Workshop on Visualisation in Environmental Sciences (EnvirVis) (2019)
R. Bujack and K. Feige and K. Rink and D. Zeckzer (Editors)

On Inconvenient Images: Exploring the Design Space of Engaging Climate Change Visualizations for Public Audiences

F. Windhager[1], G. Schreder[1] and E. Mayr[1]

[1]danubeVISlab, Danube University Krems, Austria

Abstract

If there ever was a model theme for information visualization, climate change arguably checks all the boxes. Omnipresent and relevant, yet abstract and statistical by nature, as well as invisible for the naked eye – climate change is a subject matter in need for perception and cognition support par excellence. Consequently, a large number of data journalists and science communicators utilize visual representations of climate change data to provide (a) information, and to (b) raise consciousness and encourage behavioral adaptation. Multiple design strategies have been developed to make the complex (non-)phenomenon accessible for visual perception and reasoning of public audiences. Despite of its obvious societal relevance, the visualization community has not had a systematic look at this nascent application field until now. With this paper we aim to close this gap and survey climate change visualizations to explore their design space. With specific regard to visualizations geared to inform non-expert users in the context of journalism and science communication, we analyze a sample of representations to document design choices and communication strategies, including options of persuasive and engaging design.

CCS Concepts

• ***Human-centered computing*** → *Information visualization;* • ***General and reference*** → *Surveys and overviews;* • ***Applied computing*** → *Environmental sciences;*

1. Introduction

Both as a physical phenomenon and as a topic of conversation, climate change (CC) is all over the place. It manifests as a subtle shift of local conditions – and as an accelerating drift of globally distributed meteorological metrics. As the multi-factorial behavior of a complex system, CC results from an interplay of cultural and natural forces, which merge into an ecological subject matter of pervasive relevance. This immersive subject matter is connected to a multitude of other phenomena, topics, and consequences and thus appears as an imagination-stretching construct, which is hard to comprehend and easy to dismiss (Fig. 1).

The core of it all is relatively easy to define: Climate is the "average weather", analyzed over a long period of time [MK15]. It summarizes the status of multiple meteorological variables such as temperature, humidity, wind, or precipitation from a longitudinal observation perspective. As such, climate is one of those constructs we would not have without scientists and their complex methods. It results from the measures of billions of data points, distributed in space and time, as interconnected and integrated by statistics. In short: climate is a conceptual shorthand for complex, abstract, massive, and dynamic data, which experts can show us to exist.

As with so many technical terms, we could leave it right there and with them, was it not that experts themselves are warning us to pay attention – or face unprecedented consequences down the road [Ste07, MK15, Scr15]. As such, CC concerns everyone: All of us have to firstly make sense of it, and secondly, do something on the basis of our understanding – be it revising opinions, rethinking life styles, deriving actions, casting votes, or nothing after all. Yet, how do we come to an understanding and to informed opinions about a massive assembly of abstract data?

Data and information visualization – notoriously defined as cognition-amplifying and augmenting information technology [AHGF12] – appears to be predestined in this context to make the looming (non-)phenomenon visible and accessible for human perception and cognition, and to go beyond the representational standard potpourri of polar bear-centered symbol photography and film footage, which we are used to see on TV, in newspapers and on our social media timelines [ADY]). Consequently, a great number of CC communication initiatives started to make use of computer-supported, graphic representations, turning climate data into a sprawling imaging practice.

Research gap: Despite the obvious public relevance of CC visualizations, no systematic exploration of their major design dimensions has been undertaken until now. Aside from rather early re-

DOI: 10.2312/envirvis.20191098

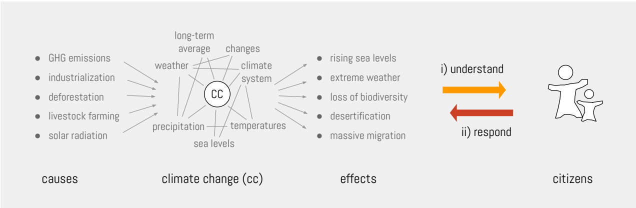

Figure 1: *Climate change as a complex phenomenon, requiring citizens to engage in activities of sensemaking (orange) - and in decisions on their behavioral response (red).*

flections on aspects of the topic (e.g., [NSB*08, JNL10, SSFB08]), no synopsis has been established to structure and organize the field. With this paper we aim to bridge this gap and to have a closer look at a diverse sample of CC representations. With a specific focus on web-based visualizations for non-expert users, we aim to assemble and consolidate the evolving field of CC visualization for public audiences. As 'inconvenient' ecological content still frequently faces reservations and adverse reactions [Bon17], we will also shed light on the potential of CC visualizations to unfold an extended impact of cognitive, affective and behavioral engagement.

2. Methodology

In contrast to comprehensive statistical surveys in well-defined knowledge domains, the core objective of this endeavor is to assemble, establish and consolidate a first, exemplary overview. As the topic of CC is distributed and communicated in multiple mediaspheres, a comprehensive review is impossible to undertake *ex nihilo*. Accordingly, our procedure is explorative and divergence-oriented and puts emphasis on the documentation and analysis of distinct, prototypical design solutions.

2.1. Search Procedures

We collected visualizations based on a multi-pronged research and sampling procedure. Throughout an initial exploration phase, we collected visualizations without a restriction on types of content provider. Thus we sampled CC visualizations from newspapers, administrative agencies, research institutions and environmental organizations, as well as work from individual experts and visualization designers.

