Beyond rationality in engineering design for sustainability

Article *in* Nature Sustainability · May 2018

DOI: 10.1038/s41893-018-0054-8

Leidy Klotz
University of Virginia

Elke U Weber
Princeton University

Eric J Johnson
Columbia University

Tripp Shealy
Virginia Tech (Virginia Polytechnic Institute and State University)

nature sustainability

REVIEW ARTICLE
https://doi.org/10.1038/s41893-018-0054-8

Beyond rationality in engineering design for sustainability

Leidy Klotz[1]*, Elke Weber[2], Eric Johnson[3], Tripp Shealy[4], Morela Hernandez[1] and Bethany Gordon[1]

If you try to ensure long-term human well-being within the limits of the natural world, then you design for sustainability. This Review organizes research describing how cognitive biases can hinder and help engineering design for sustainability. For example, designers might overlook climate change implications because of nearsighted thinking, a bias which can be overcome by vividly imagining the future. For researchers, this Review illuminates needs at the convergence of decision science and engineering design. For designers (that is, all of us), the Review promises new routes to sustainability, through changes to decision environments and through insights into our own design thinking.

Engineering, broadly defined, is the creative application of science. Design means attempting to change existing situations into preferred ones. And these preferred situations are more sustainable if they improve the well-being of current generations without compromising the well-being of future generations and the environments on which we all rely. So, regardless of your job title or college major, you probably practice engineering design for sustainability.

In your personal life, you may do so by insulating your attic for more efficient use of heating energy, or by creating a diet with less meat to reduce your ecological footprint. In your professional and public lives, designing for sustainability might mean even higher-impact changes to policies, education and business practices, or the human-built environment. This Review uses examples from the built environment because these examples are relatable and transferrable and because design of the built environment is central to the Sustainable Development Goals[1] and also influences more than half of global climate-changing emissions[2].

Regardless of the application, effective design for sustainability requires communication across stakeholder groups while considering new environmental and social goals over long-term time horizons. Consider, for example, a design goal to create more sustainable mobility within a city. Not only do designers need to account for the movement of people, they also must consider fuel use and pollution from various types of transportation, as well as quality of life implications for residents who will use the design, and for those who will not. Designing for interdependencies such as these requires input from builders, architects and engineers of all types, and also from groups ranging from planners who understand demographic trends, to ecologists who understand land-use impacts, to the residents and users who understand perceived and actual needs. Integrated design leads to multifunctional responses, such as automated toll systems, which reduce delays for drivers and also reduce emissions, including those associated with increased infant mortality rates in nearby neighborhoods[3].

Further challenging design for sustainability is the reality that, as designers, we are also humans and therefore do not always think and act 'rationally', meaning in dispassionate, consistent and purely self-interested ways. Here we use rationality (and irrationality) to imply consistency (or lack thereof) with classical decision theory, which makes the assumptions of infinite mental computational ability, and utility that is self-centred, reference independent and consistently discounted over time.

Formal models of engineering design are based on assumptions of perfect rationality[4]. Actual approaches used in engineering design, and more broadly across professional disciplines[5,6], include varying consideration of how designers[7,8] and users[9] actually think and behave. We hope our Review findings can enhance both formal models and existing approaches to design. Therefore, we have organized this Review using six common and stylized design stages: identifying stakeholder needs, defining a problem, creating design concepts, selecting a concept, developing a detailed design, and implementing and evaluating the design (Fig. 1).

Much of the evidence presented in this Review extends from a series of Nobel Prize-winning advances in psychology, economics and related fields, which describe ways that classical assumptions of perfect rationality[10] are at best incomplete, and at worst flawed. 'Bounded' rationality recognizes that perfectly rational decisions are not typically feasible in practice because the complexity of actual decisions exceeds the brainpower and time that humans are able to devote to these decisions[11,12]. Consider, for example, an engineer who frames (bounds) a design goal in terms of the cooling capacity of an air conditioning system, as opposed to thermal comfort for occupants. The system uses more energy than necessary, not because the engineer did not care about the energy use and associated climate-changing emissions, but because the engineer's framing of the goal ignored thermal comfort provided through other means such as window breezes and breathable furniture.

Given that rationality is bounded by available brainpower and time, a rapidly growing body of research is filling in details about how humans cope with their capacity limitations, documenting simpler decision processing and showing that people are not simply calculating machines (for example, refs [13–15]). Our thoughts and actions extend beyond the narrowly defined notion of perfect rationality and are shaped by factors such as contextual cues, social norms, decision anchors, and selectively recalled feelings and experiences.

