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Article

Why Pandemics and Climate Change Are Hard to Understand and Make Decision-Making Difficult

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Abstract

This paper draws on diverse psychological, behavioural and numerical literature to understand some of the challenges we all face in making sense of large-scale phenomena and use this to create a road map for HCI responses. This body of knowledge offers tools and principles that can help HCI researchers deliver value now, but also highlights challenges for future HCI research. The paper is framed by looking at patterns and information that highlight some of the common misunderstandings that arise—not just for politicians and the general public but also for many in the academic community. This paper does not have all the answers to this, but we hope it provides some and, perhaps more importantly, raises questions that we need to address as scientific and technical communities.

RESEARCH HIGHLIGHTS

- Issues including Covid and climate change are complex including aspects related to numerical literacy.
- Forms of known human cognitive biases can add to this complexity.
- This paper highlights existing approaches in HCI and related literature to visualise, explain or educate to improve decision making.
- We propose new solutions and expose open research challenges for the HCI discipline.

Keywords: cognitive bias, numeracy, Covid-19

1. INTRODUCTION

Late in 2019, the WHO (World Health Organization) reported a novel coronavirus that was detected in the city of Wuhan, China. According to the WHO Coronavirus (COVID-19) Dashboard of Feb 2023 (https://covid19.who.int/), there have been >750 million confirmed cases of COVID-19 and nearly 7 million confirmed deaths. However, based on the World Mortality Dataset (Karlinsky and Kobak, 2021), WHO estimates that, due to under-reporting, the true count is likely to be several times higher, making the death toll closer to 15 million (WHO, 2022). When the first draft of this paper was being written (May 2022), in the UK, where many felt the pandemic was over, there were still more Covid-19 deaths in 1 week than road deaths in a whole year.

The impact has varied tremendously between countries, and within countries between areas and groups often correlated with gender, ethnicity and poverty. However, nobody was spared from the virus, even those who never caught Covid-19 felt the general impact on economic, educational, and health care systems, not least lockdowns of varying severity across the world. Furthermore, numerous policy challenges emerged during the COVID-19 pandemic, including fundamental conflicts between individual freedom and state responsibility, and diverging responses at different levels of administration such as State versus Federal government in the USA and devolved nations (Wales, Northern Ireland and Scotland) versus central government in the UK.

At a government level, both in the UK and Portugal (the authors' nations) and across the world, it is clear that some problems were handled much better than others. Questions about what has driven certain decisions have become salient. Many ask why it is that the things that were apparently evident early in the pandemic seemed obscure to those with the political power to make changes? Indeed, it is still the case that many find these issues so difficult, even for those who are well informed.

At a personal level, many have struggled to make sense of the complex issues, conflicting advice and technical language. At best, this simply led to confusion, but at worst, a collapse in confidence in government and scientific advice.

This paper draws on diverse psychological, behavioural and numerical[1] literature to understand some of the challenges we all face in making sense of large-scale phenomena and use this to create a road map for Human–Computer Interaction (HCI)

[1] The use of the broad term 'numerical' here and at other points in the paper is intended to include statistics, mathematical modelling and numeric data, but also 'qualitative–quantitative reasoning' described in Section 4.8

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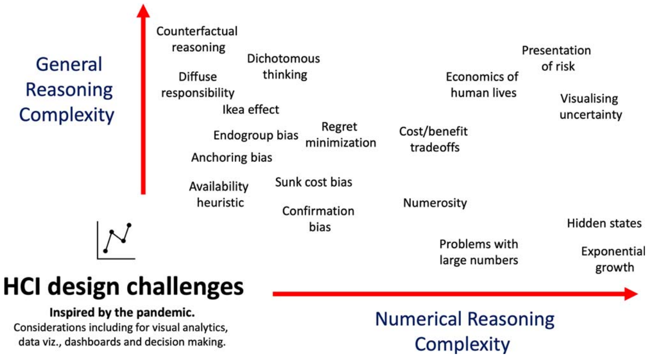

FIGURE 1. Main issues raised in this paper laid out in 'more or less' complex visualization rather than dichotomous numerical versus not numerical

responses. This body of knowledge not only offers tools and principles that can help HCI researchers deliver value now, but also highlights challenges for future HCI research. This paper is framed by looking at patterns and information that highlight some of the common misunderstandings that arise—not just for politicians and the general public, but also for many in the academic community.

There are cases of malicious or self-serving misinformation being disseminated, but we will focus on the misunderstandings of those who we assume are fundamentally well meaning, albeit differing in politics, values and knowledge. We also focus on various forms of cognitive biases or other psychological effects that are especially important when considering the understanding of Covid-19. Virtually any cognitive issue has an impact, but some are particularly problematic.

Much of good and poor information is spread through digital platforms, so there are very direct implications for HCI on these. Furthermore, the back-end digital systems used for modelling, projections, data management and visualization that are used by scientists, government and media all play a part. Even where existing digital systems are not used, there is the potential for future systems help encourage clearer understanding.

This paper does not have all the answers, but we hope it provides some and, more importantly, raises questions that we need to address as scientific and technical communities; a call to arms for HCI.

These issues are essential, not just because Covid-19 and its aftermath will be with us for years to come, but because many of the problems in understanding and reacting to Covid-19 are shared with other large-scale issues from (relatively) parochial political and economic decisions such as Brexit in the UK to global challenges of poverty, intolerance and not least climate change. Of course, Covid-19 will also not be the last pandemic.

In the rest of this paper, we will first look at three quotations from early in the pandemic—one from a university head, one from a science publication and one from the general public—and see how each contains fundamental misconceptions. These will be used to seed a more broad analysis of various forms of cognitive bias or patterns of thought that lead to these and other misconceptions or confusion. We will deal first with general reasoning and then more specifically at numerical reasoning, although the two are interrelated as illustrated in Figure 1. We will also consider issues related to the way human life is both necessarily and problematically assigned numerical value in policymaking. Each issue is accompanied by a reflection on design lessons and HCI research challenges; in some cases, there are existing partial solutions; in some, we offer design of research suggestions; and for others, we pose open research questions. The paper ends by drawing together some of these lessons to help drive future HCI research.

2. MOTIVATION: THINGS PEOPLE SAID ABOUT COVID-19

We'll first look at three quotes that highlight some of the common misunderstandings that arise—not just for politicians and the general public, but also for those of us in the academic community. Each is based on a specific statement from early in the pandemic, but in each case, the same underlying issues and sentiments have been echoed in different ways throughout the pandemic. These example quotes don't include all of the issues we will address later, but emphasize that misunderstandings are common even amongst those whom might expect to know.

2.1. The university head—Risk and dichotomous thinking

First, we'll look at the words of the head of a UK university as part of an interview on BBC Radio 4's morning news programme in March 2020. This was shortly before the lockdown started in the UK and the day after it had been announced that A-level examinations were to be cancelled. A-levels are the principal end-of-school examinations that are used to determine university entry, hence their cancellation was going to cause problems for university admissions processes. The university head was arguing that they should not be cancelled. His words were essentially (paraphrased):

> *'If it is safe to keep schools open for children of key workers, then surely it is safe for students to gather spread out in an exam hall'.*

Note that this was in a live interview, so the exact form of words may have been off the cuff. However, it was the core issue of the interview, so presumably a question that the interviewee would have considered beforehand.

What's wrong with that?

This is an example of *essentialism and dichotomous reasoning*—the idea that something is safe or not safe, with no apparent middle ground. The children of key workers are not 'safe,' but a balance between the risks to society (more than the children themselves) of increasing the spread by them attending school, and the problems that would be caused if key workers are not able to continue their jobs. It is a trade-off, a cost–benefit calculation.

Children often think in essentialist terms: metal is strong, fabric is weak—therefore metal however thin would stop a bullet and fabric would not. Of course, a thin sheet of aluminium foil will not stop a bullet and thick enough wadding can protect against an artillery shell. It is the thickness and *structural organization* of materials that give their ultimate properties.

As adults, we no longer think tin foil will stop a bullet, but sometimes elements of essentialism remain. Clearly, this was the case for the university head. In fact, things are not 'safe' or 'unsafe', they are safer or less safe when weighed against other factors. Surely, this is something a university head should be able to manage, having to weigh up financial risks and other risks…or maybe that is why so many organisations struggle to distinguish risk avoidance from risk management.

2.2. The popular science magazine—Personal versus collective action

New Scientist magazine on 28 March 2020, had a full length article focused on the immune system and its importance in protecting the body against the coronavirus.

The article started:

> *'Wash your hands religiously for 20 seconds, sneeze into your elbow, avoid touching your face, stay 1 meter away from all other people and, as a last resort, self-quarantine for a week with only your emergency rations for company. If you want to avoid getting the new coronavirus, all of these are a good idea.'* (Lawton, 2020).

It then continued to talk in an informed fashion about the immune system.

What's wrong with that?

This is perhaps the most disturbing because it was written by a science journalist and presumably read by editors. Furthermore, this is the opening paragraph of an article about the new coronavirus when the issues surrounding it and the need for social distancing were at the forefront of minds.

Although it used the words, '*if you want to avoid getting the new coronavirus*', half of the measures listed in that first paragraph are nothing to do with protecting yourself, but all about avoiding passing Covid-19 on to others. They are about overall *communal benefits*, and yet, in the West and especially the UK, we have become so used to seeing arguments phrased purely in terms of self-interest that the author fell into this line of reasoning.

As well as largely being communal, the benefits of social distancing and lockdown are diffuse—each individual action has little, or maybe no effect, but the sum total of all those insignificant actions is to reduce the rate of spread and ultimately save hundreds of thousands of lives.

2.3. Public perception—Unexpected numbers

> *'I don't understand, first it was one or two, and then thousands.'*

This is a statement from a social media post (again paraphrased) from someone who lives in the USA, reflecting a sentiment felt by many early in the pandemic when faced with the rapid rise in reported case numbers and deaths.

What's wrong with that?

The person posting here spoke for many people in their lack of comprehension of the rate and size of the growth. No wonder there are many conspiracy theories from government plots to the impact of 5G—exponential growth almost feels like magic.

In terms of mathematics syllabi, the relevant topics to understand these phenomena (notably exponential growth) are treated as 'advanced,' only studied by those specializing in science or engineering. What is needed, however, is clearly better general education in the informal understanding of numbers. It is not important for everyone to be able to do complex mathematics nor to be able to do mental arithmetic, but it is absolutely crucial to have some broad understanding of numbers for so many current issues. We will return to this issue of *numerosity* in Section 4.