We conducted keyword searches in newspaper archives (like The Guardian, New York Times, Washington Post, Bloomberg), via Google Scholar (visualization, climate change, global warming, greenhouse gases), and harvested Google searches to single out relevant blog posts, websites and communication projects from scholarly institutions, NGOs, designers, and researchers. This work was complemented through hints from visualization experts and related threads on social media platforms.

Inclusion Criteria: Climate change – as defined by its own terms – is about long-term average weather and its change. Building on this basic component analysis we decided to collect visualizations and visual representations which

- encode CC via (local or global) *temperatures*, or concentration of *greenhouse gases* as the main factor driving CC,
- encode at least some aspect of *temporal development*,
- make use of (at least one) *information visualization technique* (either as static or interactive graph),
- are either openly available *on the web* or documented by a *research paper*, and which
- mainly aim to address *non-expert users and public audiences*

While these criteria geared the survey to current, web-based, and mostly interactive content, we also saw the need to include seminal diagrammatic visualizations of the topic (such as the famous "hockeystick graph" [MBH99]). This led to a richer, more diverse review of the visualization design space. We are aware that the database of this survey is both foundational, as well as cursory, which limits our analysis. Nevertheless, exploratory studies like this one create a commonly accessible ground, on which the (self-)understanding of an emerging topic can take place and can be advanced. To do so, we collected diverse CC visualization showcases and design solutions. From 75 collected visualizations which were taken into closer consideration, 37 met our final inclusion criteria and were analyzed by the three authors independently for this review.

2.2. Categories of Analysis

To analyze the heterogeneous variety of existing CC visualizations, we established a taxonomy which looks a) at the basic data dimensions from which CC visualizations draw, and b) at the major techniques which they use to visualize the (arguably) most relevant data dimensions for CC representation, which are *temperature* and *time*. In addition to further criteria such as narrative design, we also investigated important visualization elements which we refer to as "engagement techniques" (see Section 4).

2.2.1. Data

Climate change is defined as the change of the earth's long-term average wheather – which emerges from an interplay of variables such as temperature, humidity, wind, and precipitation. Among these multiple variables, land and sea *temperature* plays a notably elevated role, as its change has critical consequences for the cryosphere, i.e. the climate system's vast reservoir of frozen water – and on the consequential rise of sea levels. Most CC visualizations thus encode the state of temperatures for a certain *region* or for the whole *globe*. Exceptions are visualizations which refrain from temperature visualization in favor of the representation of emission levels of *carbondioxide*, which is known to be the one critical driving factor of CC as global warming [RM].

On a more general level of possible drivers, our taxonomy documents, whether *causes* of CC are represented in visualizations, but also if *effects* of the phenomenon (like melting glaciers and ice caps, rising sea levels, loss of biodiversity, migration and social unrest) are elaborated. We further encoded whether visualizations chose a purely *descriptive* approach, or if they visualize *projections*, extrapolating and extending the existing time series of data and measurements. With regard to the latter, our taxonomy also captures visualization of statistic or stochastic *uncertainty*, which comes from different emission scenarios – which again depend on future actions of billions of actors.

