Perspective

Engage, don't preach: Active learning triggers climate action

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A B S T R A C T

Traditional communication of research on climate change fails to encourage individual, corporate, and political leaders to take appropriate action. We argue that this problem is based on an overly simplistic unidirectional model of science communication. Conversely, theory shows that active learning processes are better suited to initiate and mobilize engagement among all stakeholders. Here, we integrate theoretical insights on active learning with empirical evidence from serious gaming: communication should be understood as an integral design feature that relates active learning on climate change to tangible action.

1. Introduction: An overly simplistic understanding of science communication

Mitigating climate change requires collective action and rapid decarbonization, including an unprecedented energy transition. This calls for science-based decision-making across political and corporate leaders and individuals on all levels. To inform environmental governance, understanding human behavior through a complex adaptive systems lens is critical [1]. However, such an understanding of complexity is required not only for analyzing systems but also for communicating insights. In fact, our understanding of science communication may be overly simplistic, failing to recognize both the adaptive and the complexity aspects involved in information exchange and learning.

Traditional science communication has followed information deficit theory, which is again based in an overly simplistic understanding of communication. Information deficit theory implicitly relies on Shannon's linear information-theoretic model [2], which comprises sender, recipient, and noise information channel (Fig. 1A). The model assumes that the recipient learns information provided by the sender and that communication fails if the information is not correctly decoded by the recipient, or the information channel is too noisy, in which case the sender must find a new and better way to transfer the same information. While theoretically reasonable, this model fails to account for how information processing works in the real world. As a prime example, scientists tend to base their attempts to communicate the risks of climate

change on the information deficit theory of risk communication [3], suggesting that providing people with more and better information about the reality, causes, and risks of climate change encourages them to take appropriate action. Scientific evidence shows that communication strategies grounded in the deficit model have failed to elicit affective responses motivating action [4]. In the US, only 69% of citizens think that climate change is real and happening today, and only about half understand that it is mostly caused by humans [5]. This gap between scientific and public understanding has led to the emergence of a body of literature on how climate change is being communicated. Recently highlighted explanations for the communications gap include (i) misconceptions about complex systems in general, and climate change in particular; (ii) a human affinity to discount future impacts; (iii) social and cultural obstacles to learning and acting on climate change; and (iv) intentional attempts to misinform the general public and delay action [6]. Here, we draw on insights from cognitive science, understanding cognition as an embodied process, to clarify the importance of active and engaged approaches to communicating and simultaneously acting on climate change.

In the following sections, we elaborate on how active learning can address the challenge of effective climate change communication. We first address active learning and how serious gaming provides a learning environment that favors active learning. We further provide examples of such games, embedding them in the context of active learning. We then provide recommendations on how and where to integrate serious games as vehicles for active learning to stimulate and engage the general public

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to act against climate change.

2. Active learning: The perception–action–learning loop

As an alternative to the above-described information deficit theory, the action–perception–learning loop has been forwarded as an explanatory and functional model of human cognition, emphasizing that cognitive processes of internalizing the external and building structures are guided by action [7]. In fact, sensorimotor contingencies may be constitutive of cognitive processes [8,9]. Insights from computational neuroscience suggest that living organisms, and especially humans, effectively process information in coordination with (motor) action, based on continuous feedback between observing environmental stimuli and acting upon them (Fig. 1B) [10]. In the resulting action–perception–learning loop, exploratory action and active seeking of new information are intrinsically linked. For example, action for learning is taken so as to maximize information relevant for further

action [11], in accordance with neural information processing mechanisms [12]. This is a particular realization of the free energy principle: body and mind relate to the environment via an active inference that is fundamentally enacted and embodied [13]. Any living organism interacts with its environment to maintain its boundary and to defend an upper limit of its entropy, restricting the space of possible states it can be in. To do so it relies on active inference; i.e., acting on the environment to minimize surprise and maximize evidence. This principle makes an important prediction directly relevant to climate change communication: Any message that is not, or that is only very remotely, related to the organism's own action remains irrelevant. To make messages effective, they must be experienced as a result of and an interchange with the organism's own action [13].

