevant and not policy prescriptive[47].

Improving accessibility to climate science graphics therefore involves supporting viewers to make appropriate inferences. Symbolic elements in diagrams, such as lines, boxes, crosses and circles can support inference-making about relationships in the data, based on their geometric properties[48]. For example, lines indicate connections, while arrows can indicate dynamic, causal or functional information[49].

Inferences may also relate to the mappings between the visual features of the graphic and the data that they represent. Much of our cognition of conceptual ideas is thought to be metaphorical in nature[50]. For example, *more* of something is conceptualised in mind as *up,* and so temperature is said to be *rising*; similarly, financial concepts are used metaphorically in speech with regards to limiting carbon emissions, i.e. having a carbon *budget*. Using mappings that match natural or cultural metaphors can therefore aid cognition[50]. For example, colour contains symbolic meaning, with red usually associated with 'warm' and blue with 'cold'[51], and indeed these colour choices are often used to represent temperature values in meteorological graphics. Metaphors often differ between cultures[52] and so choice of metaphors should be informed by the target audience (see section below on tailoring graphics to different audiences).

How data are structured in a graphic can influence the type of information extracted, and in turn, what inferences are made about the data[53]. For example, global climate projections are typically plotted as line graphs with time on the x-axis and the variable of interest (e.g. temperature anomaly) on the y-axis, which may direct viewers to consider given points in time and their associated temperature projections. Conversely, plotting temperature anomalies on the x-axis and time on the y-axis frames the data in terms of a projection of time for a given temperature threshold[54]. Although in both cases the data are the same, the alternative graphical representations may result in viewers drawing different inferences.

Sometimes the viewer of a graphic may need to make inferences about the data that are not explicitly represented in the graphic. Examples include making inferences about the uncertainty of the data[55], relationships across multiple graphics[56], and relationships between a theory and data in a graphic[57]. Such tasks involve spatial reasoning, i.e. the viewer must mentally infer information through spatial transformations[58]. In such cases, inferences can be supported either by explicitly showing the inferences in the graphic (and so removing the need for spatial reasoning), or by supporting viewers' spatial reasoning, for example by using text accompanying the graphic (see section below).

Using text to support cognition

Graphics of climate data are rarely used in isolation of accompanying text - text labels typically indicate the referents of the data, such as what the axes and data points represent. In accordance with norms of scientific reporting, captions provide contextual information and are placed under graphics, while the relevance of the graphic and inferences that can be drawn from it are placed in the body text, sometimes spatially distant from the graphic.

Separating text from graphics comes with a cognitive cost, known as the *spatial contiguity effect*[59]. When there is distance between the spatial locations of the text and corresponding graphic, attention must be split between the two. The viewer must visually search for the corresponding elements (i.e. moving from text to graphic, or vice versa) and then integrate both sources of information. Viewers may not exert effort to do this and instead may simply treat text and graphics as independent units of information and read them independently of one another[60]. However, when the distance between text and graphic is reduced, less searching is required, and connections can be more easily made, resulting in improved comprehension[61]. Tightly integrating text and graphic has been advocated as good design practice to support comprehension, i.e. embedding text *within* a graphic (Fig. 4f), or even embedding small graphics *within* text[62].

Furthermore, language that accompanies a graphic has the potential not only to provide context, but also to influence thought about the spatial relationships of the properties of the graphic. Tasks involving spatial relationships might include comparisons of temperature anomalies at different spatial locations on a map, inferring trends in data from observed time-series data (which spatially plot x-y relationships), or comparing uncertainty ranges for future projections of climate under different scenarios. These tasks all involve spatial cognition, i.e. thinking about spatial relationships. Attending to linguistic information while looking at visual information is known to influence spatial cognition, such as supporting spatial reasoning[63]. For example, a short sentence asking viewers to ignore extreme data points when looking at graphics of time series data results in participants attending to trends during encoding[64]. Language can also influence the extent to which a static visual is mentally animated and the manner in which it is animated[65], which again might help with spatial reasoning**.** Accompanying text can therefore support viewers in making appropriate spatial inferences from a graphic.