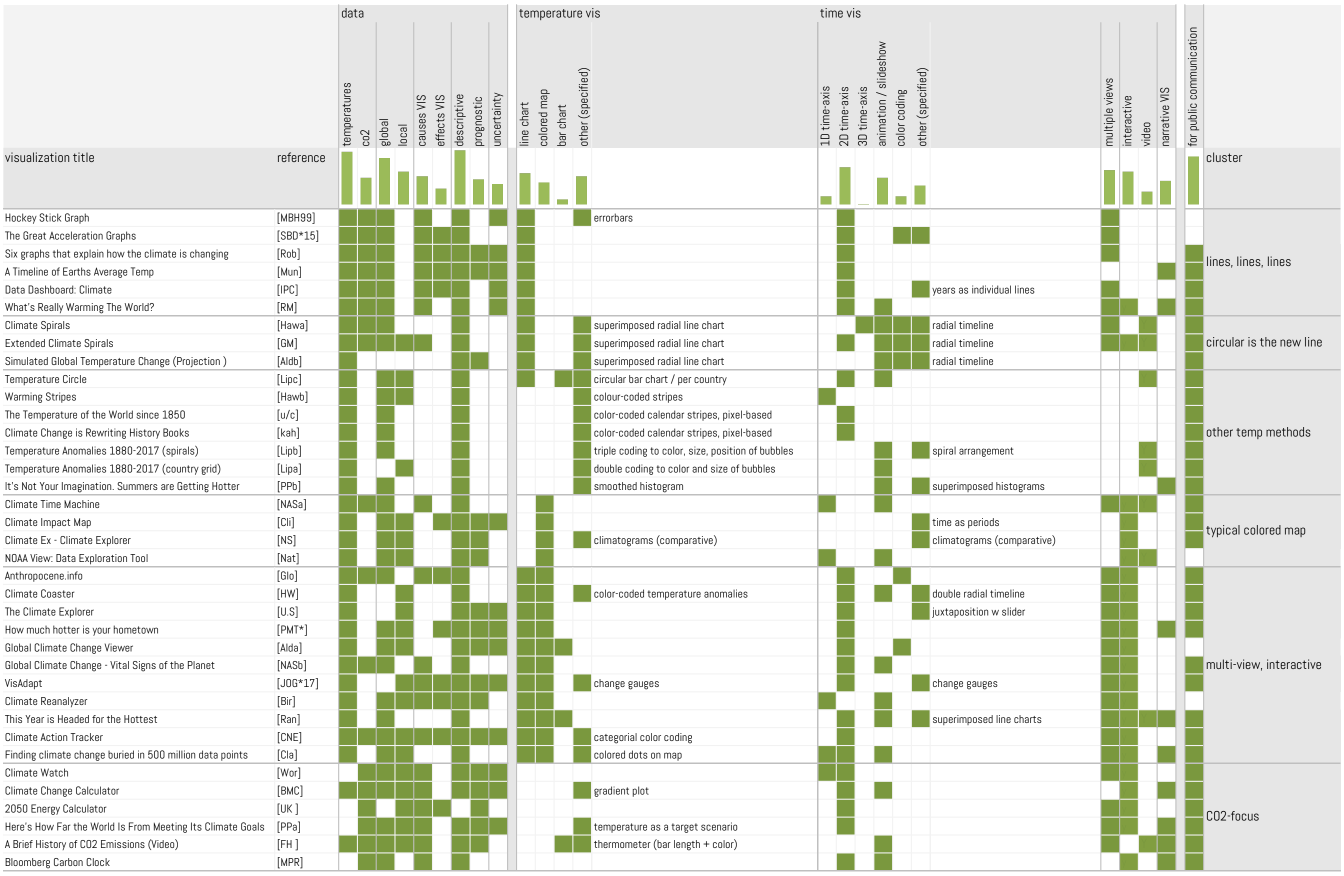

Figure 2: *Design space and categorial distribution of all surveyed CC visualizations*

2.2.2. Visualization Techniques

Arguably, the major challenge for designers of CC visualizations is to convey the development of *temperatures* (or *CO_2 levels*) over *time*. As such, we analyzed, which different *temperature visualization techniques* and which *time visualization techniques* are utilized. For the representation of ***temperature***, we found the two most prominent solutions by far to be *line charts* (21) and *colorized maps* (15), followed by *bar charts* (4) and *other techniques* (19). As for the representation of change over ***time***, we found standard solutions to be the mapping of time to a linear, spatial dimension – either by utilizing a *1D time-axis* (6), or by encoding time along a linear axis in a *two-dimensional* (25) or also in a *three-dimensional* (1) constellation. Another prominent encoding technique is given by the use of *animation*, which can also be implemented as a *slideshow* (18), by the use of *color* to signify time periods (6), or by *other techniques* (13), which we specified in more detail.

Furthermore we analyzed if a visualization or visual interface utilized combinations of *multiple views*, to provide different analytical perspectives for their selection of CC data. We further documented whether visualizations were static or offered some form of *interactivity*. The use of *video* also appeared as a distinct design element to dynamically transport information, as are techniques and strategies of *narrative design* [SH10]. Finally, we documented whether visualizations directly address *public audiences*, or if their design retains connections to expert users: Despite our focus on the former, we also included CC visualizations which originally target experts (e.g. [MBH99]), but were later taken up for public communication, or which target politicians and decision makers as a special case of semi-expert users.

3. The Design Space of Climate Change Visualizations

Figure 2 lays out all surveyed visualizations as an ordered matrix of our investigation. It discloses the feature and design space of 37 CC visualizations and profiles every approach according to our taxonomy. From an interpretive point of view, we identified six relatively distinct groups or types of CC visualizations.

3.1. Lines, Lines, Lines

Line charts are the most prominent method to visualize global climate change in our sample. We identified one group of six visualizations that exclusively use line charts – from the famous hockey stick graphs [MBH99] and their typical web-based implementations [Rob, IPC] to an entertaining and narrative variation [Mun]. Line charts can be used effectively to show the steep curve of human-caused warming in comparison to previous years. Another big advantage is the easy way to integrate uncertainty: Five out of the six reviewed examples include information on uncertainty mainly by encoding confidence intervals as a shaded area. Line charts are not only used to depict global temperatures, but also different causes and effects of climate change (e.g. as small multiples in [SBD*15]) and thus show correlative relationships between measurements. Though commonly not interactive themselves, line charts provide – alongside maps (see Section 3.3) – the standard repertoire for interfaces with multiple views (see Section 3.5).

3.2. Circular is the New Line

A derivative of the standard line chart transforms the time axis into a radial arrangement to encode months in a circular fashion – and superimposes multiple temperature trajectories to encode individual years. These "Climate Spirals" [Hawa] then use animation to show the development of global temperature. While their design emphasizes the severe increase of global temperatures, they do not include information on uncertainty. They have been extended to incorporate future projections [Aldb] and were successfully integrated with CO_2-data in a climate dashboard [GM].

3.3. Other Temperature Visualization Techniques

Many visualization techniques communicate temperature changes in other ways: Frequently, different versions of saliently color-coded stripes are used to highlight the steep rise of global temperature [Hawb, u/c, Kah]. Animated bubble charts were developed to visualize the amount of days above or below average temperature [Lipb, Lipa]. Both have been used to not only depict global changes, but also developments for individual countries. The distribution of significant hot or cold days can be seen in [PPb] as a histogram. Finally, in [Lipc], circular bar charts show the development of temperatures per country.

None of the visualizations of this group include interactive features and they do not combine data on temperatures with data on causes, effects or future prospects of climate change. As for another limitations, they do not include information on uncertainty.

3.4. Typical Colored Map

Besides line charts, choropleth maps appear as most established technique to represent CC data. Four analyzed CC visualizations use maps exclusively, but (similar to line charts) color-coded maps are also included in all of the more complex interfaces (see Section 3.5). Maps provide a global overview and the ability to compare local data points is only limited by the resolution of the map. The reviewed map tools always include some kind of interaction: Filtering and tool-tips [Nat] or data point selection [NS] support the exploration of the geographic variations of temperature. To explore geo-temporal developments, either animation with an interactive timeline [NASa] or the selection of comparative views [Cli] are offered. Three out of four visualizations in this group incorporate prognostic data, but only one provides basic information about uncertainty by showing projections based on different emission scenarios [Cli].