3. GENERAL REASONING

First let's look at some of the broad issues around human reasoning before moving on to specifically numerical reasoning in the following section.

3.1. Essentialism and dichotomous reasoning

Essentialism is the idea that things do or do not have some essential characteristics: safe/not safe, good/bad, with no intermediates, uncertainty or context. We've already discussed one example of essentialism, but there are many more. In inferential statistics, dichotomous reasoning is often used to interpret P-values even though a P-value is a continuous variable (known as the *Cliff effect*, i.e. it is either statistically significant or it isn't based on $P < 0.05$ (Lai *et al.*, 2010)).

Essentialism was central to many of the discussions around the use of face masks, surface transmission and later vaccine uptake.

Early discussion of mask use was often framed in terms of whether they are 'effective' (note framed as an essential characteristic), but of course, the real question is 'effective for what?'. If we are asking whether a particular design of face mask is 100% effective in preventing a frontline health worker catching Covid-19 from a sick patient during a close medical procedure, that is very different as to whether a far simpler mask offers some reduction in the odds that you will infect someone else if you are already infected (Howard *et al.*, 2021; Mello *et al.*, 2022).

There are similar questions around the length of time the virus can survive on surfaces. If we want total safety in the face of a heavy contamination (say in a hospital), that is different from reducing the viral load and hence, the likelihood of infection in other contexts.

Vaccine hesitancy has been a major problem across the world. In addition to dogmatic anti-vaxxers, many people were cautious about the Covid-19 vaccine, awaiting further evidence. Given the unprecedented scientific mobilization, vaccines were developed in months compared with typical decades. So in some ways, in terms of surface evidence, an element of caution could be well founded, albeit, with a little more knowledge, it was clear that robust measures were taken during the expedited process.

This last point is crucial because it is easy to view any of these cognitive tendencies or biases as 'bad'—itself an example of dichotomous thinking. In fact, we usually have these tendencies for good reasons, albeit ones that may be optimized for different contexts. In particular, the tendency to create dichotomies, or binary opposition, is seen as central to human communication both in terms of low-level attributes such as phonetics (De Saussure, 1916/2011) and high-level word disambiguation (Kayne, 1984). Binary or at least discrete classes of meanings allows reliable transmission without the gradual distortion that would arise from analogue reproduction. Indeed, Goodman argues that this is crucial even in domains such as music, if one wants to be able to say that an orchestra has faithfully played Beethoven's Fifth Symphony (Goodman, 1976).

In human relations, dichotomous thinking is a two-edged sword: on the one hand, those scoring higher on indices of dichotomous thinking (DTI) were seen by friends as being *articulate and straightforward* (Oshio, 2009); however, a high DTI rating is also correlated with borderline personality disorders (Oshio, 2012). Anecdotally, it seems clear that periods of stress or conflict can lead to more fixed modes of thought. Many of the other factors we will consider can lead to a sense of uncertainty and confusion, not least those that have a mathematical nature, which many find stressful anyway. It is therefore likely that those all serve to increase more dichotomous modes of thought.

3.1.1. *Design lessons and HCI challenges*

Sometimes one or two dimensional graphical presentations can help avoid sharp dichotomies. In this paper, we are largely classifying cognitive biases and patterns of thought as numerical or general (not numerical)—a binary opposition. In contrast, Figure 1 lays out the issues in a 2D space, placing things of greater general complexity higher in the diagram (y-axis) and those with greater numerical complexity further to the right (x-axis). This also helps show that some issues are more problematic in one way or the other, whereas some, such as risk perception, have both numerical and non-numeric complexity.

Of course, these placements are not exact, and the diagram attempts to show this tentative nature by having the axes 'incomplete' or open, i.e. not having a zero point where they meet.

Early CSCW collaborative research systems such as Conferencer (McCarthy and Miles, 1990) deliberately used 2D layout to encourage more tentative placements to encourage more creative problem solving, and this was the inspiration for the dot-com era vfridge (Dix *et al.*, 2011). Two-dimensional layouts were also exploited in the zoomable interface research such as Pad++ (Bederson and Hollan, 1994) and of course in recent commercial systems such as Miro. Despite this wealth of experience, in many digital environments, it is far easier to create discrete representations such as sections, bullet points, outlines and tables than more continuous ones such as the diagram in Figure 1.

3.2. Perception of cost and benefit

Returning again to the university head's idea of 'safe.' In both cases, children of key workers returning to school and examinations for all, the risks to the children themselves were minimal, but the risk was how much they were likely to affect others. The different treatment was never about absolute safety—indeed, it is almost certainly the case that sitting for 2 hours in silence in a well-spaced examination hall is less likely to lead to cross-infection than spending days on end in a classroom together. The core issue is one of a trade-off between costs and benefits. By allowing children of key workers to attend school, the key workers themselves were therefore able to perform their essential duties, and the benefits of this to society were judged to outweigh the additional risks of infection.

As well as these costs and benefits being crucial in terms of societal choices, individuals are implicitly making such trade-offs, even if not articulated explicitly. This personal trade-off is then strongly influenced by the consequences individuals feel (linking to issues of *availability and locality*). It is known that when the consequences are personal and in terms of losses, people are motivated to alter their behaviors to reduce their consequences.

As an example, Madeira is an autonomous region of Portugal whose economic activities are strongly based in the tertiary sector, especially in tourism-related activities (84.4% of the regional Gross Value Added (GVA)). It was estimated that ~85% of companies suffered from the consequences of Covid-19, in particular lack of tourism, leading to a high level of unemployment. As a result, the autonomous government applied more restrictive measures than in the rest of the continent: quarantine for those disembarking at Madeira airport, mandatory use of face masks and retaining curfew even after it was revoked nationally in Portugal. These strong measures might have met with substantial resistance, but this was not the case because nearly every member of the quarter million population of the island was either affected themselves or was close to someone who had experienced Covid-19–related problems, both in terms of the high number of deaths and fear of the ensuing economic crisis. This stood in stark contrast to reactions in other parts of Portugal (e.g. Lisbon and Porto) where people felt less association between restrictions and impact.

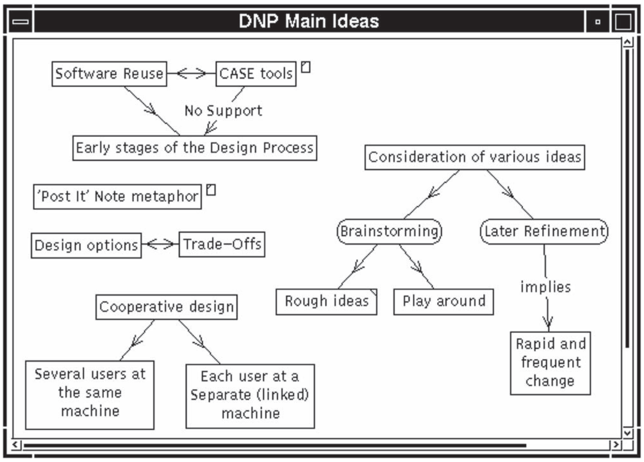

FIGURE 2. Weighing up options and alternatives in the Designers' Notepad (Twidale *et al.*, 1993)

3.2.1. *Design lessons and HCI challenges*

From a design perspective, this raises questions as to how to make some of these balances more apparent in individual choices, policy decisions and public information. Again, it is not that we are without existing work in the HCI literature to help. Early tools such as gIBIS (Coklin and Begeman, 1989), QOC (MacLean *et al.*, 2020) and Designers' Notepad (Twidale *et al.*, 1993) offered more or less easy ways to reason about trade-offs between interrelated decisions (Fig. 2).

3.3. Fixed condition assumptions and change

We often plan assuming certain things are fixed. This is sensible, especially if they are well established or outside our control. However, some of these things are not as fixed as we might initially assume.

Within the UK, the delays in implementing lockdown were around questions of how long the public would accept it and that effectively, the public had to see a certain level of death or economic crisis before the urgency sank in. However, throughout the pandemic, we saw changes in acceptance of measures that would have seemed impossible at the beginning. It is interesting that this scepticism about the public's ability to accept restrictions was informed by behavioural science (Sanders *et al.*, 2021).

We can also find it hard to adapt to changing situations. This is especially true of science, which in popular culture is assumed to deliver universal unambiguous facts, a myth that can sometimes be reinforced by scientists themselves. Most scientists would emphasize the role of process, including falsification, leading to an evolving but ever-improving understanding of reality. However, scientists also know that excessive use of subjunctive language can be used by detractors and may then use language that is more definitive than they really believe. Furthermore, even if scientists are careful, politicians may amplify their message beyond recognition.

A prime example of this was during the BSE ('bovine spongiform encephalopathy') crisis in the UK between 1986 and 1996. The Southwood working group report in 1989 (Southwood, 1989) concluded not only that, '*the risk of transmission of BSE to humans appears remote and it is therefore most unlikely that BSE will have any implications for human health*', but also that, '*if their assessment proves incorrect the implications would be serious*' (quotes from Hansard Hansard1989). The government at the time did take action based on the later warning, banning certain forms of animal feed, but used the former to argue until 1996 that British beef was 'safe' to eat, including the now-infamous images of John Gummer, the then-Minister for Agriculture, publicly feeding his daughter a hamburger before the media in 1990 (Aldhous, 2000).

Although BSE seems long ago, it is not irrelevant to the public reactions to Covid-19. Recall that Andrew Wakefield's discredited paper that seemed to link the MMR triple vaccine and autism that was published in 1998. This was just 2 years after the 'beef is safe' advice, which had been repeated for 10 years by both government and scientists, was admitted to be false. It was perhaps not unsurprising that some in the general public were sceptical of medical declarations about the safety of measles–mumps–rubella, often known as the triple vaccine (MMR), even though this time it was correct. This vein of vaccine scepticism or paranoia has, of course, persisted today and has been a major source of resistance to attempts to control Covid-19 in some countries.

Given the fast pace of the Covid-19 pandemic, there has inevitably been substantial changes in knowledge. For example, there was initially a focus on surface and large-droplet transmission before it was realized that airways and aerosols were a major transmission route of the virus. Indeed, even the WHO were slow to accept Johns Hopkins University School of Public Health evidence that the masks protected the wearer and others. We have seen similar changes in expectations of the value of vaccines, from an initial hope to create herd immunity to one more focused on ameliorating the impact of the disease once infected. Sometimes this has caused negative reactions, especially around mask wearing.