Tailoring graphics to different audiences

We have so far considered insights drawn from *general* principles of human cognition to help inform improved visual communication of climate science data. However, it is important to acknowledge that certain cognitive factors may differ between audience groups, and between individuals within those groups.

Colour is one area where there is marked individual and cultural variation. People who experience colour-blindness perceive colours differently from the general population and so colour choices for scientific graphics should be carefully chosen to avoid perceptual difficulties[66]. The native language one speaks can also influence colour perception – the number of colour terms available in a language can influence colour discrimination[67], which might result in perceptual differences in the boundaries of colour-mapped data. Such problems can be avoided by using achromatic (e.g. greyscale) colour mappings in which data values are mapped to luminance rather than hue[68], or by using colour scales that enable easy differentiation of colour.[69]

As well as perceptual differences, there are also group differences in higher-level cognitive skills, such as spatial reasoning. Experts often have strong spatial reasoning skills, as has been shown in the geosciences[70], whereas spatial reasoning by non-experts may depend on their general visuospatial abilities[71]. Moreover, how attention is directed across a page exhibits marked cultural variations, with reading direction in a language (e.g. English – left to right; Arabic – right to left) associated with the direction of attention in visuospatial tasks[72].

Other differences are more tied to an individual's personal knowledge and experience. For example, prior experience can lead to a knowledge of 'where to look' and so can limit visual attention to specific spatial locations[73]. Similarly, the extent of prior knowledge about the data being visualised and prior experience using specific graphical formats can influence the ease with which inferences can be drawn from data[74]. There can be trade-offs between using an unfamiliar graphical format that may be difficult to initially interpret but which efficiently represents a set of data, and a more familiar format whose structure can easily be grasped but which may provide an inefficient representation of the data[34]. Individuals may hold different and sometimes inaccurate mental models about complex scientific systems[75], such as the underlying physical principles of climate change[76]. Understanding a viewer's existing mental model about the data and the systems from which the data originate can inform how they can best be supported to make scientifically robust inferences.

While comprehension of a graphic can be dependent on such factors outlined above, the underlying mechanisms responsible for human cognition are shared by everyone. Hence, general principles drawn from human cognition can inform approaches to improve the accessibility of graphics, but the specific way in which they are applied needs to be tailored. Consequently, testing of graphics is important to ensure they are comprehensible to achieve the desired communication goals[8,13].

Gaps in current knowledge

Despite advances in our understanding of the comprehension of graphics, there are important gaps in current knowledge that are of direct relevance to visualising climate data. Uncertainties of data can be difficult to communicate[77,78]. Although general principles have been proposed for visually communicating probabilistic uncertainty, the deep uncertainties of climate change, in which knowledge and values are often disputed and outcomes are dependent on human behaviour, may not easily translate into visual representations[79]. Further research is needed on how different visual representations of uncertainty might support or hinder decision-making[80] and the cognitive processes involved in such tasks.

To provide decision-makers with access to data tailored to their needs, researchers and climate service providers are exploring the use of interactive web-based graphics, such as The Climate Explorer (part of the U.S. Climate Resilience Toolkit)[81] and The IMPACT2C web-atlas[82]. Interaction, such as filtering or highlighting task-relevant information[83] has the potential to support comprehension. However, there can be large individual differences in the degree to which people use interactive functions and the extent to which they use these functions effectively[84]; viewers require competence in meta-representational skills to make appropriate interactions[19]. Consequently, unless viewers have the required skills, there may be limits to how useful interactive graphics are to support comprehension and accessibility.

Both interactive graphics and animated graphics have been suggested to support the outreach of future IPCC assessments[15]. Research comparing static graphics with animated graphics is often confounded by additional information being provided in animated graphics; hence observed benefits of animation in some tasks may not be due to animation per se[85]. In some cases animation may impair comprehension[86]. Viewers may extract perceptually salient information rather than task-relevant information from animations[87,88] and cognitive processing of the visual information may not be able to keep up with the pace of the animation[87,89]. Animating graphics might be beneficial in specific situations if cognitive demands of processing the information are factored into the design of such graphics[90].