3.5. Multi-View Interactive Visualizations

We found eleven visualizations that combine different visualization techniques in multiple views. The purpose of these web applications is either to provide a dashboard-like summary of climate information [NASb, Glo] to tell a compelling story using different perspectives [PMT*, Ran], to offer specialized decision-support systems [JOG*17, CNE] or to visualize data of scientific climate models [Alda, Bir].

All visualizations in this group combine line charts, colored maps and often additional methods, such as bar charts or colored dots [Cla], and sometimes more customized and artistic techniques like a color-coded radial timeline [HW] or "change gauges" [JOG*17].

All of these visualizations use interactivity to various degrees: from a simple play button to start an animation of a line chart with mouse-over [Ran] and input fields to provide personalized information [PMT*] to sophisticated filtering techniques [U.S].

3.6. Visualizations Focusing on CO_2

Even though they do not visualize temperature, we included six further CC visualizations in our survey which focus on the most important driver of human-made climate change: greenhouse gasses, especially CO_2. Consequently, these mostly interactive and prognostic visualizations always refer to global warming as a causal effect. They aim to show the impact of policies on CO_2 levels [Wor, BMC, PPa], to let users explore their effects interactively [UK] or to outright warn of current and possible CO_2-levels [MPR] and to issue calls to action [FH]. Thus, they provide additional insights into the realm of engagement techniques used in CC visualizations that do not only sharpen our understanding, but also encourage the (re)formation of opinions and of active involvement into climate action and mitigation endeavors (see Section 4).

4. Climate Change Visualizations and User Engagement

"Can visualization save the world?", ask Sheppard and colleagues [SSFB08], pondering future scenarios of unmitigated climate change, which harbor threats of an extinction-level magnitude [MK15, Scr15]. Visualization, in turn, would mostly prefer to just save the signal from the noise, to keep things simple, to stick to a decent, objectivist style and – above all – to just *show the data*. Graphical excellence often recommends to abstain from everything but the chart, to not bank on aesthetics, to avoid redundancy, and to arrive at a careful balance of sober and parsimonious design. While this rationale seems more than agreeable in most scholarly and educational contexts, the current situation of ecological communication comprises constellations, where careful objectivism runs aground in a vast and unsettling problem area of a stalled and hyper-polarized socio-ecological conversation [HMML15]. After all, hundreds of documentaries and news specials have already told us the facts and the threats: "*The alarms have been sounded; they've been disconnected one after the other*" [Lat17, p.10].

The self-conception of InfoVis as a "cognition-amplifying" endeavor arguably requires a largely undisturbed setup akin to an *"ideal speech situation"*, which has been analyzed to be the precondition of productive discourse in the public sphere [Hil03]. In such situations, actors evaluate assertions on the basis of reason, evidence, and rational merit, in an overall atmosphere that is free from any influences of physical or psychological coercion. Such situations allow to focus on the enhancement of the cognitively active elements in our representations, and it seems safe to assume that most endeavors of visualization design and their scholarly reflections are situated in this purified and idealized space.

The communicators of "inconvenient" ecological topics, by contrast, face not only general challenges such as *attention deficit, information fatigue*, and *competing disinformation*, but also advanced forms of resistance: From psychologically constituted defense against mitigation demands [SCD*10] to politically organized defense industries of special interests [IM]. Against such a background of limited receptivity, visual communication design is well-advised to go beyond its purified focus on cognitive efficiency, and look at recent work on "user engagement", which brings a new understanding of psychological, behavioral and political implications to the representational scene.

Along the lines of the sustainable development goal No. 13, which pushes to "*take urgent action to combat climate change and its impact*" [UN 15], visualization design can deliberately go beyond its cognitive core mission: Well designed InfoVis can assist in further engagement with the CC topic. It can emphasize expected effects and foster contextual opinion formation and it can provide a better understanding, for instance of the role of individual contributions or of the relevance of collective mitigation and adaptation endeavors, which also depend on international collaborations, and on democratically legitimized institutions and mandates for large scale interventions.

4.1. Engagement in InfoVis

Typically, visualization design maximizes for cognitive effects and cognitive efficiency – which is reinforced by standard definitions of InfoVis as cognition and insight-centered endeavor. Hung and Parsons [HP], by contrast, discuss a recent shift in interest also towards affective effects of InfoVis. The concept of *engagement* combines the cognitive and affective effects of InfoVis – and adds a third one: Building on definitions from HCI [O'B], user engagement in InfoVis can be understood "as the emotional, cognitive and behavioral connection that exists between a person and an object" [ARL*, p.2] or topic in the case of CC.

To adapt the concept of user engagement for InfoVis, recent works have suggest different multi-level conceptions: O'Brien [O'B] identified four components or stages of engaging design, moving from the *novelty and aesthetic appeal* to *focused attention*, *perceived usability* and *endurable engagement*. A different approach was chosen by Mahyar and colleagues [MKK15], who built their taxonomy of user engagement in InfoVis on theories of learner engagement and distinguished five stages: From *expose* (view), to *involve* (interact), *analyze* (find trends), *synthesize* (test hypotheses), and *decide* (derive decisions).