3.3.1. *Design lessons and HCI challenges*

One lesson from this is that we need better ways to help people understand that new knowledge can change advice without invalidating the value of the initial advice. However, it is also a warning to the academic and science community that we need to be radically honest.

3.4. Bias related to change

There are several forms of cognitive bias that interact with changing evidence.

Recall the social media post: '*first it was one or two, and then thousands*'. This is in part a consequence of our tendency to acquire the first piece of information as 'the one' that is *anchoring bias*, neglecting further information, which leaves us with limited possibilities for understanding and acting. The initial 'few' created an anchor that made 'thousands' seem at best surprising and at worst suspicious. Of course, there are reasons for this rapid change including travel hubs, virus spread and rapid exponential growth, and better detection and reporting. *Confirmation bias* might lead many people to seek information that confirms low numbers or that supports ideas that refute the new data ('the virus does not really exist'), ignoring or attaching limited importance to evidence that is contradictory to that belief.

Governments, other organizations and individuals are also prone to *sunk cost bias*—once they have spent resources and committed to a line of action, they are reluctant to make different choices, despite those lines of action now being considered as possibly mistaken. This is exacerbated if they fear that changing the course of action would be perceived as the government admitting error. We seem to find it very hard both individually and corporately to say 'this was the best choice at the time even though it turned out to be wrong in retrospect'; a form of counter regret. This phenomena might also be related to the *Ikea effect*, where people ascribe greater value to the things that they invest time into building (Norton *et al.*, 2012).

Regret and this counter-regret are forms of *counterfactual reasoning*, where we need to look at a situation and ask, 'What might have happened if?' Regret can be a useful measure to aid decision-making. Jeff Bezos uses his 'regret minimization framework' to help make decisions where he uses his mind to envisage himself being an older man looking back at life, asking himself if he would look back in regret doing or not doing a task or project or whichever the decision might be (Hollins, 2019).

As the crisis of the Covid-19 pandemic transforms into longer term coping, people (politicians and general public) could look back at the sometimes draconian measures (lockdowns, border closures, social distancing, mask wearing) and at the actual deaths and ask, 'Was it worth it?' Of course, what they should be doing is comparing the restrictions with what the death rate *would* have been if there had been no lockdown.

In the UK, the per capita death rate was one of the largest in the world, ∼50 times higher than China and higher even in Wuhan where there was no warning. In New Zealand, an earlier lockdown has led to a far lower death rate. If the UK government had opted for an earlier lockdown, would they now be being chastised for overreacting? Certainly, that was the fear amongst some politicians at the time.

3.4.1. *Design lessons and HCI challenges*

Every start-up's business plan includes a spreadsheet showing a 'hockey stick' forecast of future growth. Are there equivalent tools we could provide that help people ask 'what would have happened' or 'what could have happened' questions? Of course, any such tool would itself include all of the uncertainty of predictive modelling.

3.5. Diffuse responsibility and communal benefits

Recall the the *New Scientist* article, which confused measures primarily for communal benefit, but which were stated as if primarily for the individual's good. In general, in the UK, USA and to a lesser extent the rest of the Global North, there is a tendency not merely to formulate policy in terms of individual benefit, but to believe that this is the way we *ought* to argue. To some extent, this has been drummed into us in the West for more than 200 years since Adam Smith: the idea of enlightened self-interest—if we all act in our own best interests, the workings of the free market will sort out everything and deliver the best of all possible worlds. As a religion of economics, it has stood the test of time, and undoubtedly the distributed mechanisms that arise have often been far more robust and flexible than more centralized approaches.

This is an area for which a lot is known already. We've all heard of the prisoners' dilemma. In game theory, this is an example of a Nash equilibrium that is not Pareto-optimal (Nash, 1951), i.e. a situation where every individual makes the best decision for themselves, but there is a way that all could have acted *together* that would have made things better for everyone. In the case of the prisoners' dilemma, each prisoner is acting in ignorance of the other, but in economic theory there are many hypothetical situations where even if everyone operates in full and open knowledge of what everyone else will do, the end result is less good for everyone. The shared assumption in most of these dilemmas and paradoxes is that those involved work only for their own interest and do not in any way collaborate for the common good.

This then led some economists and political theorists to posit that any sort of common resource is destined to fail unless taken into some form of large-scale ownership (private or state), the so-called *tragedy of the commons* (Hardin, 1968). However, there are many examples of successful commons both in traditional agriculture (albeit complex in details (Clark and Clark, 2001)) and more modern movements toward open resources (e.g. the OER Commons https://www.oercommons.org/). Based on this, there have been challenges to these pessimistic views of unbridled individuality, both in terms of ideas of the commons (Ostrom, 1990; Ostrom *et al.,* 1999) and the industrial economy (Raworth, 2017).

In the UK, the lockdown narrative quickly shifted toward protecting the NHS (National Health Service) and vulnerable members of the community. This had a substantial impact demonstrating that the *fixed assumption* of self-directed action can be challenged. However, despite this, there was still substantial confusion (as the *New Scientist* article shows), not least because of early messages that did not make the communal benefits clear. Within the UK, the NHS has a special position because it is seen as a national 'treasure' amplified during Covid-19 lockdowns with the idea of NHS workers as heroes. Even in a largely individualist society, although the idea of 'social good' or general benefits can be hard to communicate abstractly, more specific foci are possible: the NHS is a bureaucracy, but not a faceless one—one of *us* rather than *them*.

Looking at related areas such as climate change, these issues of communal benefit and the apparently insignificant effect of each of our actions can make it hard to frame effective messages. Similar issues arise around vaccination in general and the anti-vax movement. For many diseases, the focus of vaccination is 2-fold: (i) to protect oneself form harm and (ii) to develop sufficient coverage that the disease does not spread (herd immunity). At some point, the reason for taking the vaccine is not so much about your own or your own child's protection, but for the sake of the community as a whole. In fact, although for Covid-19, the protection against infection offered by vaccines is relatively low (particularly against later variants), but in mid-stages of the pandemic was still critical to slow infection alongside other behavioural measures.

The aforementioned discussion was prefixed with a focus on the UK, USA and Global North. Cultural differences have clearly played a role in Covid-19 responses. Asian countries and populations are less individualistic and more cooperative, and in general, have been more compliant with the government mandates.

3.5.1. *Design lessons and HCI challenges*

The various critiques of the 'tragedy of the commons' have theoretical and policy-forming value. However. they also offer potential ways for us to engage as HCI researchers and practitioners. For example, Ostrom's Nobel Prize-winning work on governing the commons (Ostrom, 1990) offers principles by which common resources have been historically well managed, several of which may be ways in which well-designed interfaces or digital interventions could be valuable supporting participatory decision-making or the monitoring of common resources.

Inspired by the responses to the NHS in the UK, we might reimagine Shneiderman's (shneiderman2003) information-seeking mantra: overview first, zoom and filter, then details-on-demand. The 'details' are usually seen as being about data and numbers, but for images or text, these may be examples. For large-scale human data such as Covid-19 cases or people effected by climate change, perhaps we need reinterpretations of this where the details are personal, stories that are chosen not only to be representative, but also are ones that appeal to human connectedness.

A good example of this is the 'Dollar Street' visualization at the GapMinder Web site (https://www.gapminder.org/). This shows examples of families around the world living at vastly different income levels to offer an alternative to the caricature images that often accompany news items. GapMinder was set up by Hans Rosling, whose coauthored book '*Factfulness*' seeks to offer more evidence-based view of world issues (Rosling *et al.,* 2018).

Similarly, we need ways to help people relate their small individual actions to collective action. For example, there are numerous apps that help one to track personal carbon costs, but it is hard to understand what a kilogram or tonne of carbon means in global terms. Learning from gamification, this could be put into comparative terms 'you are amongst the highest 10% of carbon producers in the world' or cumulative 'if everyone consumed carbon at this rate, 100 million people would lose their homes due to sea level rise by 2060'.

On the cultural issue, there has been a long literature both on exposing cultural assumptions in HCI and on designing user interfaces explicitly for different cultures (Marcus, 2001), often building on Hofstede's cultural dimensions (Hofstede *et al.,* 2005). The core question is usually about how to design better for a particular culture, but perhaps, as we face global challenges, the question should become more about how we can help each culture *learn the best practices* of each other.

3.6. Availability and locality

As well as cultural effects, recent experience is likely to have shaped the initial differences between Western and Asian countries in both government policy and individual adoption of protective measures such as mask wearing. In general, we tend to heavily weight toward information that is recent or easy to recall (so-called *availability heuristic*).

For instance, Taiwan and South Korea's effective response could have been shaped by other traumatic memories such as the 1957 Asian Flu or the 1968 Hong Kong Flu as well as more recent novel diseases such as SARS. Some of these did have worldwide impact: in 1957, in just 1 year, Asian Flu spread worldwide and led to almost 2 million deaths; similarly the Hong Kong 1968 influenza pandemic emerged in China and quickly infected nearly 4 million people across the planet (Schlingman, 2021). However, avian influenza in 1997, severe acute respiratory syndrome in 2003, influenza A in 2009, and the Middle East respiratory syndrome coronavirus in 2015 were felt more strongly in Asian countries than in the West, where human threats and natural disasters (e.g. Chernobyl, Katrina, Las Palmas Volcano, 9/11) were more salient.

The *availability heuristic* influences both large-scale and individual responses to events. In addition, at an individual level, we are prone to *endogroup bias*, where we tend to consider close people, such as family or friends, as more trustworthy and competent when compared with others. This can lead to local echo chambers or undue attention being paid to a single example of someone close, rather than more representative data. However, it can also be a strategy we can use when designing effective media campaigns or cognitive tools. For example, Captain Tom, the nonagenarian who raised nearly 40 million pounds for the NHS during lockdown, felt almost part of the family for millions of people across the UK (Davies and Lowe, 2021).

3.6.1. *Design lessons and HCI challenges*

There is significant work over many years focused on breaking the ‘filter bubble’ (Bozdag and Van Den Hoven, 2015; Foth *et al.*, 2016; Jeon *et al.*, 2021), e.g. some work by attempting to find close but different news items that are deliberately coming from a different perspective. It is known that these have limitations as presenting views that are too opposed to someone’s preconceptions can simply entrench their position; although this may be less so for examples of real people who elicit personal sympathy rather than more abstract countervailing arguments. There are examples of techniques that work in related domains, e.g. some personal knowledge management tools, such as Obsidian (https://obsidian.md/), include views that gather connected information, and people deliberately choose to use them as an aid to inspiration and creativity.