Providing an element of user-control offers the potential to overcome some of these information processing limitations[91]. The decision to use an animated or interactive graphic over a static graphic should be informed by cognitive demands and task requirements, be designed taking cognitive principles into account, and be tested with viewers to check comprehension[92].

Evidence-informed guidelines

Here we summarise the psychological insights considered by this review and provide associated guidelines that can help to improve accessibility of graphics of climate science (Table 1).

Table 1. Evidence-informed guidelines to improve accessibility of scientific graphics of climate science.

Psychological insights	***Associated guidelines to improve accessibility***
1. Intuitions about effective graphics do not always correspond to evidence-informed best practice for increasing accessibility[20,21,22]	Use cognitive and psychological principles to inform the design of graphics; test graphics during their development to understand viewers' comprehension of them[8,13]
Direct visual attention	
2. Visual attention is limited and selective – visual information in a graphic may or may not be looked at and/or processed by viewers[24]	Present only the visual information that is required for the communication goal at hand[43] Direct viewers' visual attention to visual features of the graphic that support inferences about the data[97]

3. Salient visual features (where there is contrast in size, shape, colour or motion) can attract visual attention[25,26]	Make important visual features of the graphic perceptually salient so that they 'capture' the attention of the viewer[97]
4. Prior experience and knowledge can direct visual attention[34,35]	Choose and design graphics informed by viewers' familiarity and knowledge of using graphics and their knowledge of the domain, i.e. knowledge about what the data represents[43] Provide knowledge to viewers about which features of the graphic are important to look at, e.g. in text positioned close to the graphic (see Guideline 10)
Reduce complexity	
5. An excess of visual information can create visual clutter and impair comprehension[40,41,42]	Only include information that is needed for the intended purpose of the graphic[43]; break down the graphic into visual 'chunks', each of which should contain enough information for the intended task or message[38]

Support inference-making	
6. Some inferences may require mental spatial transformations of the data[58]; experts may have strong spatial reasoning skills[70], non-experts may not[71]	Remove or reduce the need for spatial reasoning skills by showing inferences directly in the graphic[56], and/or Support viewers in spatial reasoning, e.g. by providing guidance in text[64] (see Guideline 10)
7. The visual structure and layout of the data influences inferences drawn about the data[53]	Identify the most important relationships in the data that are to be communicated; consider different ways of structuring the data that enable the viewer to quickly identify these relationships[43]
8. Animating a graphic may help or hinder comprehension[85,86]	Decisions to create animated graphics should be informed by cognitive principles[92]; consider providing user-control over the playback and speed of the animation[91]
9. Conceptual thought often makes use of cultural metaphors[50]	Match the visual representation of data to metaphors that aid conceptual thinking, e.g. ‘up’ is associated with ‘good’ and ‘down’ is associated with ‘bad’;[50] data with negative connotations may be easiest to understand if presented in a downwards direction[98]

Integrate text with graphics	
10. When the graphic and the associated text are spatially distant, attention is split[59,60]	Keep the graphic and accompanying text close together[62], e.g. use text within a graphic and locate the graphic next to the accompanying body text
11. Language can influence thought about the graphic[64,65]	Use text to help direct viewers' comprehension of the graphic, i.e. by providing key knowledge needed to interpret the graphic[43]

Guidelines in practice

To demonstrate how the guidelines can be applied in practice, we selected an IPCC SPM graphic (Fig. 1a) identified by IPCC authors (personal communication) as potentially challenging for comprehension. We first identified aspects that might hinder comprehension, especially when interpreted by non-experts (Fig. 1b). Drawing on the guidelines we then created a cognitively inspired version of the graphic, with the aim of making the data more widely accessible while retaining scientific integrity (Fig. 5 and Box 1).

[insert Figure 5]

Figure 5. **|** A cognitively inspired version of IPCC AR5 WG1 SPM Figure SPM.6[99], using the guidelines in Table 1 to increase accessibility while maintaining scientific rigour (see also Box 1).

Box 1 | Guidelines used in the cognitively inspired version of IPCC AR5 WG1 SPM Figure SPM.6.