Two axioms underline this new paradigm. First, mental capacity for processing information is limited, and perception systems filter out everything but the most important, evolutionarily relevant information. Second, only information (from past events) that is predictive about the
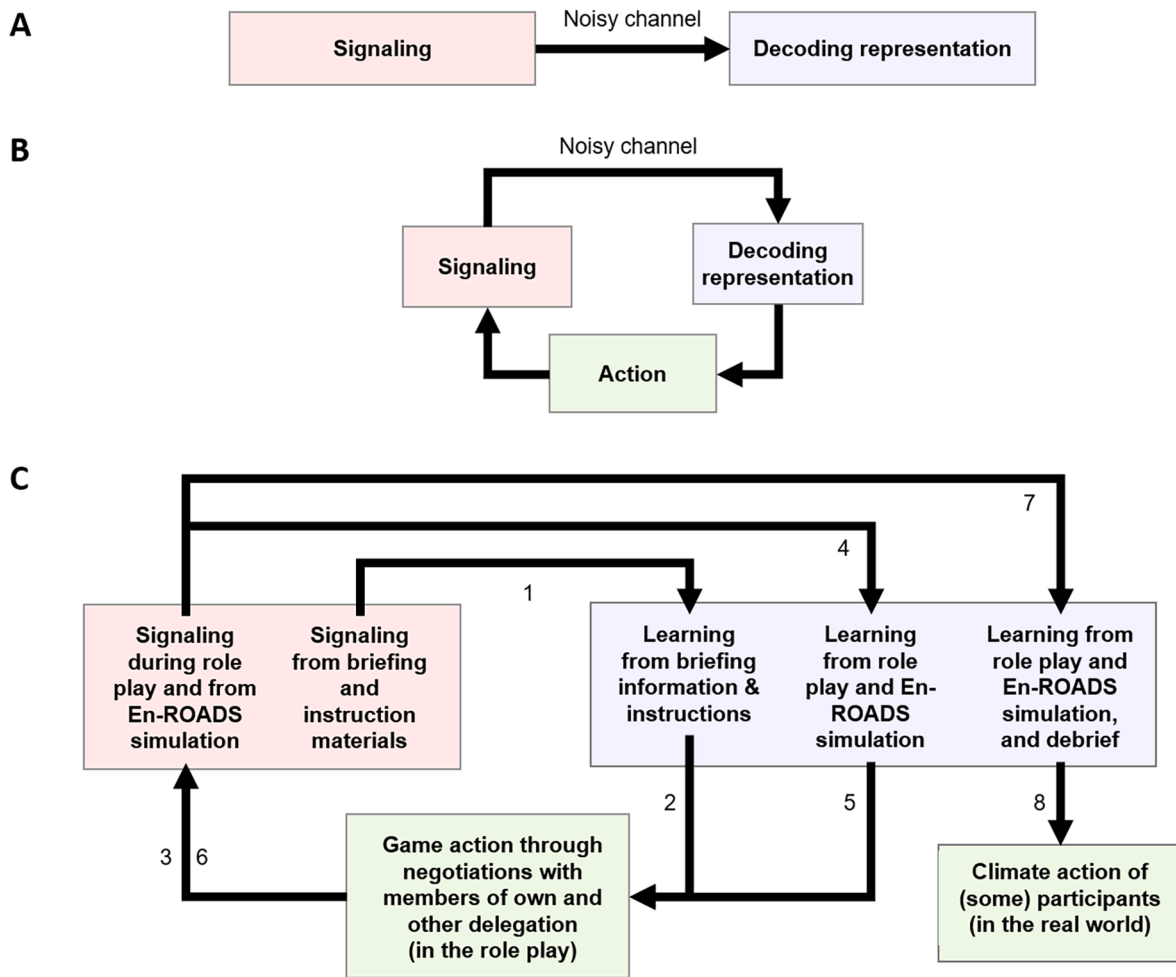

Fig. 1. Theories about information processing and communication. A) Information deficit theory, which relies on the noisy channel theorem proposed by Shannon [2]; here, the most relevant aspect is accurate coding and decoding for communication success. The optimization principle refers to finding a channel of sufficient capacity that enables optimal accurate representation of the source signal. B) The action–perception–learning model of communication; here, incoming encoded signals are specifically assessed for action-relevant information; action, in turn, is selected to keep the environment predictable, which involves seeking out further relevant information. Learning occurs, but optimal decoding is only defined recursively with action and its success. C) The action–perception–learning loop model in practice, which involves learning about climate change via a game exemplified by the simulation-based role play Climate Action Simulation with the climate-energy model En-ROADS. Participants first learn from reading delegation-specific briefings (arrow 1), wherein they interact and negotiate with members of other delegations (arrow 2). They receive signals directly from their peers in the negotiations and from their pledges entered into En-ROADS, and the impact thereof on the climate system is immediately shown (arrow 3). Here, another learning opportunity arises when participants learn about the impact of their policies and actions from both the role play (e.g., other delegations did not stick to the oral agreement) and from En-ROADS modeling output (e.g., the impact was bigger/smaller than anticipated) (arrow 4). Usually, first-round results fall short, illustrating to delegations the likely harm to their prosperity, health, and welfare. Participants then negotiate again (arrow 5), using En-ROADS to explore the consequences of more ambitious emission cuts (arrow 6). They learn yet again from the role play and En-ROADS, and additionally from the debrief (arrow 7). Some participants then transfer the lessons learned from the game and take action in the real world (arrow 8).

