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Cognition and hypocognition: Discursive and simulation-supported decision-making within complex systems☆

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ABSTRACT

Homo sapiens is currently believed to have evolved in the African savannah several hundreds of thousands of years ago. Since then, human societies have become, through technological innovation and application, powerful influencers of the planet's ecological, hydrological and meteorological systems – for good and ill. They have experimented with many different systems of governance, in order to manage their societies and the environments they inhabit – using computer simulations as a tool to help make decisions concerning highly complex systems, is only the most recent of these. In questioning whether, when and how computer simulations should play a role in determining decision-making in these systems of governance, it is also worth reflecting on whether, when and how humans, or groups of humans, have the capability to make such decisions *without* the aid of such technology. This paper looks at and compares the characteristics of natural language-based and simulation-based decision-making. We argue that computational tools for decision-making can and should be complementary to natural language discourse approaches, but that this requires that both systems are used with their limitations in mind. All tools and approaches – physical, social and mental – have dangers when used inappropriately, but it seems unlikely humankind can survive without them. The challenge is *how* to do so.

1. Introduction

Recent trends (particularly over the last century) have contributed to a need for the better management of those systems that affect our lives. These include: (a) that humans have such an impact upon their planet that geologists now declare we are in a new epoch – the "Anthropocene" (Lewis & Maslin, 2015); (b) a greater expectation of protection against risks by authorities, businesses and insurance companies; (c) a world that is increasingly interconnected in multidimensional ways and at multiple scales. Thus, regardless of whether the world we deal with really is becoming more complex, we are faced with trying to 'manage' (in some sense) some very complex systems. We briefly highlight two examples to illustrate this challenge.

- **Socio-Ecological Systems** (SES). An SES is a system in which a social system is inextricably intertwined with an ecological system (Young et al., 2006; Dearing et al., 2010). In these systems social changes impact significantly upon the ecological and vice versa.

☆ "Just as physical tools and machines extend our physical abilities, models extend our mental abilities, enabling us to understand and control systems beyond our direct intellectual reach." (Calder et al., 2018, p. 2)

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The social and ecological systems are each highly complex and the system that includes them both, even more so. Thus, when tackling a possible environmental problem – such as the impact of some new farming technology – both social and ecological factors and their interactions need to be considered. A classic early example of this is Lansing and Kremer's (1993) study of the role of Balinese water temple ceremonies in managing rice-planting schedules among villages in the Oos and Petanu river basins so as to trade off ecological constraints around water supply and pest control. Though the work was not without controversy (Helmreich, 1999, 2000; Lansing, 2000), agent-based models were used to demonstrate the role the water temples played (which was not obvious), at a time when there was external pressure to adopt more modern farming practices aimed at improving yield, but with potentially negative impacts on the rivers' ecosystems.

- **Tipping points in global warming**. There is increasing evidence that there are number of "systems" that could have global warming tipping points – that is, the temperature when a self-reinforcing process causing more warming might begin (for example the unfreezing of the Tundra releasing much more greenhouse gas or the melting of ice meaning that more light energy is adsorbed) (Lenton et al., 2019). Since these processes have not yet been observed at their fullest extent, we have to use models, including simulation models, to understand their potentiality (Ritchie et al., 2021), especially when these various tipping points might combine into a 'domino effect' with cascading consequences (Lemoine & Traeger, 2016). Even the possibility of such a domino effect as revealed by these models changes the debate about collective action to avoid it.

In both of these cases, trying a policy and then waiting to see the outcome is not a viable strategy. Ecosystems can be subject to hysteresis (Beisner et al., 2003; Scheffer & Carpenter, 2003). For example, if any trial of chemical fertilizers were not regarded as successful in Bali, restoring the riparian and estuarine ecosystems would not automatically follow simply from ceasing application. Similarly, the loops between warming and a complicated variety of processes cannot be adequately understood without detailed climate change simulations. These kinds of systems are highly complex involving different kinds of interactions and feedback loops operating in parallel and across spatial, temporal and organizational scales. Intuitions as to what policies are 'right' are not always reliable, but on the other hand one cannot deal with these choices on a "try it and see" basis because by the time outcomes are apparent, substantial damage may have already been done.