The cognitively inspired version provides knowledge of the meaning of all abbreviations (guideline 11); breaks down information into 'chunks' to reduce complexity and clutter (guideline 5); uses larger font size for headings, relative to other text, to attract attention (guideline 2 and 3); uses contrast in colour to encourage attention of the distinction between human and natural radiative forcings (guideline 3); shows the relationship between the 2011 total and the contributions to the total (guideline 7); integrates the caption text within the graphic to reduce the need for splitting attention (guideline 10); plots only point estimates and uncertainty ranges, i.e. removes bars, to reduce clutter and encourage thinking about the best estimate and uncertainty (guidelines 3 and 5); removes the need for multiple colours to represent each compound to reduce clutter (guideline 5); and uses text, and colour as a metaphor, to support understanding of link between the data and surface warming/cooling (guidelines 4,9,11).

We tested the alternative version of the graphic (Fig. 5) and the original (Fig. 1a) on a sample of experts (ten climate change researchers) and non-experts (ten psychology researchers). Eighty percent of participants indicated a preference for the cognitively inspired version, significantly more than expected by chance against the null hypothesis of there being no difference in preferences, exact binomial p = .012 (two-tailed). Such user-testing can help inform the development of graphics as part of an iterative design cycle.

Creating accessible graphics

There is the potential to develop improved scientific graphics of climate change data that are cognitively-inspired and easier to comprehend. This goal in particular aligns with the IPCC's desire to make outputs of future reports more accessible and user-friendly to diverse audiences[93].

In addition, the ease of accessibility of graphics of climate science also has implications for how society might make best use of scientific knowledge. There have been calls for climate scientists to take participatory roles in co-productive frameworks alongside stakeholders to help inform societal decision-making[94]. Graphics of climate data that are accessible to all parties involved could support improved engagement, dialogue and decision-making between scientists, policy-makers, practitioners, communities and publics. Climate service providers (who supply tailored climate knowledge to decision-makers) often use graphics to communicate findings, and although the communication goals and intended audience may be much more specific in these contexts than the global assessments made by the IPCC, data visualisation challenges remain[95].

While the science underpinning graphic comprehension is still developing, the guidelines presented in this review provide a useful reference for climate scientists to apply psychological and cognitive insights when creating graphics of data. However, as individuals and groups can differ, there is no substitute for empirically testing graphics with the target audience. Such testing need not be costly or time-consuming. Asking people to look at and interpret drafts of graphics can indicate if graphics are broadly understandable or not. Furthermore, rich diagnostic evidence afforded by eye tracking can indicate the efficiency of comprehension and can identify reasons why comprehension is impaired, such as assessing whether task-relevant information is visually salient or not. Informed by such evidence, appropriate adjustments to graphics can be made and then they can be re-tested.

Greater collaboration between the climate change research community, the psychology and cognitive science community and those working in associated disciplines, could help to realise such an approach. For example, as the IPCC looks ahead to their Sixth Assessment Report, there is an opportunity for the IPCC to open up the review process and ask these communities for feedback on drafts of SPM graphics. Climate scientists and psychologists could also jointly develop cognitively-inspired graphics of climate data, which are both accessible and scientifically robust, for use in outputs outside of the formal IPCC process (so-called ‘derivative products’). Similar collaborations between research communities have led to improved communication in related fields such as cartography[96] and geoscience[70].

Graphics of climate data are integral to scientific assessments of climate change, but only support communication and decision-making *if* they are understood. Empirically testing graphics and applying insights from the science of human cognition to help overcome comprehension problems, offers the potential to make climate science knowledge more accessible to decision-makers in society, while also retaining the integrity of the scientific data and evidence on which they are based.