future is important [14]; specifically, only information that organisms can act upon is relevant [10]. It follows that information processing is directed towards finding signals that help to guide one's own action. Inversely, action can be oriented towards exploring a new environment and thus finding more relevant information (Fig. 1B). Together, agents coordinate stimulus processing and action in order to formulate evolutionarily adequate strategies.

Together, these considerations suggest that communications about sustainability will be ineffective as long as citizens are understood as passive recipients. Instead, communication should work more effectively via active learning if recipients can (i) reasonably act upon the incoming information; and (ii) act such that they receive feedback on their action.

3. Serious games are role models of active learning

Serious games provide a learning environment that meets both of the requirements outlined in the previous section. Recent scientific findings indicate that serious gaming – computerized games for learning – provides a promising approach to effectively communicate with respect to climate change and simultaneously motivate people to act upon emerging insights [15]. Serious games allow participants to learn about the behavior of complex real-world systems consisting of feedback loops, non-linearities, accumulations, and time delays by testing policies in a safe learning environment. Many serious games address sustainability issues [16].

In the following, we describe how serious games follow the logic of the action–perception–learning loop (Fig. 1C), exemplified with participants engaged in the simulation-based role play Climate Action Simulation with the climate-energy simulator En-ROADS (www.climateinteractive.org/tools/en-roads) [6]. In the role play, participants take on the roles of leaders from private industries (Conventional energy; Clean tech; Industry & commerce), governments (Developed, Rapidly emerging, and Developing nations governments), and Non-Governmental Organizations (Land, agriculture, and forestry; Climate activists) focused on energy and climate policy. They are empowered to make decisions within their own sector, while attempting to influence other groups' decisions to agree on policies and actions to limit global warming to well below 2 °C at a fictitious climate action summit called by the UN Secretary General. Participants negotiate on 18 different policy and action levers, including introducing a carbon price, subsidizing or taxing primary energy sources (coal, oil, gas, renewables, bioenergy, nuclear), deciding on a hypothetical breakthrough of a new, cheap, and carbon-free technology for generating electricity, pushing or slowing down electrification of the transport and stationary sectors, introducing natural or technological carbon capture options, changing economic growth rates, etc., while also considering co-benefits and equity. After each round of negotiations, participants enter their suggestions into En-ROADS and immediately see the impact of their decisions on the climate system. The Climate Action Simulation contains the facets of the action–perception–learning loop, with participants traversing the loop described in Fig. 1B at least twice. Negotiations represent the motor action, as participants have to get up from their chairs and walk towards the other delegations' representatives to negotiate face-to-face. Climate activists draw posters that include their statements, demonstrate, organize walk-throughs, etc. Participants negotiate with high emotions and energy on their sectors' favorite and politically feasible actions and policies, building consensus. They prepare, discuss, and agree with other members of their delegations on their formal speeches, which they then address to other delegations. They receive feedback on their own behavior in two ways: first, from En-ROADS on the climate-energy system after having entered their decisions; and second, from their negotiation partners on how they feel about the decisions (betrayed, relieved, etc.). They then act upon these insights in the subsequent round(s) of negotiations. Thus, during these motor actions and during the briefings, participants process and internalize the information,

enabling affective learning within an immersive, social learning experience [6].

4. Games allow for intuitive understanding of complex systems

Besides the Climate Action Simulation, several other serious games on climate change and sustainability challenges in general motivate action through the action–perception–learning loop of learning. We explain three more games in more detail, describe how they relate to active learning, and provide an overview of additional games (Table 1).