For assessing the comprehensive engagement factor of CC visualizations, we consider a combination of both taxonomies to be most useful (see Figure 3). To engage users, a visualization has to (1) attract attention, e.g. by its aesthetic appeal. (2) Users then have to examine a visualization and (3) interactively explore the underlying data. (4) The next stage of engagement (often in parallel with the last two stages) is the conceptual and semantic analysis of a representation, and a reflection of the underlying meaning of its information. As a typical measure of engagement, the duration and number of interactions [ARL*] only covers the last three stages of user engagement. But if a user deeply engages with an visualization, also more endurable cognitive, affective and behavioral adaptations can be triggered [O'B]: (5) Users might form or change their understanding and opinion based on the information visualized and (6) take some form of (ecological) action.

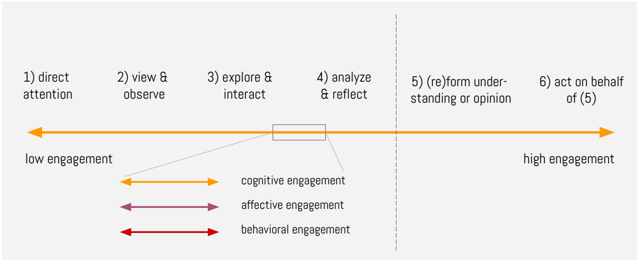

Figure 3: *A model of user engagement, discerning six levels of user involvement across three different engagement dimensions, which different design strategies can activate.*

Whether a user engages with a CC visualization or not is influenced by both, top-down and bottom-up factors: Top-down processes are influenced by prior knowledge, beliefs and interest – and are obviously out of control of InfoVis design. Bottom-up processes are steered by the information and how it is presented – visualization techniques play an important role in this context. We thus consider it highly relevant to also reflect on "engagement techniques", which have been used by the reviewed visual representations - and which might be available beyond that.

4.2. (Visual) "Engagement Techniques"

To collect a diverse tableau of engagement techniques, which have been leveraged by the visualization designs of our collection, all three authors openly annotated for each visualization (cf. Figure 2) what they found engaging (or not). These observations were qualitatively analyzed and assigned to the different stages of the synoptic user engagement model, which we revised for the area of ecological communication (cf. Figure 3).

4.2.1. Techniques to engage users' visual attention

Visualizations with a high aesthetic appeal (e.g. [Lipc, Lipb, Lipa, Hawb, Hawa, FH , RM]) attract more attention than less aesthetic ones. But also moving or changing information in animated visualizations (e.g. [Lipb, Lipa, Hawb, Ran]) attract more attention in contrast to static representations. A recent study showed that animated visualizations result in higher engagement than non-animated ones [ARL*]. Also more salient colors (e.g. emphasizing threats) can attract higher levels of attention. For instance, in the 2015 redesign

[SBD*15] of the 2004 Great Acceleration Graphs, a colour gradient was added to emphasize the rising curves.

4.2.2. Techniques to engage users in viewing

Animation not only attracts visual attention, it can also guide viewing behavior. For example, in [RM], animation is used to build up the graph, one line after the other. Thereby, users are fully presented the complex information in the multiple-line-charts. Aside from animation also other highlighting techniques can guide users' viewing behavior: For example, a single blinking value directs visual attention to specific parts of a visualization [NASb]. Many CC visualizations use multiple codings of the same data to direct visual attention to this information, for example temperature is coded by color and line height in [SBD*15, Hawa], and even in a threefold fashion in [Lipb] (bubble color, size and position).

4.2.3. Techniques to engage users in exploration / interaction

To engage users in exploration of a visualization, interaction is key. Many CC visualizations use narrative patterns [SH10] like the Martini glass structure [RM, BMC] or an interactive slideshow [MPR, Cla, PMT*] to combine author-driven presentation of content with viewer-driven free exploration of the visualizations.

Applying visual techniques for engaging users until this stage seems intuitive. But how can they be applied to guide user engagement beyond the interaction with the visualization for the last three stages? "How does the aesthetic form of infovis not only put environmental phenomena before viewers' eyes but also activate reflection on their participation in those phenomena, as either protagonists or antagonists?" [Hou14, p. 332]

4.2.4. Techniques to engage users in analyzing / reflecting data

In their conception of casual information visualization, Pousman and colleagues [PSM07] emphasize that information is likely to be reflected with respect to its personal and social relevance. Thus *personalization* helps users to connect to the displayed information. In CC visualizations, a frequent option is the selection of a location [Wor,HW,U.S]; even more notable options are the selection of birth year and place to show temperature development from birth until today and to one's 80th birthday [PMT*], but also the individual configuration of housing conditions to show the effect of CC, e.g. on expected repairs [JOG*17].

In the context of journalism, CC visualizations are frequently used to support a reporter's text-based argumentation and help users to follow their line of reasoning. Some CC visualizations enrich their timelines with historically well-known events [Mun, MPR] that can help users to make sense of the data.

In general, casual users are less patient with usability problems and less motivated to decode non-intuitive, unfamiliar visualizations. Even though we found some explainers of "how to read this graph" [CNE], one should not expect casual users to carefully read them. Therefore, the use of intuitive concepts and visual patterns is a key factor to engage casual users in deeper analysis and reflection. An example is the use of a calendar metaphor to structure data temporally [u/c], but also the provision of "multilingual" temperature scales (e.g. to let users select Fahrenheit or Celsius), and of salient temperature color scales: Sometimes full red-blue scales are mapped to small temperature differences instead of on absolute values [Lipc, NASa] – a risk for misinterpretation.

4.2.5. Techniques to engage users in opinion formation

The use of "visualization rhetorics" can assist, but also bias opinion formation by a variety of persuasion techniques. Hullman and colleagues [HD11] distinguish rhetorical techniques related to (1) the selection of data, (2) the mapping and representation of information, (3) the use of linguistic cues and (4) procedural rhetorics.