'Complex' is a term with multiple definitions (Edmonds, 1999). The number of different classes of actor and interaction in such systems means that the separation of 'complexity' and 'complicatedness' by Andersson and colleagues (Andersson et al., 2014; Andersson & Törnberg, 2018) is relevant. Broadly, characterizing complexity in terms of large numbers of interacting agents of the same kind, and complicatedness as being comprised of large numbers of different types of entity, Andersson et al. (2014) describe 'wicked systems' as being both complicated and complex, later (Andersson & Törnberg, 2018) linking wicked systems more rigorously to Rittel and Webber (1973) conceptualization of 'wicked problems'. Andersson and Törnberg's (2018, p. 126) definition of 'sub-wicked' systems as being amenable to analysis with human cognition leaves open the implication that fully wicked systems would not be, albeit that in the earlier article (Andersson et al., 2014) they argue for discursive, rather than simulation, approaches in addressing wicked systems. As Polhill et al. (2021) observe (via citations of Davies et al., 2015 and Loehman et al., 2020), there are cases where *exclusive* use of either discursive approaches or simulation in the analysis of wicked problems have led to solutions being proposed that are less useful and/or less effective.

Complexity and wickedness are both phenomena that can be underestimated by those unfamiliar with their conceptualizations – 'unintended consequences' (Baert, 1991) from high-level policy-making are well-known outcomes even if policy advisors and decision-makers are aware of the potential (Peters et al., 2013). Underestimation, and even denial, of the existence of complex and/or wicked dimensions to a problem is a clear example of 'hypocognition' (Kruger & Dunning, 1999), in which people overestimate their capabilities and performance. This, however, is only one of various ways in which human reasoning may not be adequate to the task of decision-making in such contexts. In the rest of this paper, after providing definitions of systems and governance we briefly examine the use of 'other' (non-human) intentionalities (or ascribed intentionalities à la Dennet, 1971) in past, present and future human societies, before comparing discursive and simulation-based decision-making, and discussing the themes raised before concluding that discursive and *open* simulation-based approaches need to be used together.

2. Systems, governance and systems of governance

The concept of a 'system' has multiple definitions (Backlund, 2000). Barbrook-Johnson and Penn (2022, pp. 3–4), noting that the definition of system is context-sensitive, nevertheless draw on Williams and Hummelbrunner (2011) and Meadows (2008), to describe systems as bounded organizations of causally-linked parts that perform an identifiable 'function' and/or have characteristic behaviour. The identification of a function, insofar as it entails inputs and outputs, is interesting in the emphasis it places on the context of a system – systems are not typically operating in isolation, but participate in networks of exchange of inputs and outputs with other systems. This has led to the concept of systems-of-systems, which Nielsen et al. (2015), accrediting Boulding (1956) as the earliest reference on the subject, describe as evolving, dynamically-reconfiguring, emergent compositions of autonomous, independent, interdependent,[1] spatially-dispersed, interoperable (sub-)systems.

Systems begin to be conceived as such simply through the development of nomenclatures, and relationships among their terms. The

[1] The apparent contradiction of independent and interdependent in the conceptualization of the individual systems comprising a system-of-systems is resolved with respect to goals. Independence means that a system can survive without participating in a given system-of-systems; interdependence that the goals of that system-of-systems can only be achieved through collaboration of its constituent individual systems.

process of agreeing signs, symbols and words to use to denote conceptual and observable empirical phenomena is the starting point for those phenomena to be conceived as systems. The next steps are: agreeing ontological relationships among the terms, such as part-of and is-a; grouping terms in co-constructed grammars; and, critically, establishing rules of inference and learning causal relationships. This knowledge can reach a point whereby the grammar can be represented formally by: a set of production rules for building sentences in a formal language; rules of inference (generation of new sentences from existing ones), and mathematical or algorithmic expressions of causality (generation of sentences describing a state of affairs that apply at a different point in time from the axiomatic sentences). At this point, the system is conceivable as a formal system, and in principle, a machine can be built that behaves in the same way as the formal system, and a simulation of that machine programmed in a computer. The formal system could be understood to be a model of the observed phenomena, and the computer program an instantiation of that model as a simulation. As Polhill and Gotts (2009) note, the semantics of programming and natural languages differ – the former referring to nothing outwith themselves. Gotts and Polhill (2009) posit formal ontologies (explicit machine-readable representations of shared conceptualizations – Gruber, 1993) as 'mediating formalisms' between the computational and empirical domains, which suggests that computer simulations gain empirical meaning through their user community.

Governance broadens the concept of government to include non-state actors participating in self-organizing networks of autonomous organizations steered by the state towards the achievement of policy goals (Rhodes, 2007). Just as with other phenomena, governance is associated with vocabularies having ontological relationships among terms, norms (if not rules) about inference, and causal interrelationships. These lead to the conceptualization of a particular form of governance as a system (perhaps more accurately as a system-of-systems), and the diverse means by which governance is achieved as systems of governance. Where such systems (or parts of them) can be formalized, they can be implemented by machines. It is perhaps noteworthy that both 'cybernetic' and 'govern' share a common etymology in the Greek *κυβερνάω*,[2] to steer, pilot or guide; Neumann (1987, p. 64) giving significance to the *-ρν-* 'suffix' as implying the involvement of tools or technology.