For example, in the simulation-based role play World Climate Simulation, participants in roles of country leaders negotiate over the terms of limiting global warming well below 2 °C above preindustrial levels by 2100 on a country level. Similar to the UNFCCC process, participants take on the roles of delegates to the UN climate change negotiations and specify Nationally Determined Contributions for the party they represent, while attempting to influence the other delegations through face-to-face negotiations. Participants' proposals are then entered into the C-ROADS climate policy model [17], which provides immediate feedback about the expected climate outcomes of those decisions [15]. First-round results typically fall short, which is why the delegations renegotiate and use C-ROADS again to test their pledges. In a key study with more than 2,000 participants from eight countries and four continents, 81% of participants showed increased motivation to combat climate change following participation in the game – across the political divide – with statistically significant gains in (i) knowledge of climate change causes, dynamics, and impacts (analytic learning); (ii) affective engagement, including greater feelings of urgency and hope (affective learning); and (iii) a desire to learn and do more about climate change [15].

Likewise, the board game KEEP COOL enables active learning. Here, participants represent groups of countries who decide on (i) investing in carbon-emitting or more costly carbon–neutral factories; (ii) adapting to climate change; or (iii) undertaking research and development to decrease costs of carbon-emitting or carbon–neutral technologies, while keeping the earth's temperature below a certain threshold, above which climate-related disasters happen. Participation in KEEP COOL increases participants' (i) sense of personal responsibility for fighting climate change; (ii) confidence in politics for climate change mitigation; and (iii) optimism about international cooperation in climate politics [18].

A classic serious game that jointly models natural resource dynamics and social decision-making behavior for sustainability is FishBanks [19], which was originally developed as a multi-player board game and is now available online. Participants manage fishing companies, seeking to maximize their company's net worth at the end of the game. They learn about (i) resource dynamics, (ii) the tragedy of the commons [20,21], (iii) misperceptions of feedback – the ignoring of feedback processes, time-delays, and non-linearities in decision-making [22], and (iv) the fact that successful governance of the commons is possible. Action happens through interaction with members of participants' own group and with other groups.

While focusing on different aspects of raising awareness of sustainability in general, and climate change in particular, these serious games demonstrate how interactive and engaging design, and associated social experiences, support the learning experience via the action–perception–learning loop. They enable analytic and affective learning as part of a social learning process, realized in settings where active decisions by participants are required.

This result is mirrored in the pedagogical literature that points to the success of active learning. A meta-analysis of 225 studies found that examination scores improved by about 6% in active learning compared to traditional learning. Active-learning students failed only in two thirds of cases in which traditional-learning students failed [23].

One benefit of games, and especially computer-based role plays, simulations, or management games, is their solid foundation for scalability to reach a larger audience [24]. The World Climate and Climate

Table 1
Overview on representative sustainability and climate change simulations and serious games.

	URL	Topic	Goal of game	Perspective	# of participants	Duration of game	Open educational resource?	Role play?	Computer based?	Empiri-cally evaluated?	Extent of action learning facilitated
World Climate Simulation	https://www.climateinteractive.org/tools/world-climate-simulation/	Fictitious UNFCCC Climate negotiations with heads of states (plus delegations) and NGOs	Decide on country/bloc emission pathways to limit global warming to <2 °C	Global	3–10 groups with 15–500 participants	2–5 h (incl. brief and debrief; can also be played over a semester)	√	√	√ (C-ROADS, in development as app for tablets)	√	●
Climate Action Simulation	https://www.climateinteractive.org/tools/climate-action-simulation/	Fictitious UN Climate Action Summit with political, business, and NGO leaders	Decide on policies and actions to limit global warming to <2 °C	Global	6–8 groups with 18–500 participants	2–5 h (incl. brief and debrief; can also be played over a semester)	√	√	√ (En-ROADS, available as app for tablets)	√	●
KEEP COOL	http://www.climate-game.net/en/	Fictitious meeting of global leaders	Manage global metro-policies	Global	6 groups of 1 person per group	60 min.		√	In development as app	√	◕
FishBanks	https://mitsloan.mit.edu/LearningEdge/simulations/fishbanks/Pages/fish-banks.aspx	Max net-worth of competing fishing companies who deal with variations in stocks of fish	Manage renewable resources sustainably	Fictitious marine eco-system	1 person to 10 groups (2–3 people per group)	180 min. (including briefing and debriefing)	√	√	√		◔
Clim'way	https://www.cdgr.ucsb.edu/database/game/555	Community leader	Manage community to meet climate goals	Community	1	60 min	√		√		◑
Climate Quest	https://earthgames.org/games/climatequest/	Prepare against natural disasters	Protect fragile eco-systems	USA	1	10 min. (plus brief and debrief)	√		√ (App for mobile devices)		◑
EcoChains: Arctic Crisis	http://ecochainsgame.com/	n.a.	Build food chains and protect Arctic wildlife	Arctic	2–4	40 min.	√				◑
Fate of World	http://www.soothsayergames.com/what-we-do/	Fictitious world leader	Manage climate change	Global	1	n.a.			√		◔
GREENIFY	http://gamesresearchlab.com/wp-content/uploads/2015/11/CHI-Greenify-EDITED_FINAL.pdf	Members of community making decisions to help the community flourish	Foster flourishing sustainable communities	Community	n.a.	n.a.	n.a.		√	√	◔
Losing the Lake	https://www.cse.unr.edu/~hpcvis2/Projects/LosingTheLake/LTLFacilitationGuideVersion111512.pdf	Water management in Lake Mead	Managing water level	Local	1	30 min	√		√		◔
The Other World	https://earthgames.org/2018/06/06/the-other-world-a-new-augmented-reality-experience/	Augmented-reality weather effects across University of Washington Seattle campus	Learn about environ-mental justice	University of Washington Seattle campus	1	60 min	(√) – only locally on campus		√		◑
2050 Pathways Analysis	http://2050-calculator-tool.decc.gov.uk/#/home	Fictitious leader of the UK	Create energy pathways	UK	1	n.a.	√		√		◔