These systematic patterns of deviation from classical notions of rationality are called 'cognitive biases', and influence what we view as desirable and possible. If overlooked, these processes can

[1]University of Virginia, Charlottesville, VA, USA. [2]Princeton University, Princeton, NJ, USA. [3]Columbia University, New York, NY, USA. [4]Virginia Tech, Blacksburg, VA, USA. *e-mail: lk6me@virginia.edu

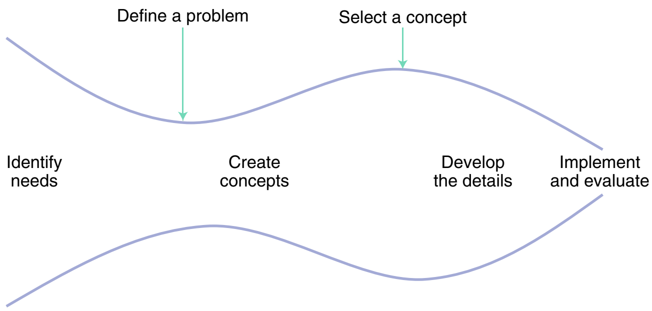

Fig. 1 | Common stages in engineering design. Engineering design progresses from left to right. The potential solution space is the area between the curved lines. Early decisions shape later possibilities.

be obstacles to core goals of sustainability. Evidence suggests, for example, that: insufficient perspective-taking limits our ability to prioritize human well-being over purely financial measures[16]; near-sighted thinking delays action on climate change[17]; and existing social norms and status quo bias make it difficult for us to see ways to decouple environmental damage from economic growth[18].

When we are aware of them, our cognitive processes can be opportunities to advance sustainability goals, in particular through 'choice architecture', defined as intentional changes to decision environments to account for cognitive biases (for example, refs [19,20]). Choice architecture is already part of daily life in everything from food menus that disclose calorie information to retirement plans that automatically enrol employees and allow them to opt out, rather than the other way around. Similar choice architecture opportunities in engineering design for sustainability are highlighted throughout this Review.

Obstacles and opportunities

Cities, nations and organizations, including the United Nations[21], the World Bank[22] and the Organization for Economic Co-operation and Development[23], are recognizing bounded rationality and cognitive biases and applying choice architecture to aid end-use decision-making. However, for design, biases and choice architecture interventions remain underexplored and disconnected across fields of practice and academic disciplines. We cannot assume end-use insights translate perfectly to engineering design, in part because of the complex nature of design and also because individuals act differently when making decisions for others rather than themselves[24,25].

While not easy, considering cognitive biases and applying choice architecture in design for sustainability can have large sustainability impacts because design decisions shape the behaviour of a large number of end-user decisions over extended periods of time. For instance, choice architecture that helps commuters choose more sustainable mass transit is only possible if designers have created the mass transit in the first place.

In the following sections, we organize and describe research showing how cognitive biases can present both obstacles and opportunities in engineering design for sustainability. High-potential research needs are also discussed within each common stage of design. Findings are summarized in Table 1 and methods are detailed in the Supplementary Information.

Identifying needs

An initial best practice step in design is to identify the needs of various stakeholders. Stakeholders include not only people who will directly and immediately use the design, but also non-users who may nevertheless face the consequences of the design now and in the future, including in indirect ways.

Stereotypes. Stereotypes can be tacit or intentional and can lead to damaging overgeneralizations because they assume characteristics based on unfounded assumptions[26]. Because designers cannot possibly identify all needs of every stakeholder, they often generalize and, therefore, are susceptible to using stereotypes. Even designers who deliberately identify user needs are prone to false assumptions that all stakeholders have similar goals and that therefore projection from a single user is legitimate.

Research indicates that gender[27] and occupational[28] stereotypes contribute to the limited diversity among professional engineering designers. Underrepresentation of groups such as women, racial and ethnic minorities, and those with low socioeconomic status is especially harmful for sustainability goals because it restricts the diversity of thought needed to design for sustainability in complex adaptive systems such as the built environment[29]. For example, a designer who grew up in a low-income community that was divided by a new highway will bring a different perspective to sustainable transit than a designer who lived elsewhere but used the new highway to get to work more quickly.

Undervalued perspective-taking. A cognitive barrier to design for sustainability in the built environment that is especially relevant to identifying stakeholder needs is our tendency to assume we know what others think and to undervalue perspective-taking. In psychology, perspective-taking (or allocentrism) entails viewing a situation from another's point of view[30]. It can enable designers to account for diverse users who have multiple and different needs from each other and from the designers. Perspective-taking also helps maintain focus on human well-being as opposed to purely financial measures. Unfortunately, research suggests engineering students can be less adept than students in other disciplines at considering users' perspectives[31].

Too much emotional empathy. Beyond cognition, emotional empathy emphasizes the affective process that enables perspective-taking[32]. A version of this empathy has been described as the first step in 'design thinking', a process increasingly used to explain and guide design for sustainability[6,9,33]. As conceived in design thinking, emotional empathy enables perspective-taking and cognitive empathy because it prompts a conscious drive to appreciate and understand stakeholder needs.

Too much emotional empathy can, like undervalued perspective-taking, also impede design for sustainability. Too much emotional empathy causes designers to focus on users they know better to the detriment of those that are more distant[34]. It can also mislead designers through user perspectives that discount the needs of future others, underestimate possible negative future impacts[35] or perceive needs that are not in their own best interest.