3. Use of the 'other' in complex decision-making

The idea that humans make decisions in complex systems through acts of rational cogitation is something of a myth; as perhaps is the idea that such acts lead to the 'right' decision being made. Equally mythologized (with racist overtones as critiqued by authors such as Buege, 1996 and Rowland, 2004) is the idea that somehow hunter-gatherer societies not 'polluted' by thinking from agrarian and industrial (or other 'unnatural') societies are intuitively in harmony with the balance of Nature or are otherwise 'simpler' (Graeber & Wengrow, 2021); and hence there is a 'rightness' to their decision-making with respect to the complex environments they inhabit. Both System 1 (intuition) and System 2 (rationality) modes of decision-making identified by Stanovich and West (2000) can therefore wrongly be assumed to be optimal in complex contexts.

Collective approaches to decision-making are no less problematic with respect to their efficacy in complex contexts. There is no known or universally recognized optimum number of members of any such collective, no optimum institutionalization with respect to their roles, nor any optimum diversity reflected in combinations of their intersectionalities of protected characteristics and assignment thereof to any of the various roles. If there are different modes of decision-making among such members, be it two as per Stanovich and West (2000) or any larger integer, there is no optimum distribution of such modes among members of the collective. Doaee et al. (2013) even provide evidence of factors that lead to lower organizational intelligence than the individual intelligence of any of an organization's members. In short, there is no reason to believe that humans, whether on their own or as a collective, are necessarily or essentially capable of making effective decisions in complex contexts.

At the same time, decisions have to be made (even if that decision is to take no specific action to address the problem in hand), and, if they are to be acted upon, in such a way that those whom the decisions affect believe them to be the right thing to do. Perhaps in recognition of the fact that individual and collective human reasoning is insufficient in complex contexts, societies have found various ways to encourage belief in the appropriateness of a proposed action based on a perceived 'external' authority with understanding that humans do not possess. Though an *ad verecundiam* logical fallacy, provided societies have normative mechanisms that reinforce collective belief in the basis on which decisions are made (often justified *ad antiquitatem*), trust in such an authority at least provides the basis for proceeding with an action, rather than being stunned into inaction by the complexity of the problem faced. When authority alone is insufficient (and in multicultural societies, there is unlikely to be any single agreed such authority), trust in the processes by which decisions are made has greater emphasis.

Historically, various ways of making decisions in complex systems have been developed that rely on an 'other' external agency to indicate the right course of action. Ryan (1999, p. 5) states that divination is done with the purpose of helping someone to make the "correct decision" or for prediction. Johnston (2008, p. 3) speculates that for people in ancient Greece, divination was an everyday occurrence, and was used to help make decisions about most aspects of their lives, including marriage, cropping plans, and sickness. Moore (1957), reflecting on reports of the Labradorian Naskapi people's use of scapula bones to decide where to hunt, argues that divination is effectively a ritual for justifying random action. In the case of hunting, this has the unintended benefit of providing their prey with no means of predicting (and hence avoiding) where hunts will take place. However, Langer's (1975) experiments suggest that people have psychological tendencies to seek control over random events, and even to delude themselves about their agency in bringing about outcomes that are random in origin. Matute et al. (2015) survey more general evidence of faulty human reasoning

[2] Collins Concise English Dictionary

about causality.

The Covid-19 global pandemic crisis has been exactly the kind of complex situation in which rational decision-making requires access to knowledge and information, and an ability to process those data, that is beyond human cognitive capacity. Political leaders could have used divination practices to decide what to do about the Covid-19 crisis. However, instead, many governments made decisions that were informed, at least in part, by computer simulations.

The 'classical' approach to simulation modelling of epidemics is based on a series of differential equations with respect to time that model the population in different proportions of susceptible to the disease, infected, and recovered (and now immune). These 'SIR' models have numbers of variations refining the various states, but each still bakes in assumptions, such as that those who have recovered after being infected cannot be reinfected, or that they cannot spread the infection (e.g. Cooper et al., 2020, p. 2, eq. 1). Evidence that such assumptions are false compromises the models' validity, but not necessarily to the extent that such models are no longer useful in decision-making.