Coding for extent of action learning facilitated:

○	No action learning
◔	Limited action learning
◑	Moderate action learning
◕	Significant action learning
●	Extensive action learning

Action Simulations, for example, were both designed for scalability. Game materials and facilitator guides for offline and online use are available free of charge via the Climate Interactive website (www.climateinteractive.org), and may be adapted to specific use. In light of COVID-19 and the need for physical distancing, resources for online facilitation of the games enable them to be played online by larger groups. Game materials for the World Climate Simulation, for example, are available in 14 languages. Via webinars, people can experience and learn how to facilitate World Climate Simulations. Since 2015, more than 70,000 people have participated in more than 1,500 registered World Climate events in 94 countries.

Per the Climate Action Simulation, briefing statements are available in 28 languages and further documents are being translated. In addition to making the materials available, future facilitators are encouraged to participate in a training plan, with an opportunity to become En-ROADS Climate Ambassadors. They are especially trained to thoroughly understand the simulation model and to facilitate interactive events using En-ROADS. Over the first six months since the training plan's launch, roughly 180 people became En-ROADS Climate Ambassadors, building a worldwide community to disseminate the climate model [25]. En-ROADS Climate Ambassadors played an important role in facilitating more than 900 registered events, with more than 24,000 participants, since the release of En-ROADS in December 2019. The Climate Action Simulation has been the second most popular intervention after the interactive En-ROADS Climate Workshop. Participants of both the World Climate and the Climate Action Simulations represent a wide range of groups, from the general public, high school and university students, and media representatives, to corporate and political leaders and climate policy-makers.

5. The way forward: Transferring insights to other channels of climate change communication

The insights on games and active learning outlined above lead to the following reflections and implications for climate change communication. Overland and Sovacool [26] highlight that:

The funding of climate research appears to be based on the assumption that if natural scientists work out the causes, impacts, and technological remedies of climate change, then politicians, officials, and citizens will spontaneously change their behavior to tackle the problem. The past decades have shown that this assumption does not hold.

We agree with this conclusion, and suggest a way forward regarding how to change communication patterns: engage stakeholders in modeling and data exploration exercises and activate their desire to become active agents of the communication process rather than passive recipients of scientific communication.

Our insights have important implications for communicating sustainability threats, such as climate change or biodiversity. First, there is high potential in using gaming for science communication. The challenge here is that gaming is a group exercise and does not work via traditional communication channels, such as newspapers or television. However, virtual gaming promises potential for upscaling, and it is important for further research to explore this option.

Second, our suggested communication model indicates that participatory processes are not only procedurally the right choice, but also an effective way to form a common understanding and to act upon this. Importantly, processes that are participatory in name only, with little room for real deliberation, are insufficient. Participants must have the opportunity to bring in their own interests and understanding and explore solutions themselves. Examples of such promising participatory interventions include the Citizens' Assembly [27] (Box 1) and living labs [28] (Box 2).