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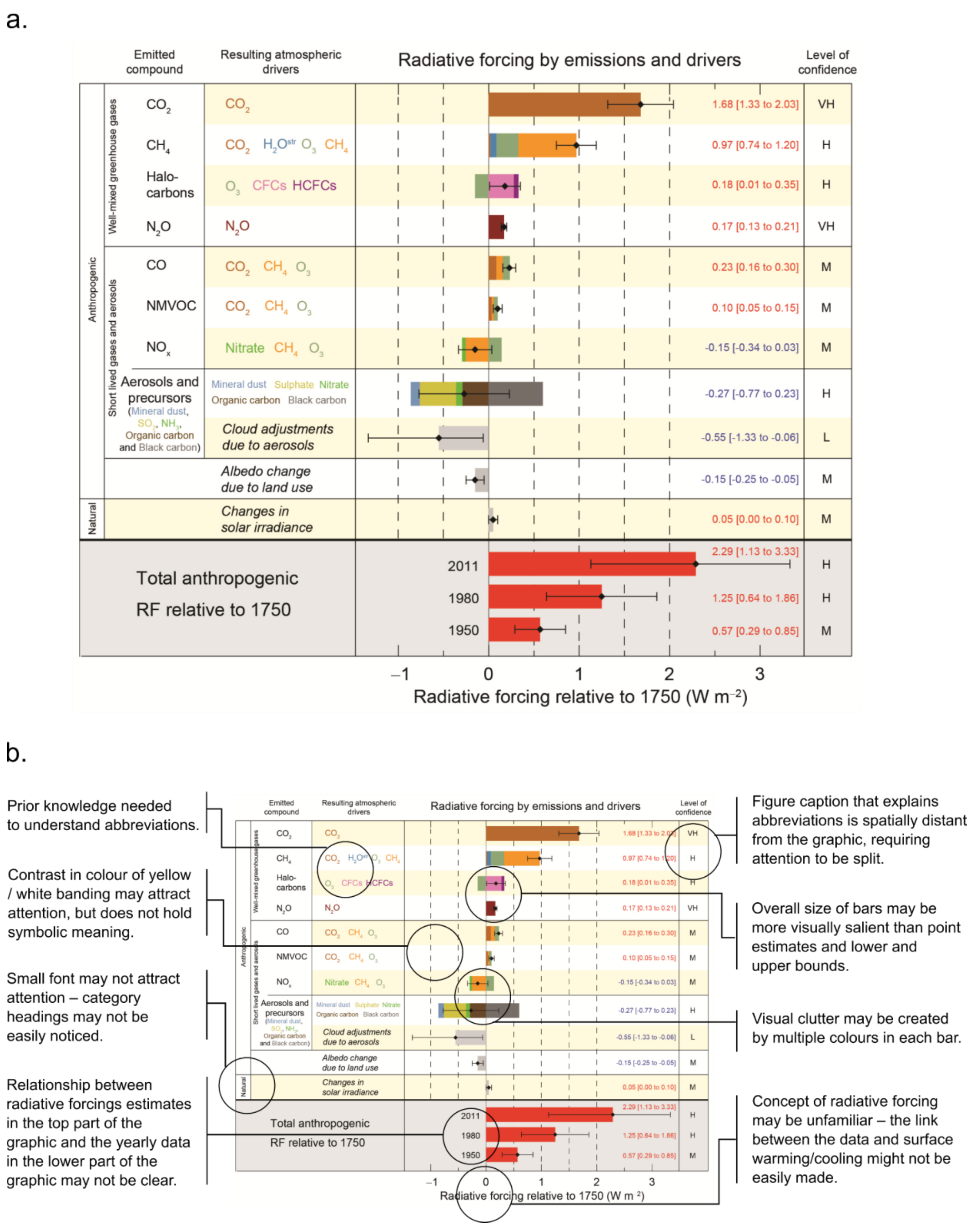

Figure 1.