Stakeholder engagement. One potential remedy to undervalued perspective-taking and stereotyping is intentional solicitation of user needs in the design process, which could lead designers to create a greater number of original design responses, perhaps because a wider range of user needs are being recognized[36]. Stakeholder engagement encompasses various approaches (for example, interviews, workshops, surveys) to identify the social and environmental issues that matter most to users to improve design decision-making[37]. Research confirms the value of stakeholder engagement to align sustainable building design with stakeholder priorities[38] and also to gather the community input needed to develop urban spaces that support social connections[39].

As designers attempting to identify stakeholder needs, we may be challenged by inaccessible stakeholders (perhaps because they are not born yet) and also by stakeholders who are susceptible to the same cognitive biases as designers. They may not know what their needs are or may inaccurately predict their needs, or

Table 1 | Cognitive biases as obstacles and opportunities in engineering design for sustainability

Obstacles	Opportunities	Research needs
Identifying needs		
Stereotypes		
Undervalued perspective-taking		
Too much emotional empathy		
	Stakeholder engagement	
		Cognitive empathy
		Overcoming stereotypes
Defining a problem		
Social norms		
	Defaults	
	Framing	
Lack of agency		
	Visioning and scenario generation	
	Serious games	
		Cognitive dissonance and self-perception
		Emotional associations and spillover effects
Creating concepts		
Premature evaluation and selection		
Fixation		
Default design		
	Anchoring	
	Analogies	
		Salience, stories and patterns
Selecting a concept		
The planning fallacy		
Risk aversion		
	Reference class forecasting	
		Perceptions of risk
		Future discounting
Developing the details		
Escalating commitment		
Heuristics in design software		
		Identifying root causes of heuristics
		Effects of decision-making systems
Implementing and evaluating		
		Designers' cognitive processes

even have the wrong needs as seen by themselves in the future. For instance, mass transit riders cannot be expected to understand the costs and benefits of every alternative type of transportation; a rider who says they want an underground subway system because they enjoyed riding one in another city probably is not prepared to weigh the environmental and social impacts of a subway system versus a potentially less disruptive approach, such as aboveground bus rapid transit. Stakeholder perspective is essential, but should complement, rather than override, designers' training and experience.

Cognitive empathy. Despite the popular discussion about the need for empathy and perspective-taking to identify user needs in design for sustainability, research in this area remains a mostly untapped opportunity. In particular, it would be helpful to know more about the functions and effects of emotional and cognitive empathy in design for sustainability, especially given the apparent contradiction between calls for designers to strive for empathy and widespread evidence that emotional empathy can distort decision-making in ways that would be especially harmful in design for sustainability[34]. In particular, it is more difficult to feel emotional empathy for out-group members, such as future generations or people in far-away areas who will be negatively impacted by climate change[40]. Existing models of how empathy is contextualized in design[41–43] are possible starting points for exploring the role of emotional empathy in design for sustainability.

Overcoming stereotypes. While some generalization is practical, damaging stereotypes contribute to misunderstanding of actual user needs and to underrepresentation of women and racial and ethnic minorities in design professions. Research is also needed to advance understanding of ways to overcome stereotypes en route to more diverse design teams and the wider-ranging and thus potentially more sustainable design options that will result[29].

Defining a problem

As designers, we apply what we have learned about stakeholder needs to define the design problem. How the problem is defined can limit the possible sustainability of future design solutions. For instance, 'the highway doesn't have enough lanes' is a narrow problem definition likely to produce design responses that increase individual automobile use. Defining the same problem more broadly as 'it takes too long to travel to work' may inspire a broader range of design possibilities, some of which may be more sustainable, such as public transportation, which reduces fuel consumption and emissions; telecommuting, which saves fuel, emissions and time; and staggered work schedules, which eliminates the need for any new infrastructure.

Social norms. When defining problems, designers should consider social norms, that is, rules of behaviour that are either prevalent or considered acceptable in a given social environment[44]. Social norms may limit innovation in some cases. In the built environment, existing social norms about weatherization[45] and heating and cooling systems may well inhibit diffusion of residential energy efficiency design options[46]. Similarly, existing diffusion of energy efficient designs in commercial buildings is probably based less on intentional consideration and more on status quo routines[47,48]. Social emulation can even help explain diffusion of city-level sustainable building policies[49].

Defaults. The power of social norms can also be used by designers to encourage more sustainable choices[50]. For example, defaults are the choices that get made if no action is taken[51]. Green electricity selection increases almost tenfold when it (rather than brown electricity) is made the automatic default option for utility customers, who still have the option to easily select a conventional electricity mix[52]. One of the reasons defaults have this strong effect on choice is that people think of the default option as an implicit recommendation, that is, as a social norm of sorts.

Framing. Another useful intervention is framing, which intentionally describes a choice option in different ways; for example, a carbon user fee labelled as a carbon tax or carbon offset[53], or as a loss versus as a gain relative to a different reference point, to take advantage of loss aversion[14]. Such variants in framing can also change preference. Experiments on framing effects in the Envision infrastructure sustainability rating system find that the level of sustainability performance sought is significantly higher when designers are given points and lose them for not maintaining high goals for sustainability as opposed to when designers start with no points and gain them for more sustainable practices. Simply posing this choice as a loss rather than a gain led to a 33% increase in intended sustainability achievement[54]. Similar experimental research on framing effects shows that modifying the default choices in the Envision rating system leads to more ambitious (43% in this case) goals for sustainability[55].