Both approaches exemplified above are co-creative, deliberative processes. They increase environmental literacy among participants by leveraging the language, stories, and local relevant context, leading to action. Enhancing environmental literacy thus leads to changes in communication and education styles [29]. As Devaney et al. [29] point out, "greater emphasis needs to be placed on promoting new modes of communication and engagement for environmental literacy," with a focus on both formal and informal education. It is here that serious games could complement these participatory interventions. First, games such as the World Climate or the Climate Action Simulations deliver gains in participants' understanding and motivation to address climate change. As they help to increase public awareness regarding the need for more ambitious climate action, they could be an ideal introduction to co-creative, deliberative processes. Second, as they – and many other games – are scalable, they could support the wider use of related interventions, addressing more people all over the world and at different societal levels.

Engaging local communities could also be embedded in design thinking processes, allowing for enhanced learning, and advocating creative thinking and finding solutions to "wicked problems" of sustainability issues [31]. Involving local – or, in the case of citizen assemblies, national – communities early on leads to increased suggestion of participants' own solutions, and thus ownership of processes, issues, and broader support of decisions; in this case the decision outcome is markedly improved compared to top-down participatory processes [27,32].

Third, simulation models could be used by individuals or groups in interactive, participatory workshops designed for policy-makers, business leaders, legislators, the media, societal leaders, and the general public. Instead of participants taking on roles such as those in the simulations described above, the perception–action–learning loop is triggered by participants exploring the effects of their decisions for themselves – for example, with the interactive climate simulation models C-ROADS and En-ROADS. Workshops using En-ROADS have been conducted with business leaders and bi-partisan representatives of the US Congress and US State Governors. Feedback from policymakers underscores that the action–perception–learning loop is active in En-

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Box 1
: Citizens' Assembly.

The Irish Citizens' Assembly on climate change from 2016 to 2018 is regarded as a best practice example in terms of design and execution, having led to policy acceptance, solutions, and actions through societal buy-in, engagement, and understanding of the climate crisis [29]. Ninety-nine random citizens from different genders, ages, social classes, and regional backgrounds were selected for engagement in the Assembly. Trained facilitators moderated the citizens' deliberations. To enlarge the base of people involved, members of the public were invited to provide submissions on the topics deliberated, leading to 1,185 public submissions, including 153 from groups. These submissions were screened and summarized by the secretariat, and the participating citizens were invited to read the signpost document and submissions. The Citizens' Assembly finally agreed on 13 climate recommendations for the entire country of Ireland. The recommendations are regarded as significantly more radical than originally expected [29].

Box 2
: Living labs.

Living labs refer to developing, deploying, and testing specific market innovations. In combined household–laboratory environments, participants from different disciplines collaborate in actual living environments [30]. Because the initiative entails co-creation by a community of people, the resulting innovation is accepted by all and is thus implemented faster. In a living lab focusing on sustainability, for example, different stakeholder groups assessed and tested innovations for thermal renovation of the historical city center of Cahors in southern France [28]. The transdisciplinary work included future users of the buildings (owners, tenants, and lessors), craftsmen, architects, developers, financial sponsors, technical partners, researchers, and city representatives. These participants not only tested different solutions through experimental renovations, but also had access to a platform through which they could interact and meet in an experimental setting without financial pressure. Further benefits included sharing of expertise, fostering communication among stakeholders, sharing resources and equipment, and saving time in identifying the best solution regarding internal thermal insulation of historical city centers.

ROADS Climate Workshops [35], also across the political divide, emphasizing that such interventions represent a different learning experience. For example:

- "Engaging with the En-ROADS climate simulation has been one of the best ways for me, as a policy maker, to learn about how solutions to tackle climate change can reinforce or interfere with one another." – Sheldon Whitehouse (US Senator, Democrat, Rhode Island)
- "What I like about En-ROADS is how it can support a really thoughtful conversation – I can see the ways that policy actions could be worth the pain." – John Curtis (US House of Representatives, Republican, Utah, 3rd District)
- "En-ROADS is quite simply a climate crisis game-changer for policymakers and people across the country. … [It] is the ultimate conversation starter." – John Kerry (Former US Secretary of State)

Fourth, in combination with big data, interactive scenarios can be provided that adequately capture the local spatial context. For example, a recent study uses machine learning to simulate climate change impacts, such as flooding, for home owners [33].