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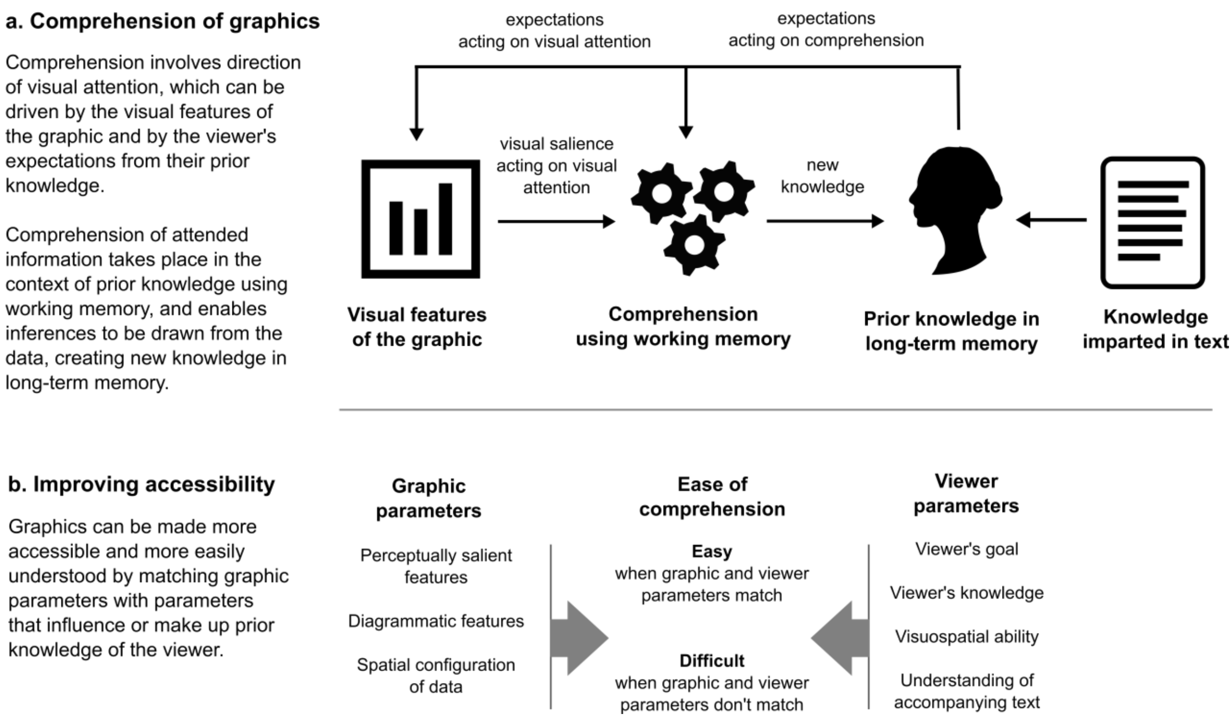

Figure 2.

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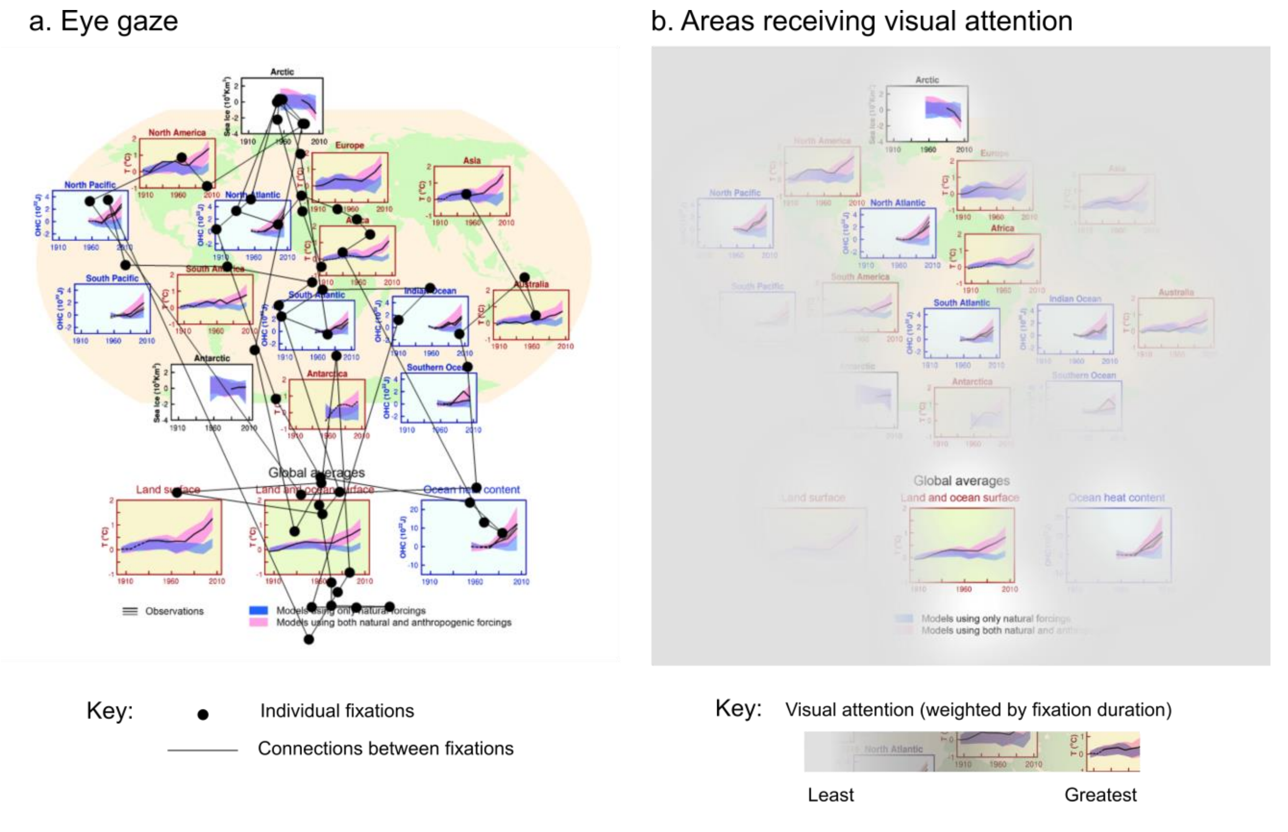