Lack of agency. Another source of decision bias during problem definition is lack of perceived agency, meaning that designers feel they cannot make a difference. The large-scale, long-term and interdependent nature of sustainability challenges separates designers from seeing the effects of their work.

Visioning and scenario generation. Visioning and scenario generation are promising approaches to overcome the barrier to more sustainable futures by creating plausible descriptions of what could happen[56]. For example, visioning and scenario generation could occur through a city-wide activity to imagine the region in 50 years, considering a range of possible futures and design alternatives. Not only do these approaches generate plans, they also give designers agency by showing how seemingly small design responses can scale up and combine with other responses to meet big sustainability challenges[57].

Serious games. One way designers can generate scenarios and visions is through serious games, which range from simple quizzes to virtual reality simulations. In general, serious games model likely future outcomes from current choices and actions and therefore show designers how they can shape future worlds, which has been shown to provide agency to designers working at scales that are large (for example, planning for climate change adaptation[58,59]) and small (for example, designing individual residential solar energy systems[60]).

Cognitive dissonance and self-perception. Future research is needed to better understand designers' desire to reduce cognitive dissonance[61] and enhance self-perception[62]. In other words, we do not just act in ways to maximize utility, we act in ways to make ourselves feel better[63], in part by confirming membership in social groups that matter to us (families, tribes, companies, countries) by acting in group-specific and group-approved ways. Such biases may partially explain findings that when organizations view sustainability as part of their overall mission, they are more likely to adopt built environment sustainability goals, even when financial incentives are lacking[64,65].

Emotional associations and spillover effects. It would be especially beneficial to design for sustainability to learn how behaviours to make ourselves feel better create positive spillover, which is when one action leads to a series of similar choices, such as when people who have been convinced to recycle become more likely to car share[66]. Researchers could have broad impact by identifying single design interventions that create positive spillover and therefore lead to a series of pro-sustainability choices.

Similarly, research is needed to understand how designers' behaviours are influenced by emotional associations, including our sense of meaningful impact and desire to leave a positive legacy. For example, explicit communication of mission and purpose could prompt designers to make more sustainable choices because doing so allows them to symbolically live on through their design choices[67]. One reason such research is so important to design for sustainability is because emotional associations often lead to negative spillover, where actions on one environmental issue make other actions less likely[68]. For example, designers who advocate for walkable neighbourhoods because they just watched a documentary film on the benefits might be less likely to consider complementary design responses, rationalizing that 'I've already done my part for sustainability'. Research could characterize and therefore help avoid negative spillover in engineering design for sustainability.

Creating concepts

With the problem defined, we can begin designing various conceptual responses, which requires that we weigh numerous considerations and alternatives. Many of the obstacles and opportunities in this section relate to preference construction theory, which refers to the numerous ways in which we construct our preferences in the process of making decisions, rather than just retrieving stored choices[69].

Premature evaluation and selection. Preference construction is harmful to design for sustainability when it leads to premature evaluation and selection of specific design concepts at the cost of wider consideration of more sustainable alternatives. This occurs if designers incorrectly apply the insights from previous projects to the current one. For example, an engineer that previously specified solar panels to produce clean energy might be prone to premature evaluation and selection of similar panels for a new design even though a geothermal system would be more effective.

Fixation. In design, research referring to many of the cognitive biases related to premature evaluation and selection of alternatives (for example, recency effect, anchoring bias[70]) is termed fixation; that is, the blind adherence to a set of ideas or concepts, often by giving excessive weight to prior experience or to early ideas[71]. Fixation can limit the breadth of sustainable design options that are generated by faculty members and expert designers[72–74]. Pictures meant to inspire designers can unintentionally introduce fixation on ideas related to the examples presented in the pictures[75].

Default design. Fixation and premature selection contribute to the default design bias, which is a tendency towards previously used designs, and limits innovation for sustainability in the building industry[76]. Meta-analysis of design research shows that providing designers with a single, uncommon example of a related design alternative consistently helps them overcome fixation, especially when such an example is provided early in the process[77].

Anchoring. In addition to providing uncommon and early examples, other forms of choice architecture can inspire more sustainable conceptual designs. For instance, numerical anchoring can lead green building designers to set higher energy performance goals than they would have in the absence of this anchor[78]. Respondents exposed to a '90%' anchor, and respondents exposed to no anchor at all, set higher energy performance goals than respondents exposed to a '30%' anchor. Similarly, an anchor in the form of a high-performing role-model project increases sustainability performance goals among infrastructure designers using the Envision rating system, in theory because the role model provides early information that motivates designers to achieve similar performance[79]. Other research introduces early information on one attribute of housing choice: commute distance. The simple act of asking participants to first consider effects of commute distance led them to select living arrangements with lower combined home and transportation energy use[80].