As for the *selection of data*, many CC visualizations show temperature differences, which obviously depends on the choice of a temperature baseline: Some use the 1990s [Glo, SBD*15], others the beginning of the 20th century [Hawa], others even differing baselines for each visualization [IPC]. As for data provenance, most visualizations make their sources transparent (at least in footnotes), as well as chosen prediction models, but sometimes a representation of uncertainty (associated with every prediction model) was missing [Aldb, NS, Nat, Bir, UK, FH] and only some visualizations let users explore multiple possible predictions [PPa, BMC].

For the *mapping of information*, we found persuasion techniques like defining axes to maximize differences [IPC], or using visual metaphors like a hurricane [Hawa], or earth as an exploding bomb [FH] to activate associations on the devastating effect of CC.

For the *use of linguistic cues*, visualizations in newspaper articles are often framed with a strong textual claim or an expressive headline, such as "This year is headed for the hottest" [Ran] or "It's not your imagination. Summers are getting hotter" [PPb].

For *procedural rhetorics*, [RM] presents different possible causes and their combinations one after the other (almost like in a quiz show) to show finally which one influences global warming. An exploration of possible causes and effects can help users to build stronger opinions based on a profound database.

4.2.6. Techniques to engage users in action

"Empowering visualizations should also allow viewers to question visual representations, utilize them to tell their own story, and shift from awareness to action" [DFCC13, p.2196]. Only one visualization in our review directly applied techniques to encourage action: In the 2050 calculator [UK] users can adjust UK's strategies (but calculators for many other countries followed) in different areas to meet an 80% CO_2-reduction target. It visualizes the effects of national strategies also involving individual actions (like using public transport or separating waste) via pictograms and a CO_2-reduction target representation on the top of the page.

A couple of interfaces outside of our sample follow similar ideas, such as the *climate change food calculator* [BH], which asks users to rethink their own food choices based on a representation of their carbon footprint. Other visualizations utilize depictions of CC effects and impacts as an engagement technique: attacking sea levels [McC], drowning cities [HKW], and vanishing glaciers [Pop17] appear as expressive examples in this category. As these approaches show us the dramatic costs of inaction, they also advocate for a shift from awareness and contemplation to counterbalancing mitigation or adaptation activities.

4.3. Revising the eco-politics of visualization

While we consider transitions from insight to actionable knowledge to practical involvement to be among the most relevant connections that CC visualizations can help to establish, numerous non-trivial barriers remain. Among others, the sheer scale of the ecological challenge requires coordination of individual actions – from regional initiatives up towards collective climate action on a planetary scale. Visualization designers thus will have to coordinate their local engagement programs with the complex engagement strategies of large inter- and non-governmental activity programs, whose "design space" of possible responses is immensely complex in itself, as a handcrafted chart of the current geoengineering discourse depicts [Inf15].

Whichever combination of engagement techniques visualization designers will realize – the extension of their cognition-supporting core program towards strategies of ecological affect and action support also requires to build up new levels of responsibility, accountability and transparency. As Sheppard and colleagues argue, we are well-advised to complement any engagement and persuasion efforts with novel modes and codes of conduct, to brace against their imminent abuse [SSFB08]. As a corresponding initiative, their promotion of "3 Ds" aims to pair an appropriate amount of *drama*, which engagement techniques generate, with the transparent *disclosure* of data sources and design choices, and match practical and political impulses with the full *defensibility* of professional visualization design.

5. Conclusions

We assembled, analyzed and discussed visualization approaches to one of the defining topics of our time. Climate change is an invisible "omnitopic", which makes human understanding essentially dependent of the internal and external representations which we are able to create. In particular, our survey aimed to

- start a more systematic reflection on this topic from a visualization point of view and consolidate this area as a research and development field of specific public interest,
- collect a rich and divergent spectrum of examples to analyze them against the background of a common design space,
- point out different design solutions for future users, such as teachers, journalists, activists and communicators, and to
- go beyond the study of cerebral visualization design to discuss elements and strategies of cognitive, affective, and behavioral engagement.

Due to the vast number of visually supported CC information and communication efforts, we put emphasis on exploration of representational diversity. We documented different types of CC-visualization, to structure an emerging application field, and to strengthen its efforts from an information visualization point of view. Decoding essential elements of CC visualizations – and assembling different design solutions – can take burden from journalists, teachers, editors, activists, decision makers or communicators, and support their oftentimes tedious work in the field of sparse public attention and competing disinformation campaigns.

Given the immensely high stakes at play in the CC topic domain, we found that most CC visualizations in our review used some kinds of engagement techniques, and thus offer a fascinating area for professional (self-)reflection for the visualization community. Especially with regard to engaging design for the advanced stages of opinion (re)formation and climate action, we see a whole new field of future research challenges, of how to counter endemic attitudes of inaction and irresponsibility with dramatic and persuasive, but also transparent and defensible design.