Agent-based modelling, entailing the simulation of individual actors and their interactions, is an alternative to (or extension of) SIR models, which saw increased use and prominence during the Covid-19 crisis (Squazzoni et al., 2020; Dignum, 2021; Lorig et al., 2021). Some governments used evidence from agent-based models as part of the decision-making process (e.g. Badham et al., 2021; Thompson et al., 2022). Though they have features making them more potentially realistic, such as geographical space, varying networks of interaction, and the capability to represent individual humans, they are no less potentially flawed with respect to the assumptions they make than are SIR models.

The premise articulated in the call for contributions to this special issue – indeed, in its very title 'simulation and *dis*simulation' [emphasis ours] is clear that the use of simulation to make decisions that are politically controversial should be questioned. Whether justified by simulations or not, it is not difficult to see that when a potentially fatal virus is spread by physical human contact, reducing opportunities for such contact will reduce the ability of the virus to spread. While simulations can be used for the purpose of estimating such things as outcomes in terms of mortality, hospitalization and economic impact from measures ranging from doing relatively little (as did Sweden) to locking down the country (as did New Zealand), it is political representatives who need to take the decision about which of these options is most appropriate. The simulation does not tell politicians to curb hard-won freedoms; rather, it provides an indication that not doing so will lead to x deaths, y hospitalizations, and will cost z units of currency: estimates that are far easier to calculate with a computer simulation than they are to calculate by hand, and will involve fewer errors in calculation than intuitive estimation.

Looking to the future, suppose we accept that computer simulations are necessarily part of the processes of managing socio-(techno)-ecosystems dominated by human influence. Then technology becomes embedded in the water cycle (Fig. 1), the survival of species (Fig. 2), and other processes traditionally seen as 'natural'. Moving beyond the idea of 'pristine ecosystems' not interfered with by humans (and problematic conceptualizations associated with this) to the idea of 'pristine socio-ecosystems' unaffected with by technology, we are led to the idea of ecocyborgs: ecosystems that blend computers, robots, sensors, artificial intelligence, technology, nature and humans.

The concept of the 'ecocyborg' is defined by Clark and Kok, 1998 and Parrott and Kok (2006) as an engineered, autopoietic, intelligent, technologically-enhanced ecosystem. Reporting on a small relevant scenario exercise involving six laypersons and two experts, Marinakis et al. (2018) characterize the reactions from both laypersons and experts into categories of superfluous technology, dangerous tampering, and concerns about consequences for public health – suggesting the scenario was not greeted with enthusiasm. At the same time, they point (ibid., p. 101) to various technological innovations suggesting the plausibility of such a scenario. In an article outlining an associated ethics, van Wynsberghe and Donhauser (2018) list and taxonomize contemporary examples of what they call environmental robots. Ecocyborgs are by no means a far-fetched concept.

Haraway's (2016) concept of sympoiesis – making the earth's future together with other humans and other species – is perhaps blasphemed by the concept of the ecocyborg in much the same way as Haraway's (1987) cyborg manifesto was posited as a blasphemy of the human. Perhaps this blasphemy is a reason for the suspicion of the use of computer simulation in decision-making processes. However, treating simulation as a scapegoat for unpopular outcomes changes nothing about the dynamics of a virus taking advantage of human-to-human contact to replicate itself. With a system-of-systems lens, the autonomous, independent systems in which viruses replicate themselves and humans maintain their health are interdependent. Each must adapt to the other to achieve its goals (both of which amount to survival). Whether humans decide what to do collectively or individually, or whether they use voting, conversations among learned academics, the entrails of ritually slaughtered animals, or billions of transistors, the viral replication system only needs access to its next host. If computers can help the human health system understand how this access can more effectively be interrupted, is it such a blasphemy to use them? The scale transition from the sub-cellular to the global has all the hallmarks of a challenging, complex social, technological and ecological environment (Ahlborg et al., 2019) about which humans now have to reason, and where computers can help. Such are the contractions heralding the birth of the ecocyborg.

4. Characteristics and limitations

All methods of making decisions – individual or collective, humanistic or technocratic, informal or scientific – have their limitations and biases. Below, we compare the limitations of human discursive and simulation-assisted methods of decision-making. We dedicate a subsection to emphasizing the limitations of discursive methods of decision-making, which may seem disproportionate. However, the assertion that all models are wrong (but some are useful), attributed to Box (1976), is embedded in modelling lore. While we are all, quite rightly, sceptical of models, there is generally less willingness to apply the same levels of scrutiny to human reasoning. For example, in computer simulations, we might worry about corrupt or conflicting input data, mislabelled data, false assumptions