Analogies. Research shows how analogies can also be used to help overcome fixation by facilitating the transfer of knowledge from one design situation to another[81]. In one study, architectural design concept generation was improved through visual analogy via intentionally selected pictures, photographs and drawings not only from architecture, but also from art, engineering and nature[82]. In a similar way, requiring designers to create collages of sensory descriptor terms and images helped them evaluate the sustainability of various alternatives, which is a particularly challenging task in design for sustainability because sustainability features, such as decreased energy use or recyclability, are often invisible[83].

Salience, stories and patterns. The use of analogy to overcome fixation shows the promise of additional research to understand ways designers seek and use salience, stories and patterns in design for sustainability. Such research would complement work examining how such techniques can be used to translate science and technology knowledge to policy action for sustainable development[84].

Selecting a concept

At some point during design, we hone in on a single design response among many design concepts. This marks the transition from conceptual to detailed design.

The planning fallacy. During this transition, designers are especially susceptible to the planning fallacy, in which individuals underestimate the resources needed to implement a project[85]. This is a problem because when projects require more resources than expected, then options discarded earlier in design may have actually been more sustainable. In some cases, planning errors result from deliberate deception by self-interested designers with financial incentive to see a specific project move forward[86]. However, the planning fallacy can also stem from designers' self-deluded thinking that the selected project is best[87]. Professional designers typically receive a substantial portion of their fee when a project is implemented. Designers therefore have an incentive to make whatever project is selected seem as favourable as possible. While the planning fallacy research focuses on self-delusion about cost and schedule, this same delusion probably extends to overly optimistic projections about sustainability performance.

Risk aversion. The planning fallacy can result from overly optimistic risk-seeking projections, which occur when designers extrapolate their predictions from limited specific circumstances and from personal experiences[88]. Alternatively, designers reactions to new approaches may be overly cautious and risk averse, which can constrain innovation for sustainability in civil infrastructure[89], including in urban water systems[90].

Reference class forecasting. One approach to prevent irrationally optimistic or cautious projections is reference class forecasting, in which designers make planning predictions based on actual performance of similar projects[91]. If the proposed response were a bus rapid transit system, for instance, then designers undertaking reference class forecasting would compare their projections with actual data from already-implemented bus rapid transit projects in similar cities.

Perceptions of risk. Just as scholars have investigated the role of risk perceptions in policy reactions to climate change[92], research is needed to understand how designers perceive climate change risks. For example, how does (and how should) a structural engineer weigh the risks of bridge collapse against the risks of the materials used in its design contributing to climate change? Such research would advance understanding of the interactions between human and environmental risks and challenges, which are a core need for sustainability.

Future discounting. Likewise, research is needed about how we discount the future and lack foresight. Sustainability choices require us to weigh costs and benefits that are distributed over often long periods of time[93]. Discounting, a dominant approach to predicting and comparing future financial outcomes, is a central question for sustainability, for example in the valuation of ecosystem services[94], in cooperative efforts to mitigate climate change[95] and in risk forecasts for infrastructure design[96]. Better understanding how designers do and should discount the future would inform long-term responses to sustainability challenges.

Developing the details

During the detailed design stage, we refine our conceptual designs, perhaps with the help of virtual or physical models. At this stage, typically only one main design concept is carried forward and the focus becomes figuring out the details so that the design can be implemented, evaluated and refined.

Escalating commitment. It takes resources and time to go 'backwards' and consider other design concepts after beginning detailed design. Still, doing so is far better than revisiting other design concepts after the design has been built. During detailed design, designers have already devoted substantial effort to creating concepts and

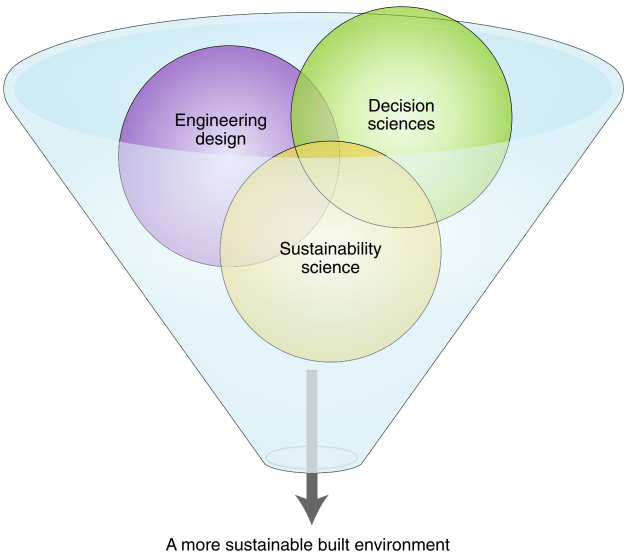

Fig. 2 | Convergent research is applied and interdisciplinary. Convergent research is driven by a social issue and therefore requires deep and persistent integration across disciplines. The approaches and challenges discussed in this Review are likely relevant to convergent research for other sustainability issues.