The issues here also have lessons for our own practices in HCI. It may be that designers are biased in their current user interface (UI) design choices based on their salient ordeals with recent user experience (UX) projects. We certainly know on the research side that when Liu *et al.* (liu2014hcicoword) used co-word network analysis to seek historical trends in HCI, they concluded that ‘the only tradition in HCI is that of having no tradition in terms of research topics’.

4. NUMERICAL REASONING

We’ll now move on to *numerosity*, aspects of reasoning that are related particularly to numerical phenomena.

These cause particular problems, not only because they can be difficult for many people, but also because attitudes to even attempting to understand can be negative. There is often a shocking level of pride as many say ‘*I could never do maths at school*’ in a way they would never say ‘*I could never write at school*’ or ‘*I could never read at school*’. Of course, there are many reasons why people may have difficulties with any of these and one should certainly never feel ashamed of not being able to read, write or add up. However, that is not the same as the way in which innumeracy is perhaps carried almost as a badge of honour amongst many otherwise highly educated and privileged people.

It is not that everyone needs to understand advanced mathematics, just like everyone does not need to be a great poet, artist or composer to appreciate culture.

The term numeracy already has many connotations in education, hence the use of the term *numerosity* above. This is neither arithmetic nor mathematics, but more about the appreciation of numbers and numerical arguments. Aspects of this area are taught early in primary school, notably in estimation skills, but seem to fade later in the curriculum. If those who do not have an advanced mathematical education gain a gut feel for numbers, it is typically not because it has been explicitly taught.

4.1. Exponential growth

Exponential growth is clearly hard to grasp, but happily there are now many widely publicized visualizations that help. Logarithmic scales are also now common in news media, albeit needing further knowledge to interpret. It is not that there are not everyday exponential growth phenomena, from the interest on a payday loan to inflation in the economy. However, these are often far slower and hence easier to grasp because the current growth can be set against a current figure.

Happily, after initial utter confusion by many, there have been many visualizations developed from early in the pandemic to help the general public (and maybe also policymakers) understand exponential phenomena, e.g. videos of a sports stadium filling. Even before the pandemic, one exercise that was used to teach about the spread of the virus was to coat a small number of people’s hands with dye at an event and then ask people to shake hands with those they talked to during an initial icebreaker session. The spread of the dye was then apparent. Of course, this particular exercise could not be repeated during periods of social distancing!

4.1.1. *Design lessons and HCI challenges*

For most people, an equation such as K^x is not intuitively meaningful, even if one has learnt, say, how to manipulate these in school. Indeed, one study of visualizing Covid-19 exponential growth starts, ‘*Humans are woefully inept at intuitively grasping exponential growth functions.*’ (Hutzler *et al.*, 2021). Possibly the one exception is in tech start-up business plans where a ‘hockey stick’ growth projection is *de rigueur*, but even then misunderstood because customer projections would rapidly outpace the world population. For those with an understanding of the issue, static graphics can be useful, in particular logarithmic axes. It has even been found that non-experts can accurately project exponential growth using logarithmic axes (Hutzler *et al.*, 2021), although this, of course, does not mean they understood them. Exponential growth is definitely a topic that emphasizes the need for animation and interactivity.

As noted, there are many practical visualizations of exponential growth, often using disease infection (even before Covid-19) or the Legend of Paal Payasam, who invented the game of chess. In the fabled story, as a reward Paal Payasam asked the king for one rice grain on the first square, two on the second, four on the third, and so on; there are several excellent YouTube videos illustrating this (e.g. (Britton, 2011)). Note that the doubling of grains on the chess board, while giving rise to very rapid growth, seems to be one of the easiest forms of exponential growth for people to grasp; hence, communications about Covid-19 often made use of doubling time compared with, say, a percentage growth per day (Nunes-Vaz, 2020).

These animations and videos and indeed the most powerful static infographics use pictorial representations, for example, presenting graphical representations of people as opposed to representing people as mere points, lines or bars. This is important to aid empathy when reading data, especially for policymakers and politicians. This is perhaps akin to the *framing effect*, where the reader’s interpretation and decision can change based on how the information is presented; hence, the framing of information in HCI and animated infographics is something that we need to consider.

Russo *et al.* (russo2020exploring) explored the teaching of exponential growth with elementary school children and emphasize the importance of *real-world problems* including paper-folding and a pocket money version of the chessboard story. In particular, they found that when presented in an appropriate manner, even the younger children can appreciate the difference between linear and exponential patters, even if they lack the mathematical concepts to describe them formally.

Interactive visualizations are less common, but as a general principle, simply adding interactivity to a fixed visualization can be surprisingly powerful (Dix and Ellis, 1998). For example, standard exponential growth charts were often shown during the pandemic overlaying the shape for different values of R. Online, it would be very easy to add a slider for R, seeing the simple exponential graph move from decay (when $R < 1$) to flat (at $R = 1$)

and then exponential growth (when $R > 1$). Similar techniques can of course be used for more meaningful pictorial visualizations although combining animations, pictorial representation and interactivity seems to be an area worthy of further study.

4.2. Understanding of large numbers

The pandemic and indeed climate change and Brexit are beset by large numbers, often incomprehensibly large. This was evident in the debate around the £350 million figure on the Leave campaign battle bus during the Brexit campaign. Most of this was about whether £350 million a week to the EU was the correct figure or whether it should be smaller (£170 million a week was probably a fairer figure). Of course, the reality is that, compared with overall UK public expenditure, this figure is pretty much in the noise . . . but that is a hard message to communicate to someone earning £350 a week.

Before the Covid-19 crisis, there were massive wildfires across Eastern Australia, and before those wildfires there was a drought. News articles about this stated that ‘megalitres’ or ‘millions of litres’ of water were wasted in the dam and river system during the period (60 Minutes Australia, 2019; Taylor, 2019). This sounds bad at first, but actually megalitres is not much, perhaps 30 truckloads. The figure was used throughout a 20-minute documentary about the issue (60 Minutes Australia, 2019) produced by *60 Minutes*, a well-respected Australian documentary programme. If one refers to the original report (Slattery and Campbell, 2019) that the news article and documentary were based on, the true figure was indeed gigalitres being wasted, not megalitres. The environmental journalist, the writer and editors of the documentary will all have read the script and watched the filmed material, yet none of them noticed an order-of-magnitude error in what they were reporting; the figures all just sound big.

In Covid-19 itself, we are beset by huge numbers: tens of thousands, hundreds of thousands, millions of cases and deaths, and also small numbers: 1–4% death rate across those who were infected as a whole, 0.1% death rate for younger age groups, very small *proportions* of people affected, but large numbers of people one might meet individually, and even larger once aggregated.

In the early days in the UK, there was considerable discussion of herd immunity, but even before government seemed to become aware of the more detailed modelling from Imperial (Ferguson *et al.*, 2020), it was easy to do the sums. To achieve herd immunity 60–70% of 60 million people would need to have caught Covid-19. At that time, before vaccines and treatment had been developed, the death rate was ∼1%, which would have meant ∼2 million needing intensive care (IC) and half a million deaths *even if* the health service had coped, or several million deaths if not. Somehow, the enormity of these figures did not sink in. However, it is perhaps exactly because they were so enormous that they were hard to grasp. Of course, these figures have to be set against the normal annual death rate through age and illness, which is ∼600 000, and an ordinary flu season might kill 30 000. Big numbers and individual lives.

Note that these were issues even for those well informed at the heart of government, who should be used to dealing with large numbers.

4.2.1. *Design lessons and HCI challenges*

Happily, small differences in presentation can make a difference. Later in the pandemic, infection rates were quoted not in terms of absolute numbers (too big to be meaningful) or proportions (too small), but as cases per 100 000. These case figures ranged

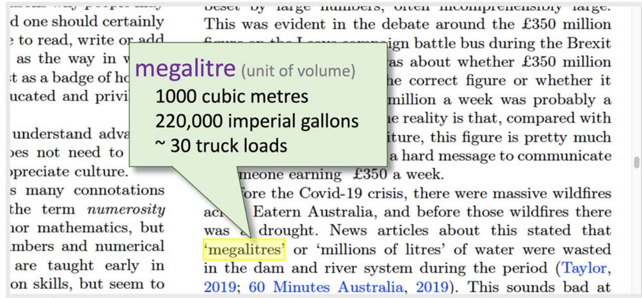

FIGURE 3. Pop-up to show alternative ways of representing numerical information

from tens to hundreds, and it was thus easier to gauge differences between areas and over time.

In a similar way, the *60 Minutes* documentary (60 Minutes Australia, 2019) also mentioned two Sydney Harbours-full and visualized this with an animation. From a public presentation point of view, this is clearly more meaningful than raw numbers, but it is also noteworthy that while the journalist lost an order of magnitude in the numerical volume, the discrepency was not noticed.

What tools or other support would make this easier? It is now common to have rollovers or pop-ups offering alternative word spellings, translations into other languages or information boxes. In addition, many search engines or bespoke tools offer conversions between units, for example, cubic feet into cubic metres. It would seem possible to have such a pop-up whenever a quantity is mentioned in a document that offers a suitable scale comparison for any numeric term. If, for example, the document mentioned ‘megalitres,’ the pop-up might say ‘30 truckloads’ (Fig. 3), or if it said ‘800 square km’ the popup might say ‘twice the area of the Isle of Wight.’ This would help the writer verify that they had the right general scale and also prompt them to consider offering a similar comparison for their readers. With suitable personalization, say by country, analogies could be chosen that are more meaningful for the particular user.

4.3. Dependencies, networks and feedback effects

Many of these big issues involve complex network dependencies and positive or negative feedback effects . . . indeed, it is precisely the positive feedback effects that lead to exponential growth.

In climate science, temporarily eclipsed by the Covid-19 pandemic, there has recently been concern over unexpectedly high ice melt in Greenland: the clearer skies due to global warming are leading to less fresh snow and more sunlight. Furthermore, the reduced snowfall is leading to a darker surface of the glaciers, reducing their albedo and so further exacerbating warming.

In human contact networks, these interrelationships are, if anything, more complex, and in particular, small numbers of highly connected individuals have a disproportionate effect. Early in the spread of the virus to Europe there was considerable talk of ‘super spreaders’ (Cave, 2020; Rambo *et al.*, 2021), i.e. individuals with very large numbers of contacts whether socially or professionally (one early case was a doctor returning from a skiing trip).