Fifth, interactive scenarios could be combined with more traditional communication outlets, such as online newspapers. For example, recently Bloomberg News published an interactive story in which readers could experiment with En-ROADS via a simplified interface and assess impacts of different policies and actions to slow global warming. Such interactive initiatives provide readers the opportunity to learn for themselves instead of simply reading, replacing passive learning with more action-oriented learning by providing instant feedback on users' decisions [34]. The effectiveness of such interactive news requires additional research.

Researchers and communicators should see information deficit theory in the context of climate change communication for what it is: a dead-end street. Instead, learning will emerge simultaneously via the design of sustainability transitions and climate solutions from the active and joint engagement of scientists, citizens, and policy-makers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] C. Schill, J.M. Anderies, T. Lindahl, C. Folke, S. Polasky, J.C. Cárdenas, A.-S. Crépin, M.A. Janssen, J. Norberg, M. Schlüter, A more dynamic understanding of human behaviour for the Anthropocene, Nat. Sustain. 2 (2019) 1075–1082, https://doi.org/10.1038/s41893-019-0419-7.

[2] C.E. Shannon, A mathematical theory of communication, Bell Syst. Tech. J. 27 (1948) 379–423.

[3] D. Dickson, The case for a 'deficit model' of science communication, SciDev Net. (2005) https://www.scidev.net/global/communication/editorials/the-case-for-a-deficit-model-of-science-communic.html (Accessed 4 August 2020).

[4] W. Pearce, B. Brown, B. Nerlich, N. Koteyko, Communicating climate change: Conduits, content, and consensus, WIREs Climate Change 6 (2015) 613–626, https://doi.org/10.1002/wcc.366.

[5] A. Leiserowitz, E. Maibach, S.A. Rosenthal, J. Kotcher, P. Bergquist, M.T. Ballew, M. Goldberg, A. Gustafson. Climate change in the American mind: April 2019, Yale University and George Mason University, New Haven, CT: Yale, 2019.

[6] J.N. Rooney-Varga, F. Kapmeier, J.D. Sterman, A.P. Jones, M. Putko, K. Rath, The climate action simulation, Simul. Gaming 51 (2020) 114–140, https://doi.org/10.1177/1046878119890643.

[7] F.J. Varela, E. Thompson, E. Rosch, The embodied mind: Cognitive science and human experience, MIT press, 2017.

[8] J.K. O'Regan, A. Noë, A sensorimotor account of vision and visual consciousness, Behav Brain Sci 24 (2001) 939–973.

[9] F. Creutzig, From predictive coding to percept–a computational approach, Geist Wiss, Interdiszip. Ansätze Zur Bewusstseinsproblematik. (2009) 151.

[10] N. Tishby, D. Polani, Information theory of decisions and actions, in: V. Cutsuridis, A. Hussain, J. Taylor (Eds.), Perception-Action Cycle, Springer, New York, NY, 2011, pp. 601–636.

[11] D.-Y.-J. Little, F.T. Sommer, Learning and exploration in action-perception loops, Front. Neural Circuits 7 (2013), https://doi.org/10.3389/fncir.2013.00037.

[12] F. Creutzig, H. Sprekeler, Predictive coding and the slowness principle: An information-theoretic approach, Neural Comput. 20 (2008) 1026–1041, https://doi.org/10.1162/neco.2008.01-07-455.

[13] M. Allen, K.J. Friston, From cognitivism to autopoiesis: Towards a computational framework for the embodied mind, Synthese 195 (2018) 2459–2482, https://doi.org/10.1007/s11229-016-1288-5.

[14] F. Creutzig, A. Globerson, N. Tishby, Past-future information bottleneck in dynamical systems, Phys. Rev. E. 79 (2009), 041925, https://doi.org/10.1103/PhysRevE.79.041925.

[15] J.N. Rooney-Varga, J.D. Sterman, E. Fracassi, T. Franck, F. Kapmeier, V. Kurker, E. Johnston, A.P. Jones, K. Rath, Combining role-play with interactive simulation to motivate informed climate action: Evidence from the World Climate simulation, PloS One 13 (2018), e0202877, https://doi.org/10.1371/journal.pone.0202877.

[16] P. Hallinger, R. Wang, C. Chatpinyakoop, V.-T. Nguyen, U.-P. Nguyen, A bibliometric review of research on simulations and serious games used in educating for sustainability, 1997–2019, J. Clean. Prod. 256 (2020), 120358, https://doi.org/10.1016/j.jclepro.2020.120358.