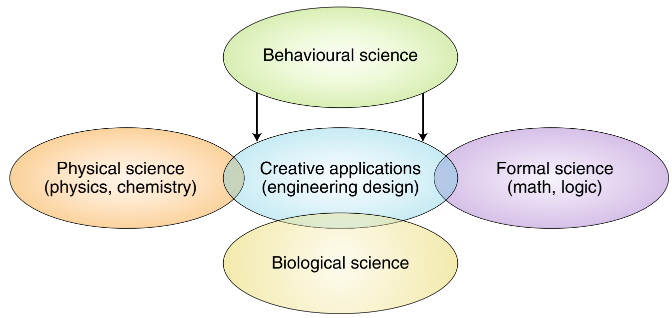

Fig. 3 | Present-day sustainability goals require closer links between behavioural science and engineering. Engineering design has a long history of creatively applying physical science (for example, physics, chemistry) and formal science (for example, math, logic). More recently, creative application of biological science has led to innovations from artificial hearts to bullet trains.

selecting one and are therefore increasingly susceptible to biases related to escalating commitment of money and time, even when the course of action is proving ineffective. For instance, on two transportation infrastructure projects in the Netherlands, escalating commitment led designers to ignore less expensive alternatives in favour of costlier ones[97]. A similar thinking process also inhibits innovation at a much smaller scale when the act of building physical models of conceptual designs leads to fixation, in part because of escalating commitment[98].

Heuristics in design software. Designers can receive support during detailed design from software that allows for rapid simulation of multiple alternatives. For example, transportation modelling software helps designers simulate and calculate the environmental impacts of various traffic patterns during construction and use. For processing efficiency, but not necessarily to encourage the most sustainable choices, software relies on heuristics, some of which are modelled after similar decision-making shortcuts used by humans. A review of computational optimization in sustainable building design finds that common heuristics embedded in design software included both direct search (that is, comparing new solutions with the best found so far) and evolutionary heuristics (that is, maintaining a population of solutions and eliminating the poorest in each iteration)[99].

Identifying root causes of heuristics. Future research should examine how decisions change when we use rules of thumb to save time and thought[100]. Heuristic thinking is adaptive, but can also be misleading, for example, when it relies on inappropriate information. One example is when our climate change beliefs are influenced by less-relevant but available local weather information in place of more diagnostic but less-accessible information such as global climate change patterns[101]. Research identifying heuristics common to design[102] provides initial steps towards identifying the root causes of, and ways to leverage, heuristics with direct sustainability implications. For example, whereas direct search and evolutionary heuristics are relatively neutral on sustainability outcomes, choice architecture approaches could introduce and encourage heuristics in software that lead designers to set more ambitious sustainability goals.

Effects of decision-making systems. Similarly, the effects of decision-making systems and shortcuts are an opportunity for future research, with possible implementation in building design software. Sustainable design requires consideration of varied, broad and longer-term design goals, which means more details are considered, which in turn increases the likelihood of bias because available information exceeds our ability to process it[103]. Numerous decision-making systems aim to address these cognitive limits to working memory. Yet, with the exception of preliminary research on choosing by advantages[104,105], none have been studied for their ability to facilitate design for sustainability.

Implementing and evaluating

Eventually, designs are introduced into the world and their performance can be evaluated. Evaluation informs and improves future design iterations.

Designers' cognitive processes. Much research examines user thought and behaviour during implementation and evaluation. The field of environmental psychology, for example, studies the interplay between humans and our physical environments[106]. Understanding occupant behaviour is vital for more sustainable buildings (for example, refs [107,108]). This understanding can help close the gap between design predictions and actual performance of heating, cooling and lighting systems. Despite the fruitful examples of research from user decision-making, this Review did not uncover any research examining cognitive biases among those making design decisions during evaluation.

Given the central role of evaluation in the iterative process of design for sustainability, research on design decisions during this stage holds great promise. Many of the research needs described in the other design stages also apply to evaluation. In addition, it would be especially useful to learn why design decisions during evaluation are underexplored. For example, do design decision-makers feel agency during evaluation? How might agency during evaluation be enhanced?

New directions

Throughout this Review, we have identified and described high-potential research needs, which are listed in the right column of Table 1. All of these needs require both an applied focus (that is, sustainability in the built environment) as well as deep integration across multiple disciplines (that is, decision and sustainability sciences, engineering design; Fig. 2). This applied and interdisciplinary, or 'convergent', approach to research is both widely needed and underdeveloped[109].

One challenge in convergent research is the need for study beyond the laboratory. However, through the stakeholder engagement needed in design for sustainability, designers and researchers have an opportunity to work together to run natural experiments in 'real-world' contexts. Convergent research on decision framing, for example, could be done by asking stakeholders about needs framed either as abstract concepts (for example, mobility) or in terms of what the abstract concepts provide (for example, connections to family and friends). Designers would learn more about stakeholder preferences and researchers would learn whether and how framing shapes these preferences.

Convergent research needs must also be pursued in new cultural contexts. The research uncovered by this Review (including the authors') comes exclusively from the developed world. Certainly, to respond to the global challenge of sustainability, future research must consider developing-world scenarios and cultures. In addition, research in new cultural contexts provides an opportunity to manipulate variables in ways that are otherwise impossible. The degree to which people are loss averse, for example, varies across cultures[110]. Studying design for sustainability in cultures where loss aversion is less influential could therefore lead to insights about how to overcome it in cultures where it is.