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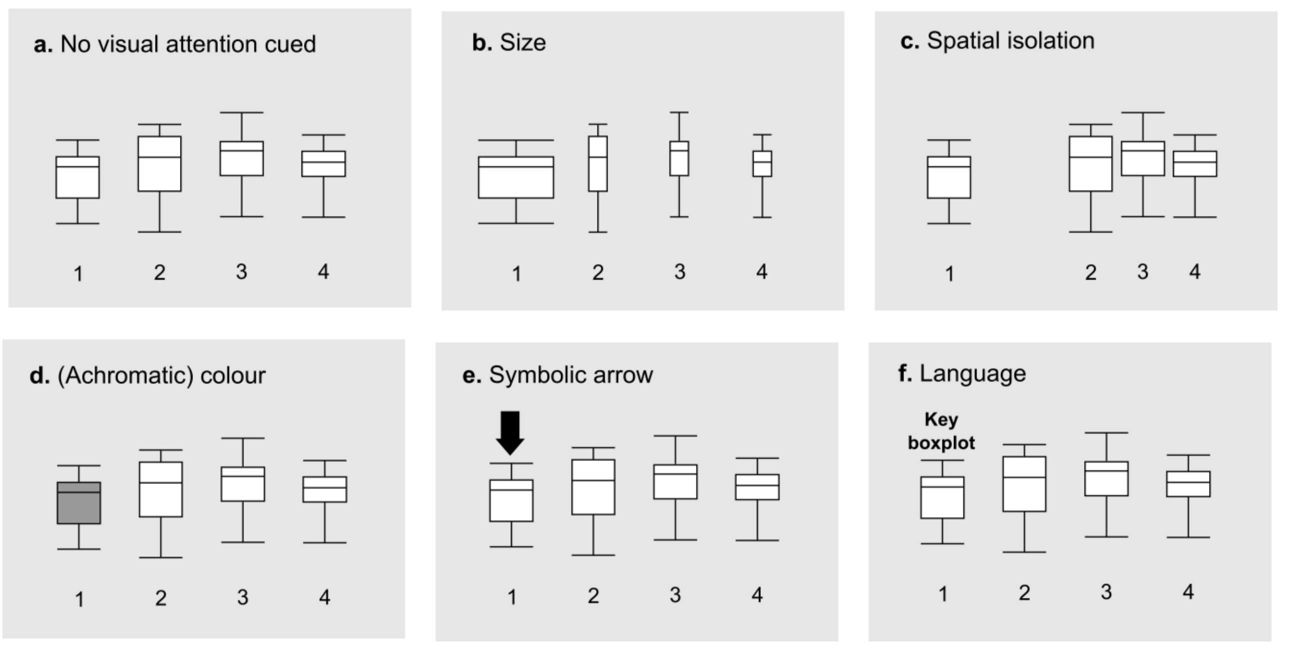