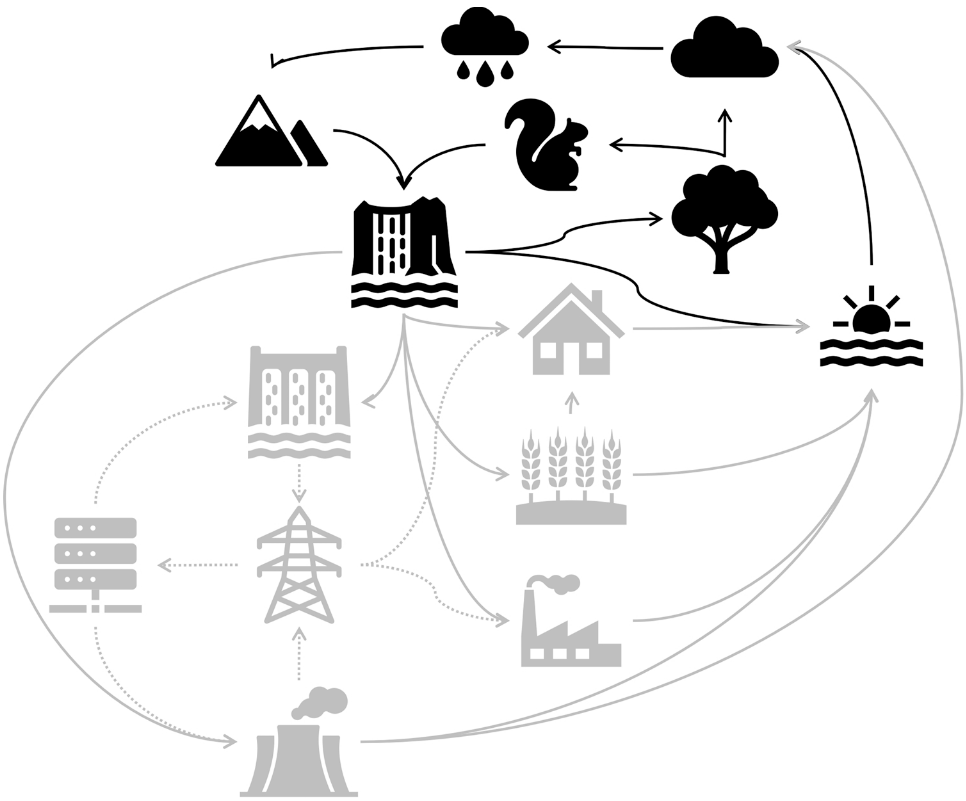

Fig. 1. Water cycle ecocyborg. Natural movement of water is represented using solid black arrows. Grey solid arrows indicate movement of water by machines. Machine control and (electric) power flows are shown with grey dotted arrows.

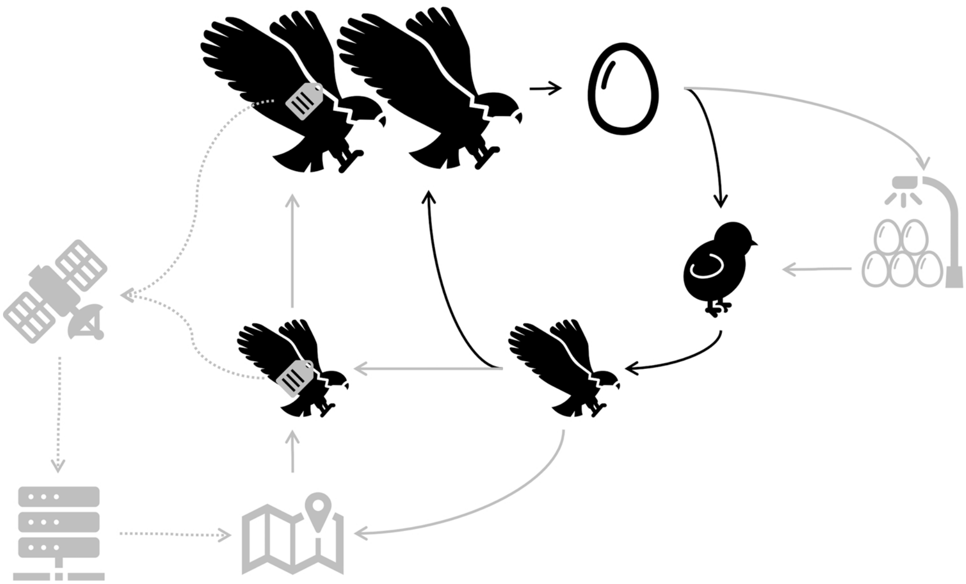

Fig. 2. Bird lifecycle and conservation ecocyborg. Natural processes are indicated with a black arrow, while grey solid arrows represent technological integration – artificial incubation, introduction to computer-identified habitat sites, and attaching tags for satellite tracking. Grey dotted arrows represent information flows.