Among designers, more complete understanding of our own perceptions and behaviours offers new pathways to create and test interventions for the fundamental shifts in goals and actions needed for sustainability. Many of the opportunities discussed in this Review are subtle changes in choice architecture (for example, adding defaults in the Envision rating system; introducing analogies intended to break design fixation; requiring reference class forecasting to avoid the planning fallacy.) Choice architecture should become part of designers' toolkits not only because it works, but also because it is relatively low-cost compared with physical interventions and with regulations based on self-interested penalties and incentives[111,112].

Perhaps most importantly, this Review shows how considering just one area of behavioural science in design for sustainability promises transformative advances in theory and practice — by enabling integrated consideration not only of how we design and build but also of how we determine our needs and wants. Sustainability improvements at the scale we need require integrated consideration of the social, technological and environmental systems (Fig. 3)[113,114]. A sustainable future therefore depends on our collective ability to apply behavioural sciences, in addition to physical, formal and biological sciences, to inform and inspire design for sustainability.

Received: 2 May 2017; Accepted: 29 March 2018;
Published online: 15 May 2018

References

1. *Transforming our World: The 2030 Agenda for Sustainable Development* A/RES/70/1 (United Nations General Assembly, 2015).
2. *International Energy Outlook 2016* (United States Energy Information Administration, 2016).
3. Currie, J. & Walker, R. Traffic congestion and infant health: evidence from E-ZPass. *Am. Econ. J. Appl. Econ.* **3**, 65–90 (2011).
4. Hazelrigg, G. A. A framework for decision-based engineering design. *J. Mech. Des.* **120**, 653–658 (1998).
5. Norman, D. *The Design of Everyday Things: Revised and Expanded Edition* (Basic Books, New York, NY, 2013).
6. Rowe, P. G. *Design Thinking* (MIT Press, Cambridge, MA, 1991).
7. Cross, N. Designerly ways of knowing. *Des. Stud.* **3**, 221–227 (1982).
8. Lawson, B. *How Designers Think* (Architectural Press, Oxford, 2006).
9. Brown, T. Design thinking. *Harv. Bus. Rev.* **86**, 84–95 (2008).
10. Friedman, M. *Essays in Positive Economics* (Univ. Chicago Press, Chicago, IL, 1953).
11. Simon, H. A. *Models of Man: Social and Rational* (Wiley, London, 1957).
12. Gigerenzer, G. in *Contemporary Debates in Cognitive Science* (ed. Stainton, R.) 115–133 (Blackwell, Oxford, 2006).
13. Tversky, A. & Kahneman, D. The framing of decisions and the psychology of choice. *Science* **211**, 453–458 (1981).
14. Kahneman, D. & Tversky, A. Prospect theory: an analysis of decision under risk. *Econometrica* **47**, 263–292 (1979).
15. Simon, H. A. *Models of Bounded Rationality: Empirically Grounded Economic Reason* (MIT Press, Cambridge, MA, 1982).
16. *Consuming Differently, Consuming Sustainably: Behavioral Insights for Policymaking* (United Nations Environment Programme, 2017).
17. Weber, E. U. Breaking cognitive barriers to a sustainable future. *Nat. Hum. Behav.* **1**, 0013 (2017).
18. *Decoupling Natural Resource Use and Environmental Impacts from Economic Growth: A Report of the Working Group on Decoupling to the International Resource Panel* (United Nations Environment Programme, 2011).
19. Johnson, E. J. et al. Beyond nudges: tools of a choice architecture. *Mark. Lett.* **23**, 487–504 (2012).
20. Thaler, R. & Sunstein, C. *Nudge: Improving Decisions about Health, Wealth, and Happiness* (Yale Univ. Press, New Haven, CT, 2008).
21. *Behavioural Insights at the United Nations: Achieving Agenda 2030* (United Nations Development Programme, 2016).
22. *World Development Report 2015: Mind, Society, and Behavior* (World Bank, 2015).
23. *Tackling Environmental Problems with the Help of Behavioural Insights* (Organisation for Economic Co-operation and Development, 2017).
24. Eisenhardt, K. M. Agency theory: an assessment and review. *Acad. Manag. Rev.* **14**, 57–74 (1989).
25. Hsee, C. K. & Weber, E. U. A fundamental prediction error: self–others discrepancies in risk preference. *J. Exp. Psychol. Gen.* **126**, 45–53 (1997).
26. Greenwald, A. G., McGhee, D. E. & Schwartz, J. L. Measuring individual differences in implicit cognition: the implicit association test. *J. Pers. Soc. Psychol.* **74**, 1464–1480 (1998).
27. Bell, A. E., Spencer, S. J., Iserman, E. & Logel, C. E. Stereotype threat and women's performance in engineering. *J. Eng. Educ.* **92**, 307–312 (2003).
28. Loosemore, M. & Tan, C. C. Occupational stereotypes in the construction industry. *Constr. Manag. Econ.* **18**, 559–566 (2000).
29. Page, S. E. *Diversity and Complexity* (Princeton Univ. Press, Princeton, NJ, 2010).
30. Batson, C. D., Early, S. & Salvarani, G. Perspective taking: imagining how another feels versus imaging how you would feel. *Pers. Soc. Psychol. Bull.* **23**, 751–758 (1997).
31. Rasoal, C., Danielsson, H. & Jungert, T. Empathy among students in engineering programmes. *Eur. J. Eng. Educ.* **37**, 427–435 (2012).
32. Davis, M. H. *Empathy: A Social Psychological Approach* (Westview Press, Boulder, CO, 1996).
33. Kouprie, M. & Visser, F. S. A framework for empathy in design: stepping into and out of the user's life. *J. Eng. Des.* **20**, 437–448 (2009).
This framework distils the psychology of empathy into a stepwise process tailored to engineering design.
34. Bloom, P. *Against Empathy: The Case for Rational Compassion* (Random House, New York, NY, 2016).
35. Wade-Benzoni, K. A. A golden rule over time: reciprocity in intergenerational allocation decisions. *Acad. Manag. J.* **45**, 1011–1028 (2002).
36. Johnson, D. G. et al. An experimental investigation of the effectiveness of empathic experience design for innovative concept generation. *J. Mech. Des.* **136**, 051009 (2014).
37. Pidgeon, N., Demski, C., Butler, C., Parkhill, K. & Spence, A. Creating a national citizen engagement process for energy policy. *Proc. Natl. Acad. Sci. USA* **111**, 13606–13613 (2014).
38. Bal, M., Bryde, D., Fearon, D. & Ochieng, E. Stakeholder engagement: achieving sustainability in the construction sector. *Sustainability* **5**, 695–710 (2013).
39. O'Hara, S. U. Community based urban development: a strategy for improving social sustainability. *Int. J. Soc. Econ.* **26**, 1327–1343 (1999).
40. Markowitz, E. M. & Shariff, A. F. Climate change and moral judgement. *Nat. Clim. Change* **2**, 243–247 (2012).
41. Walther, J., Miller, S. E. & Sochacka, N. W. A model of empathy in engineering as a core skill, practice orientation, and professional way of being. *J. Eng. Educ.* **106**, 123–148 (2017).
42. Strobel, J., Hess, J., Pan, R. & Wachter Morris, C. A. Empathy and care within engineering: qualitative perspectives from engineering faculty and practicing engineers. *Eng. Stud.* **5**, 137–159 (2013).
43. Hess, J. L., Strobel, J. & Pan, R. Voices from the workplace: practitioners' perspectives on the role of empathy and care within engineering. *Eng. Stud.* **8**, 212–242 (2016).
44. Schultz, P. W., Nolan, J. M., Cialdini, R. B., Goldstein, N. J. & Griskevicius, V. The constructive, destructive, and reconstructive power of social norms. *Psychol. Sci.* **18**, 429–434 (2007).