There has been extensive study of the ways in which *scale-free networks* emerge naturally including in the Web (Barabási and Albert, 1999) and social connections (Johnson *et al.*, 2014). Crucially, in such networks, a small number of highly connected hubs have a disproportionate impact on behaviour; such as the super spreader events in Covid-19. Because of this, these have

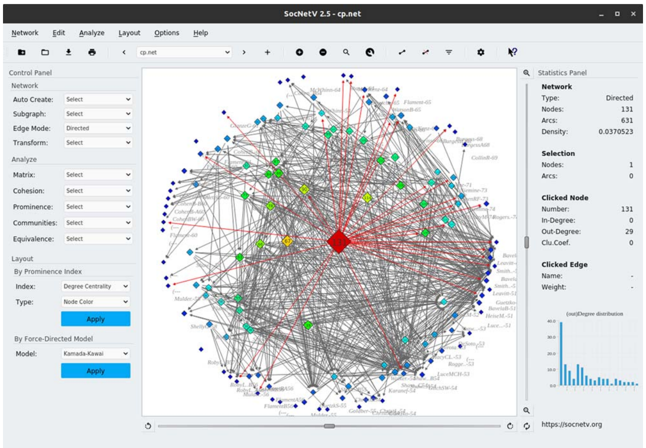

FIGURE 4. SocNetV—open source social network visualizer (https://socnetv.org/)

very different large-scale statistical properties described by *power laws* (Ward, 2002) rather than distributions such as the normal distribution, which are common in non-network phenomena. This in turn means that description in terms of average behaviour of individuals is less informative.

There are specific visualizations designed to help comprehend these more complex networks of connectivity, and these have been among the armoury of tools used in Covid-19 response (Chen *et al.*, 2022; Dykes *et al.*, 2022). However, these are currently aimed more at those who have some existing analytic knowledge or deal with the phenomena frequently, notably epidemiologists. There is still need to help more infrequent users comprehend the different behaviour of these networks at an informal level.

For example, during late 2021 when Omicron variant first spread in the UK, the numbers rose quickly and then peaked very early in London. The speed with which it peaked led many to believe that it had effectively reached herd immunity level, but the raw numbers were too small for this. In fact, based on the informal understanding of networks, it is more likely (borne out by slower longer term decay) that this was due to initial fast spread amongst subcommunities with higher levels of interconnectivity, which would then be followed by a slower pattern of infection in the wider community. For epidemiologists, this is a common pattern; e.g. seen at the midpoint of HIV spread. However, we need ways to convey these types of behaviour more widely.

4.3.1. *Design lessons and HCI challenges*

As citizens, we are part of many social networks, both digital and physical; we interact with network-connected data especially on the Web and are part of larger economic, logistic and environmental networks. As HCI researchers and UX practitioners, these are also part of the subject matter of our study and design. The growth of network analysis as a field is because these networks, although ubiquitous, have many surprising features, not least the 'six degrees of freedom,' which most people find fascinating when they first learn about it. This suggests that effective public representations can capture the public imagination if designed appropriately; indeed, a search of 'six degrees of separation' and 'art' yields many results, albeit some inspired by the words more than the idea (Rathbone, 2023).

The visualization community have many tools for representing both networks themselves including classic systems such as the Hyperbolic browser, originally designed for large hierarchies (Lamping and Rao, 1996) and subsequently used for the Web (Munzner and Burchard, 1995) and RDF ontologies (Eklund *et al.*, 2002), as well as more recent work on network visualizations, noted previously, applied during the Covid-19 response.

Several aspects of networks make them difficult to represent in 2D diagrams: (i) the exponential rise in the number of connected nodes as one looks further from a single node and (ii) non–local-connections patterns that can fill node-plus-arc diagrams with a dense spider's web of connection lines (Fig. 4). Some representations try to tackle this by focusing on a single node at a time, just showing the relatively small number of closely connected nodes, although even then the number rises exponentially as one takes a wider number of steps. Some attempt to represent the whole network but have to find ways to reduce complexity, including forming clusters where this is possible for the dataset.

Because of this complexity, many of the most effective visualizations require extensive explanation and training before they are useful, which is not suitable for public use. However, the ubiquity of networks and their critical nature suggest that such public-facing and more generally non-expert network visualizations are a pressing challenge for HCI and visualization research.

Within HCI, it is also important to realize that many statistical and sampling methods have assumptions that do not apply to power law distributions, which are common when encountering network phenomena. Using these standard techniques without adaptation means that results may be misleading or incorrect (Dix, 2020).

4.4. Hidden state and time

At the beginning of the pandemic, there was very little testing in the UK, so one of the few (relatively) reliable figures was the number of Covid-19–related deaths—for many countries this continues to be the case to this day. In the early days, there were just a handful of confirmed community-transmitted cases of Covid-19 and a small handful of deaths.

Of course, given a death rate of 1%, a single death indicates ~100 mostly unnoticed infections...at the time the fatality was first infected. It takes several weeks for someone to become ill and then die, so this means 100 infected people 2 weeks before the first death, and with a doubling rate at the time of about every 2–3 days, 2 weeks corresponded to somewhere between 30 and 100 times growth. That is, at the moment of the very first Covid-19 death, this was evidence of somewhere between 3000 and 10 000 cases ... mostly hidden.

The hidden state, the things we cannot see, can be predicted, but their obvious effects are usually only visible in retrospect. When this hidden state is combined with rapid exponential growth, we have the seeds of disaster. They say 'a week is a long time in politics,' but actually, for most things, decisions can be delayed. But with Covid-19, a week meant 10 times as many cases. At the point there were 10 deaths a week, this already corresponded to a future death rate 30–100 times that figure, even with near-total lockdown. A week more delay, and we are at the level we have seen. Days, not weeks are a long time in pandemic spread.

As the pandemic progressed, temporal effects continued to cause confusion because the impact of interventions would typically not be apparent in confirmed cases until around a week later, and then this would not affect fatality statistics for several weeks. Furthermore, the statistical variation in both infection and progression of the disease meant that this was not a simple time lag, but the current observable phenomena more weighted average of past hidden state. This is of course also the case for climate change, where we are only now seeing the accumulated impact of human actions for more than a hundred years, and interventions now will similarly take many years to have an impact.

4.4.1. *Design lessons and HCI challenges*

There are numerous examples of everyday phenomena that lie hidden, e.g. rot in houses, and also analogies of the idea of hidden problems being greater than visible ones, not least the common 'tip of the iceberg' visualizations (National Geographic, 2018). So here, it is not the underlying phenomenon that is difficult but the way this plays out numerically, especially when compounded with rapid exponential growth.

The numerical visualizations at the height of the pandemic usually showed current observable data (deaths and confirmed infections) and projections, but rarely, if ever, estimations of current people infected but undiagnosed, even though asymptomatic carriers were known to be major vectors. In contrast, anyone involved in modelling disease flow would look at current data, say deaths, use this to map back to past levels of total infection, and then from this, estimate current hidden state and future observable outcomes. This has complexity, but does not seem altogether unexplainable. Clearly, we need further work to visualize such flows in ways that are understandable by all.

The word 'hidden' is commonly used in modelling 'hidden values' 'hidden Markov models', but is another example where wording may be critical. Both Covid-19 and climate change have given rise to numerous conspiracy theories and the idea of something being 'hidden' suggests an active attempt to cover things up. Although the technical language is accepted and understood, it may be that terms such as 'unseen' are less open to misinterpretation.

4.5. Uncertainty

Imperial College's policy engagement channel *The Forum* begins its article describing the Covid-19 modelling efforts led by Professor Ferguson with the words:

> '*Many people struggle to properly grasp probabilities, risk and concepts like exponential growth*' (Czyzewski, 2022).

Indeed, there are fundamental psychological barriers to understanding probability and statistics (Shermer, 2008; Dix, 2020). In particular, whereas our low-level, unconscious learning is built up over many repetitions (i.e. semi-probabilistic), our higher level, conscious reasoning is based more around a single world or small number of alternatives. One example of this is an experiment where participants had to choose between packs of cards with different levels of rewards or penalties. One pack was better than another, and long before the participants were able to consciously say that there was a difference, they registered (subconscious) emotional responses to the 'bad' pack detected by skin conductivity (Bechara *et al.*, 1997).

4.5.1. *Complexity of uncertainty*

Furthermore, we are often dealing with mixtures of probability and absolute uncertainty— a state of affairs that is cognitively, emotionally and philosophically challenging, as evidenced by Einstein's 'God does not play dice.' As scientists, we constantly need to emphasize that there are rarely absolute facts (as put by Nietzsche, 'There are no facts, only interpretations' [(Nietzsche *et al.*, 1967), Sec. 481], but there are *levels of evidence*; however, this is a hard message to accept ourselves let alone convey to the general public.

This is all hard enough for normal phenomena, but creates a perfect storm when combined with hidden state, exponential growth and a political blame culture.

If we have a linearly growing phenomena, then a difference in 50% of some factor will lead to a difference in 50% in the result. With viral growth, a difference in the growth rate per day of 50% between 0.8 and 1.35 is the difference between decay and disappearance and pandemic, where the cases multiply 10-fold each week. The error bars of exponential processes are very wide.

There are two problems with this for the government, and indeed all decision-makers and the public.

First, we naturally think of mathematical models as precise; indeed, when scientists talk about imprecision, they are often told 'so you don't really know'. This is another form of essentialism—'you either know or you don't'—of course, in reality, we have degrees of evidence and levels of confidence. Amongst other things, this can lead to scientists being less forthcoming about these uncertainties, and then perhaps contributing to the UK Justice Secretary Michael Gove's infamous mistrust of experts (Mance, 2016).

Second, we attach greater blame for wrong action than culpable inaction (*omission bias*). If a car driver thinks (wrongly) that a child is about to run into the road, swerves and then hits another car, they will be judged more harshly than one who breaks too late if a child does run out. Politicians are aware of this and this can make them risk-averse, waiting for more information, for more certainty before acting, knowing that if they get it wrong, if they call lockdown and it seems to be a false alarm, they will be blamed more strongly than acting late 'following science' but leading to the avoidable deaths of tens of thousands.

This can also explain why people avoid getting vaccinated or vaccinating their children; they anticipate regret. If a child is ill, then that is due to the disease or government health response. However, if you actively choose to vaccinate your child and they experience a bad reaction, then you are responsible. This emergent bias toward inaction is unreasonable (not doing something is itself a decision) but common, especially if there is uncertainty over relative levels of danger.