embedded in the computer code, or even malicious attempts to manipulate the output by hacking the model code. But equivalents of these phenomena exist in human discourse; respectively: misremembering, malapropism, misbelief, and gaslighting or false memory implantation.[3]

4.1. Characteristics and limitations of discursive methods of decision-making

Human discursive methods, where the medium of representation is primarily natural language, are no exception to such limitation and biases. Natural language is: semantically rich (in the sense that words and phrases can represent a complex of ideas and subtleties), flexible (that it can be applied in analogical ways to new situations), context-sensitive (have different appropriate meanings in different kinds of situation) and is deeply embedded in our history and culture. However, it is also not precise (meaning arises from use in context, and each person has a slightly different interpretation of any bit of language), it is poor at representing a lot of detail (it is not a compact representation), it is not good at representing the causation or dynamics of large numbers of entities and it is not very amenable to automatic processing.

It is no longer controversial to assert that humans are irrational – indeed various cognitive distortions have at least a historical evolutionary advantage, if not a current one (Gilbert, 1998). Haselton et al. (2016) go a little further, arguing that supposedly irrational reasoning might not be as flawed as it might appear once environmental factors are taken into account. However, as Mercier and Sperber (2017, pp. 249–250) observe, the environments in which we now find ourselves having to make decisions are very different from those in which humans evolved. For example, Lovallo and Kahneman (2003) outline various cognitive biases leading business executives to be overoptimistic when making investment decisions that are difficult to imagine having any corollary in hunter-gatherer socio-ecosystems. Indeed, humans now have an unprecedented impact on the environments they inhabit, to the extent that we have named both a geological age (Crutzen, 2006; Lewis & Maslin, 2015) and a sixth mass extinction event (Wake and Vredenburg, 2008; Ceballos et al., 2015) after ourselves. Haraway (2015) is explicit that this is an atrocity: is there then any sound basis on which to argue any human's fitness to reason about appropriate actions in such a context? Given the potentially catastrophic outcomes predicted in the coming decades and centuries, it might even be reasonable to posit that humans are the last species on earth to be in a position to make the right decisions about ways forward.

4.2. A comparison of characteristics and limitations

Table 1 summarises the characteristics and limitations of human-discursive and simulation-assisted methods of decision-making to highlight their different strengths and weaknesses. Neither is universally superior to the other with respect to communicability, comprehension, ambiguity or accessibility. As we observe in the introduction, there is evidence that transdisciplinary work in which either is excluded has led to ineffective outcomes. However, bibliometric evidence points to a one-sidedness in which social simulation work is more likely to cite mainstream social science than vice-versa (Squazzoni & Casnici, 2013). It is also noteworthy that McDowall and Geels's (2017) article commenting on the advent of simulation in the societal transitions literature concludes by advocating (p. 47) "plural and diverse approaches rather than integration and synthesis," albeit that this is stated as requiring a level of interaction among the protagonists of these approaches.

5. Discussion

If one thing has marked human (as opposed to other species') adaptability to multiple environments, it is the use of tools to overcome physical limitations. While some may posit that the human brain is the best reasoning engine evolution has developed (despite various attempts at measuring size or ratios to body mass of brains or parts of brains such as the cerebral cortex suggesting otherwise), that does not mean it is the best possible, nor that it is necessarily sufficient for the decisions humans now have to take. We are accustomed to using our innate abilities in conjunction with external tools – especially that of writing – to the extent we are often not conscious of how they extend our mental and communicative abilities (Clark and Chalmers, 1998; Smith & Semin, 2004). Why, then, should we be squeamish about the augmentation of human reasoning with silicon-based computation to overcome mental limitations? Is it some fetishization of intuition or instinct? Or lingering cultural memory of resentment at historical disasters perpetrated through adherence to arbitrary authority? For the former, there is no cure except the weight of accepted contrary evidence; neither is there insight nor escape from authority. For the latter, there is at least the remedy of a democratized authority that people can access and inspect the basis on which a decision is made for themselves. Science, supposedly, is such an authority, and hence so is simulation, insofar as it qualifies as a scientific endeavour, in that it is repeatable, and, in the case of policy contexts, transparent and open.

At worst, the use of simulation as part of decision-making is merely digital divination, continuing *in silico* a practice that, though questionable rationally, is as old as human civilization. If birds, clouds, bones, entrails and tea leaves can be used for divination, then why not computers? MacLure (2021) even defends divination as a method for creative qualitative research practice, while Struck (2016) argues that cognitively, divination is simply an esoteric means for people to arrive at knowledge that is nevertheless useful to them.