References

[ADY] ANNE DIFRANCESCO D., YOUNG N.: Seeing climate change: the visual construction of global warming in canadian national print media. 517–536. doi:10.1177/1474474010382072. 1

[AHGF12] ARIAS-HERNANDEZ R., GREEN T. M., FISHER B.: From cognitive amplifiers to cognitive prostheses: Understandings of the material basis of cognition in visual analytics. *Interdisciplinary science reviews 37*, 1 (2012), 4–18. 1

[Alda] ALDER J.: CMIP5 global climate change viewer | region and global climate. URL: https://tinyurl.com/199q7s8. 4

[Aldb] ALDER J.: Simulated Global Temperature Change (Projection). URL: https://www.usgs.gov/media/images/simulated-global-temperature-change-0. 4, 6

[ARL*] AMINI F., RICHE N. H., LEE B., LEBOE-MCGOWAN J., IRANI P.: Hooked on data videos: assessing the effect of animation and pictographs on viewer engagement. In *Proceedings of AVI 2018*, ACM Press, pp. 1–9. doi:10.1145/3206505.3206552. 5

[BH] BRIGGS C. G., HELEN N. S.: Climate change food calculator: What's your diet's carbon footprint? URL: https://www.bbc.com/news/science-environment-46459714. 6

[Bir] BIRKEL S.: Climate Reanalyzer. URL: https://climatereanalyzer.org. 4, 6

[BMC] BURN-MURDOCH J., CLARK P.: Climate Change Calculator. URL: https://ig.ft.com/sites/climate-change-calculator/. 4, 6

[Bon17] BONNI C.: An Inconvenient Sequel: Truth to Power, 2017. 2

[Cla] CLARK D.: Finding climate change buried in 500 million data points. URL: https://flourish.studio/2018/02/27/climate-weather-map/. 4, 6

[Cli] CLIMATE IMPACT LAB: Climate Impact Map. URL: http://www.impactlab.org/map/. 4

[CNE] CLIMATE ANALYTICS, NEW CLIMATE INSTITUTE, ECOFYS: Climate Action Tracker. URL: https://climateactiontracker.org/. 4, 6

[DFCC13] DÖRK M., FENG P., COLLINS C., CARPENDALE S.: Critical infovis: exploring the politics of visualization. In *CHI'13 Extended Abstracts* (2013), ACM, pp. 2189–2198. 6

[FH] FH POTSDAM: A brief history of CO2 emissions. URL: https://vimeo.com/232557105. 4, 5, 6

[Glo] GLOBAIA: Anthropocene.info. URL: http://www.anthropocene.info/great-acceleration.php. 4, 6

[GM] GIESEKE R., MEINSHAUSEN M.: Climate Spirals - From Emissions To Global Warming. URL: https://tinyurl.com/y2sy6yvc. 4

[Hawa] HAWKINS E.: Climate spirals. URL: http://www.climate-lab-book.ac.uk/spirals/. 4, 5, 6

[Hawb] HAWKINS E.: Warming stripes. URL: http://www.climate-lab-book.ac.uk/2018/warming-stripes/. 4, 5

[HD11] HULLMAN J., DIAKOPOULOS N.: Visualization rhetoric: Framing effects in narrative visualization. *IEEE Transactions on Visualization & Computer Graphics 17*, 12 (2011), 2231–2240. 6

[Hil03] HILLIER J.: 'Agon'izing over consensus: Why habermasian ideals cannot be 'real'. *Planning Theory 2*, 1 (2003), 37–59. 5

[HKW] HOLDER J., KOMMENDA N., WATTS J.: The three-degree world: cities that will be drowned by global warming. *The Guardian*. URL: https://tinyurl.com/y82j4ahb. 6

[HMML15] HOWE P. D., MILDENBERGER M., MARLON J. R., LEISEROWITZ A.: Geographic variation in opinions on climate change at state and local scales in the usa. *Nature Climate Change 5*, 6 (2015), 596–603. 4

[Hou14] HOUSER H.: Aesthetics of environmental visualizations: More than information ecstasy? *Public culture 26*, 2 (73) (2014), 319–337. 6

[HP] HUNG Y.-H., PARSONS P.: Affective engagement for communicative visualization: Quick and easy evaluation using survey instruments. In *Visualization for Communication (VisComm)*. 5

[HW] HINCHCLIFFE G., WHITELAW M.: ANU climate coaster. URL: http://gravitron.com.au/climatecoaster/. 4, 6

[IM] IYENGAR S., MASSEY D. S.: Scientific communication in a post-truth society. doi:10.1073/pnas.1805868115. 5

[Inf15] INFORMATIONISBEAUTIFUL: Geoengineering the Climate. Extreme Global Warming Solutions Currently on the Table, 2015. URL: https://tinyurl.com/y3kpt9bg. 7

[IPC] IPCC CARBONBRIEF: Data dashboard: Climate (archive). URL: https://tinyurl.com/y2d7ga2v. 3, 6

[JNL10] JOHANSSON J., NESET T.-S. S., LINNÃĽR B.-O.: Evaluating climate visualization: An information visualization approach. In *14th International Information Visualisation Conference* (2010), IEEE, pp. 156–161. doi:10.1109/IV.2010.32. 2

[JOG*17] JOHANSSON J., OPACH T., GLAAS E., NESET T.-S., NAVARRA C., LINNÉR B.-O., RØD J. K.: Visadapt: A visualization tool to support climate change adaptation. *IEEE Comp. Graph. & Appl. 37*, 2 (2017), 54–65. doi:10.1109/MCG.2016.49. 4, 6

[Kah] KAHN B.: This graphic puts global warming in full perspective. URL: https://tinyurl.com/y6puwkck. 4

[Lat17] LATOUR B.: *Facing Gaia: Eight lectures on the new climatic regime*. John Wiley & Sons, 2017. 4

[Lipa] LIPPONEN A.: Temperature anomalies 1880-2017. URL: https://www.youtube.com/watch?v=7RygVNrKMs0. 4, 5

[Lipb] LIPPONEN A.: Temperature anomalies 1880-2017 (spirals). URL: https://tinyurl.com/y4j6po4v. 4, 5, 6

[Lipc] LIPPONEN A.: Temperature circle. URL: https://anttilip.net/temperature-circle/. 4, 5, 6