More broadly, these uncertainties open the way for numerous cognitive bias to fill the void of definitive information. For example, when faced with uncertainty about vaccination, people may seek to ease the discomfort of *cognitive dissonance* by searching for definitive, but inaccurate, information about the vaccines to eliminate the dissonance (*confirmation bias* again).

4.5.2. *Types of uncertainty*

Taylor 1994 guidelines distinguishes two forms of uncertainty:

Type A. those which are evaluated by statistical methods,
Type B. those which are evaluated by other means.

The first is essentially based on understood probabilities, e.g. if there are 400 cases of a disease in a large population, then we know (from the binomial distribution) that this figure will have a standard error of ±20, which can be displayed using error bars or similar visualizations. Of course, the viewer needs to have some appreciation of what the error bar means, but it is at least well defined.

Even the most complex techniques typically offer an intuitive idea of which values are more uncertain than others, although this can become more difficult for non-point estimates such as

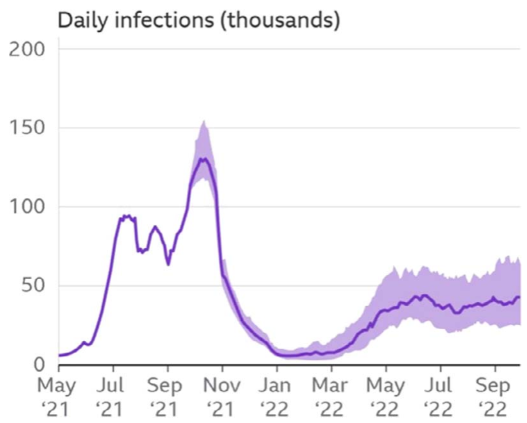

FIGURE 5. Projection reported in the BBC (Triggle, 2021) showing both historic and forward projection, with range of possible outcomes (derived from Figure 6). Note these projections began before the UK's control measures in late 2021 and early 2022 and also before Omicron emerged as the dominant variant.

fitted lines or trajectories. For these, sometimes showing multiple samples can help (Ellis, 2008); e.g. showing animated correlation lines or other measures by repeated subsampling of the data (bootstrapping).

As an example of a static uncertainty visualization produced for the general public by the BBC (Triggle, 2021) based on an academic report (Barnard *et al.*, 2021a), Figure 5 shows a projection of possible Covid-19 infection for late 2021/early 2022 that uses a combination of precise past data (single solid line to the left) with a mid-estimate projection (solid line on right) and range of possibilities (light coloured range to the right).

Type B uncertainty is more about things that are fundamentally unknown. For example, on both Covid-19 and climate modelling, each run of a single model is usually stochastic, yielding type A uncertainty, but this can be dealt with by running the model many times to create an average and range of variability. However, more fundamentally, each model takes into account different factors and uses different techniques, and so inevitability leads to different predictions. The range of projections in this case is not about random sampling and probabilities, but more a range of *possibilities*.

At worst, cherry picking from this wide range of results can be used as arguments to bolster existing positions (*confirmation bias*). However, on the positive side, the fact that Covid-19 modelling projections became common in newspapers and TV screens may have helped to educate readers to better grasp the fact that models can be uncertain and yet be still helpful—as stated by Box, 'all models are wrong, but some are useful' (ref https://www.goodreads.com/quotes/680161-essentially-all-models-are-wrong-but-some-are-useful).

As an example of type B visualization, consider Figure 6 from a working paper describing modelling by a team from London School of Hygiene and Tropical Medicine (Barnard *et al.*, 2021a). First, you may recognize that the centre left graphic is the one that the BBC report used in Figure 5, except that the BBC version has simplified the graphic, removing some of the information from the original to make it easier to grasp at a glance. In addition, the original version in Figure 6 includes multiple possible scenarios, which is as well as the type A uncertainty expressed in the range of outcomes of modelling; it is also showing type B uncertainty about unknown potential spread characteristics of the infection. It is interesting too that when a version of the working report (which was expected to be read by journalists and policymakers as well as academics) was published for a purely academic audience (Barnard *et al.*, 2021b), the graphics omitted the historic data. From a factual point of view, the past data was constant and uninformative, but when produced for the non-academic audience had rhetorical force because it emphasized the continuity of the model from past data and hence its sense of reliability.

4.5.3. *Design lessons and HCI challenges*

There has been an increasing volume of work looking at visualization of uncertainty (Greis *et al.*, 2017; Padilla *et al.*, 2022; Weiskopf, 2022), from simple box plots or error bars (Potter *et al.*, 2011) to bespoke colour palettes (Correll *et al.*, 2018). Most techniques are targeted at professionals, and of these, many are really only suitable for statisticians or data analysts. There are clear opportunities for modifying existing visualizations or developing new ones aimed at users beyond the data world including politicians, journalists and the general public.

The techniques based on showing multiple simulations or samples seem particularly promising, i.e. sequentially showing different potential predictions rather than trying to visualize uncertainty as an additional layer on potentially already complex visualizations.

4.6. Risk perception

Risk perception is a known hard area from simple day-to-day decisions to gambling addiction. For example, air accidents, which are rare but serious when they happen, are perceived as a greater risk than car accidents, which are far more common, even though for most people, the latter is far more likely to lead to death or serious injury. In a similar way, we are very familiar with influenza and know how quick and how easy it is transmitted, and yet we are not much worried about it because each case has slow mortality, so it seems safe. In contrast, meningitis is rare, but when it happens is serious and often fatal. The rare but serious condition seems more worrying, whereas in fact the death risk of influenza in the UK is ~5000 times higher than that of meningitis.

These effects can be magnified by reporting, which by its nature is selective. For example, the most common adverse effect of Covid-19 vaccination is a sore arm, but the tiny number of serious blood clots can dominate perceptions of the vaccine especially if there is any existing worry about vaccination. This is effectively a combination of *availability bias* and *confirmation bias* influencing risk perception negatively.

The opposite effect is also possible especially for rare events: *optimism bias*, which leads to low risk perception (the belief that adverse events such as getting Covid-19 is more likely to happen to others) or *present bias* (preferring immediate benefits in the present to even larger benefits in the future). In such cases, some preferred to go out and be exposed to the virus rather than follow prevention measures designed to mitigate the spread/contagion. These biases can always be a problem, but the combination of the hidden nature of virus spread and non-local impact means that not only will the consequences of an individual's action only be apparent in retrospect, but they may never be apparent at all except in aggregate.

4.6.1. *Presentation of risk*

Methods of presentation can affect these perceptions and go some way to mitigating cognitive bias or prejudice.

Wording can make a difference. An early WHO statement read:

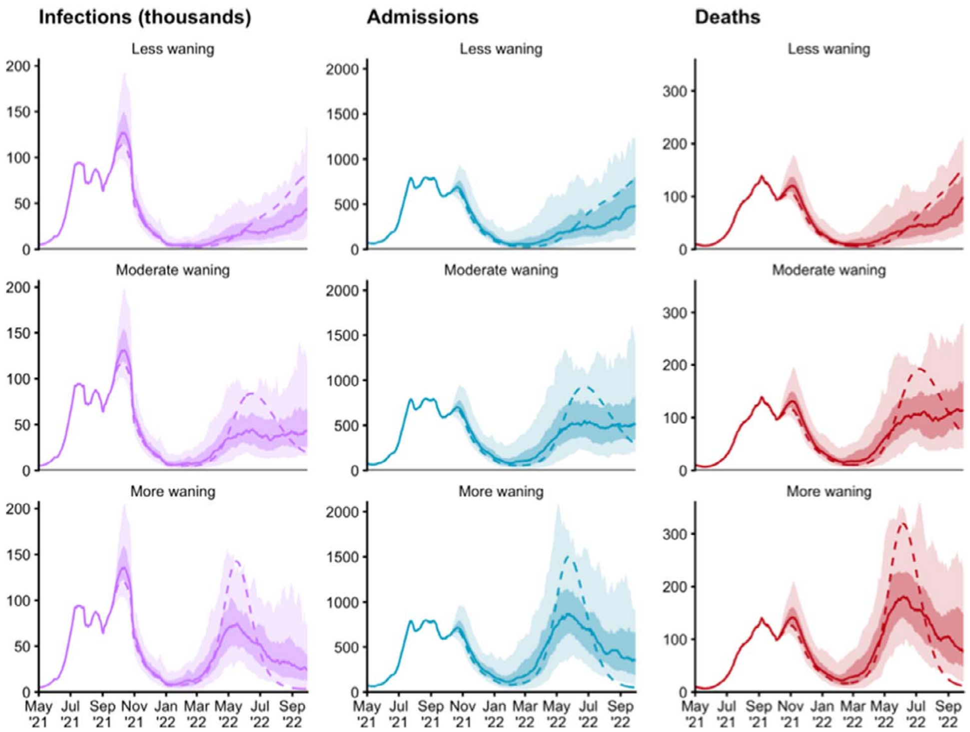

FIGURE 6. Projections in original LSHTM report (Barnard *et al.*, 2021a) including more complex graphics for each projection (type A) and also multiple scenarios (type B)

> '*In hindsight,...politicians and the public mainly ignored the PHEIC declaration and Tedros's [Director-General of the WHO] corresponding recommendations in January 2020, but started listening when the organization used the unofficial term "pandemic" to describe COVID-19 in March, once the disease was spreading on multiple continents. Unlike the PHEIC, "pandemic" is not a defined declaration, and countries haven't agreed to take any actions once it's used.*' (Maxmen, 2021).

Initially, WHO did not use the term 'pandemic' because it is not an official designation, and also because of worries about public panic. However, the technically accurate term 'Public Health Emergency of International Concern' (PHEIC) was perceived to be less serious and did not elicit sufficient response.

Different variations in the way numbers are presented can also make a difference. For example, imagine reading about a 'mortality rate of 1286 of 10 000 people' for a cancer compared with a 'mortality rate of 24 of 100 people', or '25 people in the area have been diagnosed with Covid-19' versus '2 of 25 people in your area have been diagnosed with Covid-19'. These different ways of presenting information influences whether we choose to be proactive or reactive. For example, most people are more influenced by the relative size of the numerators (1286 vs 24 deaths) rather than the actual proportion (12 vs 24%) (Schissler & Knudson, 2022, p.259).

In a study of infographics used in the principal Indian Newspapers found a strong focus on the impact on vulnerable people and more widely what are often termed'fear appeals' (Jacob, 2020). Government heath communications try to tread a line between efficacy and avoiding panic, and toothpaste and mouthwash advertising (as an example) alternates between prevention of decay (fear) and freshness. Meta-analysis of the 'fear appeal' literature has shown that it is usually successful in influencing attitudes and behaviour, but more so when presented alongside 'high-efficacy' messages—what you can do (Witte and Allen, 2000; Tannenbaum *et al.*, 2015).