[3] We are grateful to an anonymous reviewer of an earlier draft of this article for these examples.

Table 1
Comparison of the strengths and weaknesses of human-discursive and simulation-assisted methods of decision-making.

Aspect	Human Discursive	Simulation-Assisted
Semantic expressivity	Rich semantics – a few words can express a whole complex of ideas and associations	Thin formal semantics depending on skill of modeller and the modelling approach used – it takes lots of complex code to do anything that even touches on meaning
Ability to track detail	Can be done but is very cumbersome at even a superficial level	It was developed for this, it can track huge amount of interacting detail in parallel
Precision	Language varies according to its vagueness but is not ever completely precise – each individual will have a different interpretation of any bit of natural language	Simulations are formal and so can be communicated without error, however *how* they are mapped onto what they model can vary in formality (e.g. some only relate to ideas and not to data)
Rigorously Checkable	Some level of analysis and critique of natural language arguments is possible but not completely – the cognitive processes behind language are never 100% transparent	Open to modelling experts to complete and rigorous checking by re-running simulation experiments or even replicating them but this is time consuming (so not always done)
Democratic Accessibility	Almost everybody has considerable expertise in natural language and can understand a lot of what is said and join in at some level, still possible to exclude people by using technical language etc.	It can be hard for modellers to completely understand their own models let alone anyone else's. It is possible for other modellers to replicate models (and so check them rigorously) but this is time consuming and not always done. Not accessible to non-experts.
Ability to Persuade	Almost everybody has some expertise in judging and critiquing natural language processes and pronouncements; During discursive processes, however, personalities of the interlocutors can be instrumental in the persuasiveness of points.	A simulation can impress with its results in terms of technical nature, animations and graphs way beyond its veracity or reliability. Results can also be over-interpreted with respect to the scenario being modelled, through applying domain knowledge beyond the scope of what is being simulated.
Clarity of implications	The implications for decision-making vary in clarity, unless the decision-making is embedded within the process of deliberation itself (in which case the reasoning can be unclear)	How the results of simulations are interpreted in terms of decisions can be very unclear, but could be clarified with better protocols distinguishing roles of modeller, decision-maker etc. Equally, the clarity of the implications of modelling results can be made clearer when expressed graphically and factoring in geographical and demographic variation.
Causal dynamics	Can express complex and general ideas about causality and change but not good at animating this in detail as threads are easily lost.	An indefinite ability to animate and explore dynamics producing different trajectories of change in detail
Consistency	Most people have some expertise in assessing the consistency of natural language discussion, but is prone to hidden assumptions, subtle inconsistencies and group-think influences	The consistency of a simulation and its results is enforced by the computer system, but the consistency of the simulation with its intended design or the data is more difficult to check, however it can be indefinitely inspected (and compared against other models) and experimented upon to help this
Flexibility	Language is naturally flexible, adapting to different contexts and can be used analogically. People can confuse analogy and reality when reasoning, and over-stretch metaphors.	Simulations can be applied in new contexts and purposes, but many subtle errors and mistakes can happen when one does this. A lot of work is usually necessary to check and adapt a simulation
Ability to relate to formal data	Language can do this, but not easily – it does this cumbersomely and not compactly	Being a formal object, a simulation can be compared well to formal data but sometimes is done in a limited manner (e.g. using a single measure or graph)
Ability to relate to qualitative accounts	Language is already the medium in which qualitative accounts are usually expressed and related so ideally suited to this	Some methods for relating qualitative accounts to the micro-level of agent behaviour and to the outcomes from simulations exist but have limitations and are at an early stage of development
Historical embedding	Language and discursive methods have co-evolved with history and culture, it is sometimes hard to separate out unwanted implicit associations and assumptions	Simulation methods are relatively new – protocols and methods for effectively and openly embedding this tool within decision making processes are not mature and so open to new kinds of abuse
Openness to a diversity of viewpoints	Natural language processes can be open to a diversity of viewpoints; but discursive decision-making processes must be carefully constructed to involve people with diverse backgrounds if such openness is to be achieved. Homophily, established power structures, and groupthink too often act against this happening.	A single simulation usually encodes some aspects of a single viewpoint. Different simulations or simulation options can be implemented to compare the effect of different viewpoints but this is time consuming and not often done
Ability to relate to different cultural and ethical values	Natural language processes can encompass a range of different values	The usefulness of a simulation lies in how it is used and what is included in it. Technocratic decision-making processes (which they can facilitate) has been used to limit consideration of outcomes measures and hence limit the discourse on values
Overall Reliability	Depends on how it is done, particularly whether it is done with its limitations in mind	Depends on how it is done, particularly whether it is done with its limitations in mind