[MBH99] MANN M. E., BRADLEY R. S., HUGHES M. K.: Northern hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophysical research letters 26*, 6 (1999), 759–762. 2, 3

[McC] MCCANDLESS D.: When sea levels attack! URL: https://tinyurl.com/y66rkoka. 6

[MK15] MANN M. E., KUMP L. R.: *Dire predictions: Understanding climate change*. DK, 2015. 1, 4

[MKK15] MAHYAR N., KIM S.-H., KWON B. C.: Towards a taxonomy for evaluating user engagement in information visualization. In *Workshop on Personal VIS: Exploring Everyday Life* (2015), vol. 3, p. 2. 5

[MPR] MIGLIOZZI B., PEARCE A., ROJANASAKUL M.: Bloomberg carbon clock. URL: https://tinyurl.com/kcnzs46. 4, 6

[Mun] MUNROE R.: Earth Temperature Timeline. URL: https://xkcd.com/1732/. 3, 6

[NASa] NASA: Climate time machine. URL: https://climate.nasa.gov/interactives/climate-time-machine. 4, 6

[NASb] NASA: Global climate change: Vital signs of the planet. URL: https://climate.nasa.gov/. 4, 6

[Nat] NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION: NOAA view: Data exploration tool. URL: https://www.nnvl.noaa.gov/view/globaldata.html. 4, 6

[NS] NETZEL P., STEPINSKI T.: ClimateEx (climate explorer). URL: http://sil.uc.edu/webapps/climateex/. 4, 6

[NSB*08] NOCKE T., STERZEL T., BÖTTINGER M., WROBEL M., ET AL.: Visualization of climate and climate change data: An overview. *Digital earth summit on geoinformatics* (2008), 226–232. 2

[O'B] O'BRIEN H.: Theoretical perspectives on user engagement. In *Why Engagement Matters: Cross-Disciplinary Perspectives of User Engagement in Digital Media*, O'Brien H., Cairns P., (Eds.). Springer, pp. 1–26. doi:10.1007/978-3-319-27446-1_1. 5

[PMT*] POPOVICH N., MIGLIOZZI B., TAYLOR R., WILLIAMS J., WATKINS D.: How much hotter is your hometown than when you were born? URL: https://tinyurl.com/yawlnyd7. 4, 6

[Pop17] POPOVICH N.: Mapping 50 Years of Melting Ice in Glacier National Park. *The New York Times* (May 2017). URL: https://tinyurl.com/khxq9vo. 6

[PPa] PLUMER B., POPOVICH N.: Here's how far the world is from meeting its climate goals. URL: https://tinyurl.com/y9ukuddk. 4, 6

[PPb] POPOVICH N., PEARCE A.: It's not your imagination. summers are getting hotter. URL: https://tinyurl.com/yaaewjkm. 4, 6

[PSM07] POUSMAN Z., STASKO J., MATEAS M.: Casual information visualization: Depictions of data in everyday life. *IEEE transactions on visualization and computer graphics 13*, 6 (2007), 1145–1152. 6

[Ran] RANDALL T.: This year is headed for the hottest on record, by a long shot. URL: https://tinyurl.com/y5lqxjph. 4, 5, 6

[RM] ROSTON E., MIGLIOZZI B.: What's really warming the world? URL: https://tinyurl.com/zjl37kf. 2, 5, 6

[Rob] ROBERTS F.: IPCC: Six graphs that explain how the climate is changing. URL: https://tinyurl.com/y5b9lyld. 3

[SBD*15] STEFFEN W., BROADGATE W., DEUTSCH L., GAFFNEY O., LUDWIG C.: The trajectory of the anthropocene: The great acceleration. *The Anthropocene Review 2*, 1 (2015), 81–98. 4, 6

[SCD*10] SWIM J., CLAYTON S., DOHERTY T., GIFFORD R., HOWARD G., RESER J., STERN P., WEBER E.: *Psychology and Global Climate Change: Addressing a Multi-faceted Phenomenon and Set of Challenges - Report of the APA*. Tech. rep., 2010. 5

[Scr15] SCRANTON R.: *Learning to Die in the Anthropocene: Reflections on the End of a Civilization*. City Lights Publishers, Sept. 2015. 1, 4

[SH10] SEGEL E., HEER J.: Narrative visualization: Telling stories with data. *IEEE Transactions on Visualization & Computer Graphics 16*, 6 (2010), 1139–1148. 3, 6

[SSFB08] SHEPPARD S., SHAW A., FLANDERS D., BURCH S.: Can visualization save the world? Lessons for Landscape Architects from visualizing local climate change. In *Proceedings of Digital Design in Landscape Architecture,* (Dessau, 2008). 2, 4, 7

[Ste07] STERN N.: *The Economics of Climate Change: The Stern Review*. Cambridge University Press, 2007. 1

[u/c] U/CAVEDAVE: The temperature of the world since 1850 [OC] - r/dataisbeautiful. URL: https://tinyurl.com/zbryt49. 4, 6

[UK] UK DEPT. OF ENERGY & CLIMATE CHANGE: 2050 Energy Calculator. URL: https://tinyurl.com/jclnywb. 4, 6

[UN 15] UN GENERAL ASSEMBLY: *Transforming our world : the 2030 Agenda for Sustainable Development, A/RES/70/1*. Tech. rep., 2015. URL: https://undocs.org/A/RES/70/1. 5

[U.S] U.S. CLIMATE RESILIENCE TOOLKIT: Climate Explorer. URL: https://crt-climate-explorer.nemac.org/. 4, 6

[Wor] WORLD RESOURCES INSTITUTE: Climate watch. URL: https://www.climatewatchdata.org/. 4, 6