4.6.2. *Design lessons and HCI challenges*

For public communication, there are undoubtedly opportunities for new forms of visualization, especially using animations or interactive tools that use clear baselines and comparisons to improve the integrity of their interpretations. However, as we have seen, tools and techniques are also needed that use existing knowledge to help those preparing both textual statements and graphical visualizations to form their messages in ways that are both accurate and carry the correct force. This may include the provision of 'just in time' of evidence-based perceptual and psychological advice embedded into graphical design tools.

In HCI, the user experience literature is focused primarily on causing positive effect, but there are circumstances, notably health and security, where a level of unease is appropriate. This raises ethical as well as theoretical and methodological issues, especially if this overrides user preferences (you may not want to be warned repeatedly about poor passwords) or if the benefits of negative experience accrue socially rather than individually.

4.7. Common sense is a two-edged sword

So called 'common sense' can be misleading: '*my great-uncle smoked 100 a day and never had a day's illness until he died at 97.*' We have all heard this kind of statement, focusing on a single personal example and forgetting the hundreds of smokers who did die of lung cancer. This kind of reasoning is especially dangerous in the face of some of the effects we have described such as hidden state and rapid exponential growth—if only 10 people have died in the whole country, it is only common sense that there is nothing to worry about.

However, for those of us in academia, common sense and every-day data can be a powerful check to abstractions. The detailed

Imperial modelling (Ferguson *et al.*, 2020), which happily did eventually drive the UK government to action, quite rightly used the most up-to-date WHO figures on transmission rate and incubation period. If you read the paper, this led in the models to a doubling period approximately every 4.5 days. However, at the time of its publication, the actual doubling rate in the UK in terms of reported deaths was <3 days. For exponential growth, this is a huge difference, do the numbers increase 10-fold over 2 weeks or one.

The reason for this discrepancy is not that complicated. First, there are differences between nations in terms of behaviour and built environment that alters transmission, so there will be variations (uncertainty), and the scientists will have chosen conservative figures to avoid being branded alarmist. In fact, the very earliest figures for Wuhan were doubling every 2 days and this then slowed to about every 5 days before the Chinese lockdown. The Chinese population had seen the impact of SARS, and clearly, the general public of Wuhan had begun to socially distance themselves before the official lockdown. The WHO figures were for a society already taking action.

The explanation for the difference is not complex, and the data were all evident and easily accessible at the time; the crucial question was why didn't the government scientists at the time notice this?

A large part of this is due to our tendency in science to live within our worlds of abstractions. We are so aware of the potential misleading effects of the everyday that we ignore the useful check they can have. If there is a discrepancy, it may be 'just one of those things,' a fluke, like the 100-a-day nonagenarian, but it might also be a sign that our model is wrong or incomplete.

4.7.1. *Design lessons and HCI challenges*

There is both an information systems and HCI design challenge here. It is critical that data are easily available in ways that make it easy to cross-check outputs of models with real numbers. Although the raw data are often (but not always) available, they are often difficult to locate and even more difficult to interpret once found. There are initiatives to make data more easily found and better documented when they are, notably the FAIR principles (Findable, Accessible, Interoperable, Reusable), which have become an established paradigm for scholarly data management (Wilkinson *et al.*, 2016; Koster and Woutersen-Windhouwer, 2018). However, it was salutatory to note that a colleague, who was a major part of national Covid-19 modelling efforts, often resorted to the Web site and Twitter feed of a schoolboy from Aberytwyth, who made it his lockdown hobby to gather and present Covid-19 data; this was often more up-to-date then the official sources (Williams, 2020).

David MacKay's (2008) '*Sustainable Energy–without the hot air*' is exemplary in using comprehensible numerical models and estimates to explain the challenges and potential of an environmentally sustainable future. However, it was written before so much data were available. One part estimates miles drive in the UK to estimate the electricity needed if all transport went electric. The estimate looked convincing and suggested there couldn't be sufficient energy production in the UK. However, reading it 15 years after it was first written, it is possible to look up total fuel oil imports (and using this to estimate back road miles) and see that the original estimate was significantly higher, sufficiently to make a major difference in the findings.

This reinforces the message about the availability of data, and although in this case the data could be found now, as we've seen this is far from solved. MacKay's book is unusual in the clarity and accessibility of its argumentation, numerical and otherwise; it would be far harder to reexamine the data and arguments in most books or academic papers. It is always difficult to question one's own assumptions, but openness makes it possible for others to do so. It also reinforces the requirement for tools that can manage this mixture of data, textual argument and approximate and precise numerical calculations, We'll see a prototype of such a tool later (Fig 10).

Finally, we need ways to bridge the gap between population-level analysis and concrete examples. We've seen elsewhere that this is important for communication, but it is also critical for grounding abstract discussions to help ensure they remain anchored in reality. Although a very early example now, the Information Lens is still a paradigm for this, representing clusters/classes of documents using examples of typical documents supplemented by more aggregate representations such as frequent terms in the cluster (Malone *et al.*, 1986). In a very different way, Rapid Serial Visual Presentation (de Bruijn and Spence, 2000) performs a similar job for images. One can think about similar techniques for richer data such as individual medical cases or scenarios.

Returning to Shneiderman's (shneiderman2003) information-seeking mantra, we suggested the 'details' should be richer than the data, but reach into richer representations of people. However, the importance of constant grounding suggests that for some visualizations, these rich details should not be merely 'on demand' but in some sense be insistent. The real end sers are often those represented in the data; if we want to give them a voice, then we need to give the data voice to speak back to the modeller. In addition, as well as drilling down, we may want to 'drill up'—when focused on one concrete example to be shown other examples that are alike but different, such as someone who smoked 100 a day and died at 50.

4.8. Intrinsically difficult?

This sounds like a litany of disaster, and indeed, this was the case with several countries' Covid-19 response. However, none seem intrinsically difficult. As noted, it is not about everyone being mathematical geniuses nor being able to add up 50-digit numbers in our heads, but about having that 'gut maths,' that qualitative appreciation of the effects of these numerical phenomena.

One approach to this is pedagogical. Across the world, governments compare themselves against international metrics such as OECD PISA (Organisation for Economic Co-operation and Development Programme for International Student Assessment) (OECD, 2020) and have policy and educational programmes aimed at improving numeracy (Jones, 2002; Dauncey, 2013; Hill, 2021). This is complimented by popular mathematics books aimed at children (e.g. (Seagull, 2019)).

However, more broadly, we need ways to help those already in the workplace: for those journalism, science, politics and for the general public to perform *qualitative–quantitative reasoning*, to be able to make judgement about numeral phenomenon without necessarily being able to perform detailed calculations or grasp advanced mathematics (Dix, 2021).

In particular, journalists are particularly important because they often act as the bridge between data and the public. However, they can often feel overwhelmed by numeric data, and this feeling of incapacity can lead to underuse of numerical evidence; indeed, a survey of data journalism in the UK found that of 3000 articles sampled from major media outlets, only 106 included data (Knight, 2015). This impacts even the best data journalism; Young

FIGURE 7. iVolver allows users to extract data from published graphics and choose their own visualizations (Nacenta and Méndez, 2017)

et al. (young2018datajournalism) studied Canadian finalists and winners of major national and international awards for data journalism between 2012 and 2015 and found that the styles of infographics were limited to a very small number of types, with interactive maps most common, and the authors concluded that often, 'projects defaulted to deploying interactivity for interactivity's sake.' Crucially, they also found that very few engaged in active storytelling through data, which then limits effective meaning-making. This is echoed across different countries and cultures; in a study of journalists of the principal Indian media outlets, one respondent said, 'if there is data in the form of tables or graphics, we are often overwhelmed to discuss it in an argumentative language' (Hidayat and Hidayat, 2020).

4.8.1. *Design lessons and HCI challenges*

This is a big challenge and also an opportunity for HCI to make a difference. There are numerous Web services that offer visualization services for the non-expert, many inspired by IBM ManyEyes, which until it's decommissioning enabled rich sharing of data as well as visualization (Viegas *et al.*, 2007). In addition, it is becoming easier to embed rich visualizations including narratives and timelines into Web sites using tools such as the Knight Lab tools, which are used extensively by journalists (Knight Lab. Projects, 2023). Looking earlier in life, Construct-a-Vis is a visualization application for young children based on rich studies in the classroom (Bishop *et al.*, 2020).

Beyond visualization tools, spreadsheets are still the most common way for non-experts to interact with data, and many governments routinely provide open data in CSV or spreadsheet formats as well as graphics. However, very often, information is presented only in graphics, which may present a particular slant on the data. Figure 7 shows iVolver, a tool designed to help people interrogate this kind information (Nacenta, 2017). Using iVolver, users can extract numerical and other data from pie charts, histograms and other visualizations and then easily manipulate and revisualize these in different ways.