[17] J.D. Sterman, T. Fiddaman, T. Franck, A. Jones, S. McCauley, P. Rice, E. Sawin, L. Siegel, Management flight simulators to support climate negotiations, Environ. Modell. Software 44 (2013) 122–135, https://doi.org/10.1016/j.envsoft.2012.06.004.

[18] J.N. Meya, K. Eisenack, Effectiveness of gaming for communicating and teaching climate change, Clim. Change 149 (2018) 319–333, https://doi.org/10.1007/s10584-018-2254-7.

[19] Dl. Meadows, T. Fiddaman, D. Shannon, Fish Banks Ltd, Lab. Interact. Learn. (1986).

[20] G. Hardin, The tragedy of the commons, Science 162 (1968) 1243–1248.

[21] E. Ostrom. Governing the commons: The evolution of institutions for collective action, Cambridge University Press, Cambridge, MA, 1990.

[22] J.D. Sterman, Misperceptions of feedback in dynamic decision making, Org. Behav. Hum. Decis. Processes 43 (1989) 301–335, https://doi.org/10.1016/0749-5978(89)90041-1.

[23] S. Freeman, S.L. Eddy, M. McDonough, M.K. Smith, N. Okoroafor, H. Jordt, M. P. Wenderoth, Active learning increases student performance in science, engineering, and mathematics, Proc. Natl. Acad. Sci. 111 (2014) 8410–8415, https://doi.org/10.1073/pnas.1319030111.

[24] Jason S. Wu, Joey J. Lee, Climate change games as tools for education and engagement, Nat. Clim. Change 5 (2015) 413–418, https://doi.org/10.1038/nclimate2566.

[25] Bhandari B., En-ROADS Impacts: A Closer Look at the Numbers of Participants, Ambassadors, and More!, Clim. Interact. (2020). https://www.climateinteractive.org/blog/en-roads-impacts-by-numbers/ (Accessed 4 August 2020).

[26] I. Overland, B.K. Sovacool, The misallocation of climate research funding, Energy Res. Social Sci. 62 (2020) 101349, https://doi.org/10.1016/j.erss.2019.101349.

[27] Citizens' Assembly. Third Report and Recommendations of the Citizens' Assembly: how the state can make Ireland a leader in tackling climate change, Citizens, Assembly, Dublin, 2018.

[28] S. Claude, S. Ginestet, M. Bonhomme, N. Moulène, G. Escadeillas, The Living Lab methodology for complex environments: Insights from the thermal refurbishment of a historical district in the city of Cahors, France, Energy Res. Soc. Sci. 32 (2017) 121–130, https://doi.org/10.1016/j.erss.2017.01.018.

[29] L. Devaney, P. Brereton, D. Torney, M. Coleman, C. Boussalis, T.G. Coan, Environmental literacy and deliberative democracy: a content analysis of written submissions to the Irish Citizens' Assembly on climate change, Clim. Change. 1–20 (2020), https://doi.org/10.1007/s10584-020-02707-4.

[30] P. Ballon, D. Schuurman, Living labs: Concepts, tools and cases, info 17 (2015), https://doi.org/10.1108/info-04-2015-0024.

[31] T. Brown, B. Katz, Change by design, J. Prod. Innov. Manage. 28 (2011) 381–383, https://doi.org/10.1111/j.1540-5885.2011.00806.x.

[32] R. Cowell, G. Bristow, M. Munday, Wind energy and justice for disadvantaged communities, Joseph Rowntree Foundation, York, UK, 2012.

[33] V. Schmidt, A. Luccioni, S.K. Mukkavilli, N. Balasooriya, K. Sankaran, J. Chayes, Y. Bengio, Visualizing the consequences of climate change using cycle-consistent adversarial networks, ArXiv Prepr. ArXiv190503709 (2019).

[34] E. Roston, P. Murray, The best way to slow global warming? You decide in this climate simulator, Bloom. Green. (2020) https://www.bloomberg.com/graphics/2020-global-warming-simulator/ (Accessed 4 August 2020).

[35] Jones AP, Johnston E, Cheung L, Zahar Y, Kapmeier F, Bhandari B, Sterman JD, Rooney-Varga JN, Reed C. 2019. Facilitator Guide to the En-ROADS Climate Workshop. Climate Interactive and MIT Sloan Sustainability Initiative: Cambridge, MA. https://www.climateinteractive.org/wp-content/uploads/2018/04/World-Climate-Facilitator-Guide-v34.pdf (Accessed 24 January 2020).