At its best, simulation is an open, data- and evidence-based means for people to explore scenarios that they are cognitively ill-equipped to process without algorithmic aid. At some point we have to accept that humans don't have the cognitive capacities needed to make difficult decisions in complex contexts with multidimensional variables and multiscale interactions. With such decisions nevertheless needing to be made, people will seek a means to reach a conclusion they have confidence in. Although simulation can be done badly, we still might prefer it to an alternative, not least because there is no universal acceptance of alternative forms of divination, leaving decisions open to dispute.

Although not our main purpose here, there is a considerable amount of self-reflection within parts of the simulation community resulting in suggestions for a more careful and democratic approach to using simulation in areas that might touch on policy making. There have been standards for better and more accessible simulation documentation (Grimm et al., 2006; Grimm et al., 2010; Grimm et al., 2020), archives for the public deposition of simulation code along with its documentation (e.g. the Network for Computational Modeling in Social and Ecological Sciences, https://www.comses.net/) mirroring calls for better practices in doing this (Polhill & Edmonds, 2007), calls for a more robust process of simulation comparison and critique along similar lines to those of climate change modelling (Bithell & Edmonds, 2021) and the beginnings of frameworks for the interaction of policy actors and modellers (HM Treasury, 2015, Calder et al., 2018). Interestingly, there is a school of simulation modellers that gives considerable power to the stakeholders over the whole model development process in the "Companion Modelling" approach (Barreteau, Étienne, 2003, 2013). There is also a growing awareness of the dangers of a naïve or over-optimistic view of simulation (Aodha & Edmonds, 2017). This can all be seen as a process of the socialization of simulation – the injection of social science approaches, data and awareness into the methodology.

There is still a considerable way to go in this regard. However, the problem of how to interface the use of simulation with policy processes, is not a totally new one. The underlying tension between utilising expertise of any kind and that of democratic accountability is similarly present with other technical tools, such as statistical or analytic mathematical modelling. Simulation has different characteristics to these other tools and some different dangers, and procedures to guard against such dangers will need to be adapted to ensure democratic accountability.

6. Conclusion

All tools – physical, mental and social – have their own characteristics: affordances, limitations, and dangers. Practitioners who are skilled at one particular set of such tools tend to be more aware of the advantages and possibilities of their preferred set and the disadvantages and dangers of other sets (particularly new tools). However, tools are a fact of life; it is unlikely we could live without them. It is true that simulations can blind their makers and users as to their weaknesses and lead to a collective myopia as to what is considered as evidence, what factors are included in a simulation and how its results are interpreted (Aodha & Edmonds, 2017), however there are other dangers of policy-making about complex systems without them – particularly when it involves systems with many thousands of interactions that can result in emergent outcomes not guessable or intuitable without simulating them.

This paper has addressed what may appear to be reasonable concerns about the use of complex computer simulations to inform policy decisions in complex contexts (involving different kinds of actor, engaging in different kinds of interactions across multiple scales). We considered the outcomes of *not* using such simulations, which raise two main concerns. The first is the implicit assumption that human cognition (including intuition), whether acting individually or collectively, is sufficient to make effective decisions about systems that some believe to be beyond human comprehension due to their complexity. We have briefly referred to a little of the vast volume of psychological evidence that it is insufficient. This leads to the second concern: for all that computer simulations may be technocratic, require expert skills to develop and interpret, and even potentially flawed, human-discursive approaches can be as inscrutable, unaccountable, and potentially open to abuse. Ideally both systems should be used in a complementary fashion. We do not advocate blindly following what the computer simulations indicate should be done. The decision is ultimately made through a human discursive process that evaluates simulation results, and indeed provides the social context in which those results have meaning.

Clearly, we are in a period of adjustment to our *in silico* extensions – we are not yet as comfortable with these as we are with that of the tool of writing, nor do we have the social institutions to facilitate the full evolution of this new socio-techno-ecological integration. Thus, there are dangers we have to be mindful of at this time. However, there are also dangers in ignoring simulation-based tools for decision-making, because there are complications to address that are beyond our innate cognitive ability – either individually or collectively. As the examples of tipping points in global warming illustrate, the very existence of many peoples and species could depend upon us growing in this direction. We are only starting to explore *how* to bring effective ecocyborgs into being. An alternative to being prejudiced against these strange new beings is to embrace them and educate them to be well-adjusted and useful members of our society.

Data Availability

No data was used for the research described in the article.

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