Although heavily used and studied, spreadsheets have well-known problems, particularly due to the hiddenness of formulae (Hendry and Green, 1994). Figures 8, 9 and 10 show WS2, a prototype tool inspired by the successful aspects of spreadsheets. WS2 facilitates the embedding of numerical calculations in Web pages so that readers can explore the model. In Figures 8 and 9, we see a portion of an embedded table demonstrating the simplest version of the susceptible-infected-recovered (SIR) model, which was used extensively for Covid-19 modelling (Cooper *et al.*, 2020). As the user hovers over a table header, the overall formulae for

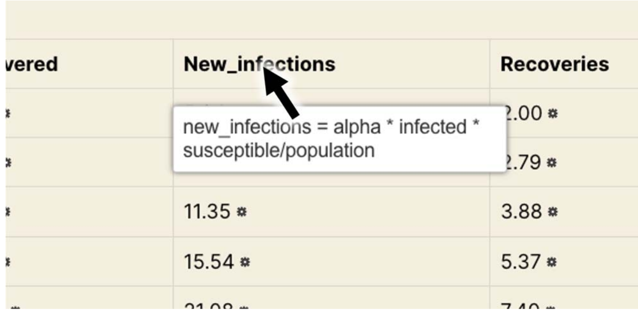

FIGURE 8. WS2 tool showing column formulae for table demonstrating SIR model

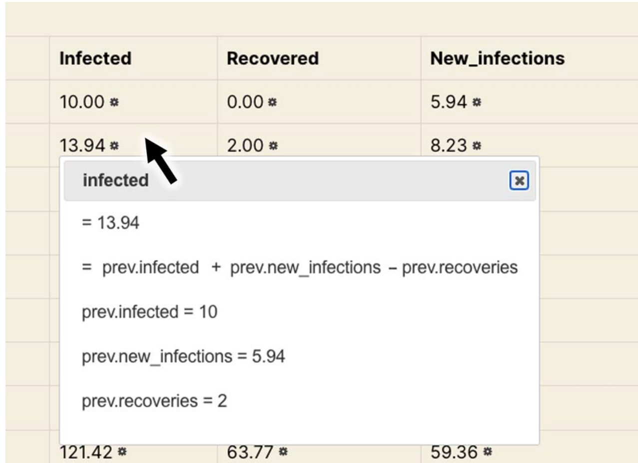

FIGURE 9. WS2 tool showing explanation of specific number

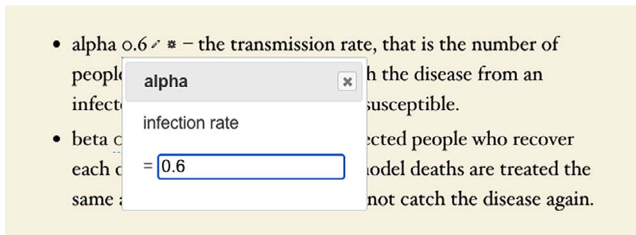

FIGURE 10. Editing a value in a Web page enhanced by WS2

that column is displayed (Fig. 8), then as the user moves down and interrogates a specific value, both the item's derivation is shown with the formulae and the values of all of the other variables contributing to it. Elsewhere on the page, a constant for the table is embedded within a paragraph (Fig. 10); normally, this would be a fixed example value, but the user is able to edit this value and hence interactively explore the model.

5. THE ECONOMICS OF DEATH

We now move to the area where numbers and humanity meet—the cost of death.

We often hear people saying that you cannot put a price on a human life, each person is precious, invaluable. However, the hard truth is that we do put a price on life.

NICE, the National Institute for Health and Care Excellence, is the body that regulates NHS use of drugs in England and Wales. Its criteria are not about safety and efficacy, that is managed by a separate body, the Medicines & Healthcare products Regulatory

Agency (MHRA). NICE is considering cost-effectiveness—not '*does it work?*' or '*is it safe?*', but '*is it worth the money to use?*'

To make this assessment, NICE puts a figure on human life—£20 000–30 000 per QALY (NICE, 2013). A QALY is a Quality Adjusted Life Year, both counting how long the drug will extend life and whether it does so in ways that are meaningful—a year in a coma is not considered as valuable as a year of full health.

If you price using QALYs, saving the life of a healthy 30-year-old, giving another 40 years plus of healthy life is worth £1–1.5 million. In contrast, an 80-year-old with an existing condition that is making them less active and healthy might be worth a mere £100 000. This sounds harsh, but of course, it is the kind of calculation that has to be made; with a fixed health budget and market prices for drugs (*fixed-state assumptions*), money spent treating one person is not available for another.

Similar figures can be found in other areas; for example, when deciding on road safety measures such as straightening a dangerous bend.

5.1. Covid-19 support versus lives saved

Now, let's think about these cold figures in relation to the Covid-19 lockdown and its effect on the economy. There are many estimates of the impact on companies, but an easy figure is the actual government spend.

Soon after the lockdown was implemented in the UK, the government announced a support package for industry of £350 billion, which really is a BIG number, £5000 for each adult and child in the UK. Note this was not the full cost to the Exchequer because it did not include the support for furloughed staff, nor losses in tax revenues. However, it is a good round figure to work from.

First of all, it may be worth comparing this £350 billion figure with the additional £14 billion announced for the NHS in the same package and £750 million (three-quarters of a billion) announced to support charities. Money isn't everything, but it does betray priorities.

Returning to the £350 billion, it is possible to use the NICE figures to compare this with lives: £350 billion is the NICE value of 250 000–350 000 fit 30-year-olds, or 3.5 million sick 80-year-olds.

Put yourself in the Cabinet office early in the crisis, weighing up the cost to the economy of various actions versus the death toll of inaction. What do you do?

We do need to have open discussions about these issues rather than hiding behind platitudes. They sound hard and cold, but they are decisions being made daily, and they are decisions that we collectively make as a society. The equivalent figures to the NICE figures are somewhat higher in Germany, but that is in part due to the fact that Germany has chosen to spend 50% more on its health service than the UK over recent years. The cost of a life in the UK is directly related to how the population has collectively chosen to weigh that life against other things such as education, burgers in McDonalds, Brexit preparations, company director bonuses and winter holidays to Alpine ski resorts. Before Covid-19 threw the funding of the NHS into the spotlight, estimates of the additional deaths due to 10 years of austerity were chilling (Martin *et al.*, 2021).

Even given these figures, there is a point where scale makes a difference. One hundred fatal car accidents with two deaths each feels different to a plane with 200 passengers crashing.

5.1.1. *Design lessons and HCI challenges*

We need to have these discussions, not dispassionately, but certainly reasonably. As an HCI community, can we develop ways that both allow users to see the large-scale figures, which is essential for reasoned debate, and also dig into the individual human stories, which are essential for compassion?

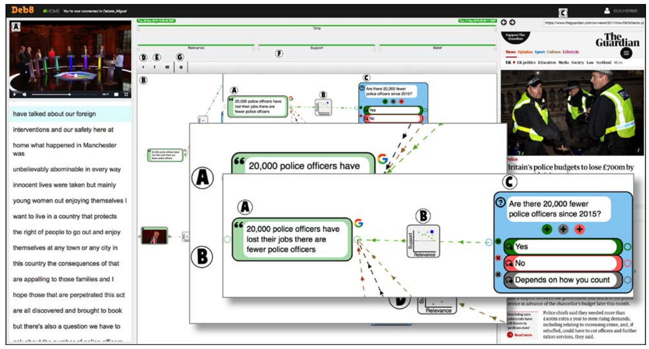

FIGURE 11. Collaboratively creating an argument structure using Deb8

6. SO, WHERE DOES THAT LEAVE US?—CHALLENGES FOR THE HCI COMMUNITY

As academics, technologists and designers, what can we do to help?

In some ways, as we emerge from the pandemic, we are in a better position to look forward. We have seen that rapid, dramatic change is possible in many aspects of life (refuting *fixed assumptions*), which will surely be needed as we address climate change and other global challenges. In addition, the general awareness of some of the numerical issues such as exponential growth is greater (R values have been hammered in relentlessly). Furthermore, from an academic and design point of view, we have also seen what has and has not worked in terms of actions and messages that influence human understanding and behaviour. However, there is clearly more to do.

For the long term, we need to think about education—what are the numerical and reasoning skills that are essential for day-to-day life, the education that builds a capable and informed citizenry? Some of this is about the skills for day-to-day finance, but it also needs to include a literacy with the large numbers and complex phenomena that we need to make sense of the big issues facing us as a society. This is partly an education problem, but also a design challenge because innovative pedagogical tools, especially game-based experiences, are an area where HCI and education intersect.

However, we cannot wait 20 years for a fresh generation to grow up. Now, we urgently need better tools, visualizations and skill in providing advice to politicians, journalists and the general public as well as those for scientists to use within their own communities.

Happily, we have seen throughout examples where partial solutions are emerging, or where there are clear challenges we can address. In many cases, the cognitive biases and patterns that may be problematic can also be used to help address issues. For example, we saw the way the story of Captain Tom inspired many in the UK; here, a combination of *endogroup bias* and *narrative* was critical. This relates to the potential we discussed earlier to reimagine Shneiderman's (shneiderman2003) 'information-seeking mantra.'

We clearly need tools that help journalists, decision-makers and the general public to collate, analyse and present complex arguments, and we've seen several examples already.

Looking back, the paper introducing Notecards (Halasz *et al.*, 1986), the early hypertext system, used as a driving example its use by someone writing an article about intermediate range nuclear weapons of the time…an issue very current today. The graphics look crude by current standards, but in terms of functionality, it not only allowed easy hyperlinking, but also the linkable items included both text and graphics and it supported network-style visualizations as well as click-and-connect–style hyperlinks. Although there are now many personal knowledge-management systems and professional content-management systems, this level of flexibility is still rare. In principle, one can imagine tools using AI techniques that help journalists to gather these materials, but if anything, tightening budgets in mainstream media are looking toward AI technology such as ChatGPT to replace human writing, which risks replicating any widespread misconceptions (Yerushalmy, 2023).

Consumers of media can also be encouraged to question and dig beneath the surface of the information they are presented with. This can be facilitated by the media itself; e.g. the Four-Corners project, a collaboration between OpenLab Newcastle, the International Centre for Photography and the World Press Photo Foundation, embeds information into photos allowing viewers to access additional information about the background and provenance of images (ICP, 2016). Some of this information can be gathered automatically, e.g. the time and location of the photograph; others may need hand editing. Most media outlets allow means for readers and viewers to share or comment on news stories. The Deb8 systems developed at St Andrews University shows how this could be taken a step further, allowing those viewing, say, a TV debate to seek evidence supporting or refuting statements made during the debate (Carneiro *et al.*, 2019). Using Deb8, they collaboratively create an argument, which does not necessarily give a definitive answer to the question raised, but rather encourages an active engagement with the complexity of issues (Fig. 11).

In the numerical domain, we can also see examples of good practice. For example, the use of cases for 100 000 effectively exploits the *numerator bias* by deliberately choosing a scale that is impactful and yet comprehensible. Similarly, often the best risk explanations make use of a form of *availability bias* by comparing new risks with ones we are familiar with. For example, the introduction compared road deaths with Covid-19 deaths because the former are a societal risk we are used to considering in relation to safety measures such as speed limits or drink driving laws. This can also be adopted at a finer scale, e.g. in the UK in mid-2021, the risk to others of attending a 30-person meeting (without strong infection prevention measures) was equivalent to 10 years' driving—far easier to weigh up than a raw risk-to-life figure.

In summary, we have seen that human reasoning, especially numerical reasoning, is limited and prone to all sorts of distortions that may interact badly with complex issues including Covid-19 and climate change. However, the good news is that as designers of digital technology, we can use this knowledge to guide where to make interventions, and furthermore, use our knowledge of those very cognitive limitations as levers in effective design—using bias to undo bias! Good design should mitigate cognitive biases and provide transparent insight into the data.

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