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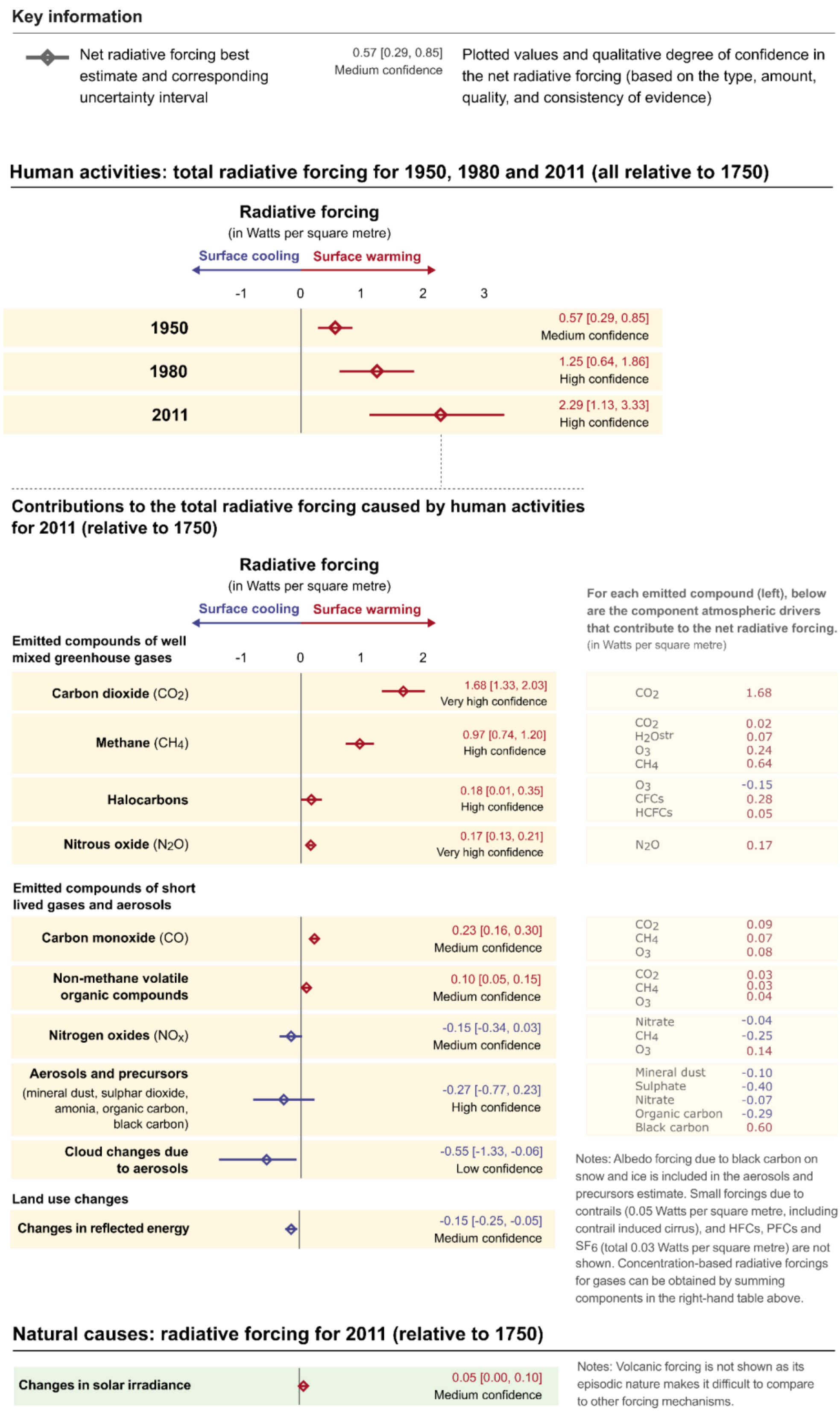

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