45. Southwell, B. G. & Murphy, J. Weatherization behavior and social context: the influences of factual knowledge and social interaction. *Energy Res. Soc. Sci.* **2**, 59–65 (2014).
46. Noonan, D. S., Hsieh, C. & Matisoff, D. Spatial effects in energy-efficient residential HVAC technology adoption. *Environ. Behav.* **45**, 476–503 (2013).
47. Vermeulen, W. & Hovens, J. Competing explanations for adopting energy innovations for new office buildings. *Energy Policy* **34**, 2719–2735 (2006).
48. Dieperink, C., Brand, I. & Vermeulen, W. Diffusion of energy-saving innovations in industry and the built environment: Dutch studies as inputs for a more integrated analytical framework. *Energy Policy* **32**, 773–784 (2004).
49. Kontokosta, C. Greening the regulatory landscape: the spatial and temporal diffusion of green building policies in US cities. *J. Sustain. Real. Estate* **3**, 68–90 (2011).
50. Nyborg, K. et al. Social norms as solutions. *Science* **354**, 42–43 (2016).
51. Johnson, E. & Goldstein, D. Do defaults save lives? *Science* **302**, 1338–1339 (2003).
52. Ebeling, F. & Lotz, S. Domestic uptake of green energy promoted by opt-out tariffs. *Nat. Clim. Change* **5**, 868–871 (2015).
53. Hardisty, D. J., Johnson, E. J. & Weber, E. U. A dirty word or a dirty world? Attribute framing, political affiliation, and query theory. *Psychol. Sci.* **21**, 86–92 (2010).
54. Shealy, T., Klotz, L., Weber, E. U., Johnson, E. J. & Bell, R. G. Using framing effects to inform more sustainable infrastructure design decisions. *J. Constr. Eng. Manag.* **142**, 04016037 (2016).
Restructuring a rating system for sustainable infrastructure to invoke the endowment effect can bolster engineers' resolve for achieving sustainable designs.
55. Shealy, T. & Klotz, L. Well-endowed rating systems: how modified defaults can lead to more sustainable performance. *J. Constr. Eng. Manag.* **141**, 04015031 (2015).
56. Wiek, A. & Iwaniec, D. Quality criteria for visions and visioning in sustainability science. *Sustain. Sci.* **9**, 497–512 (2014).
57. Kishita, Y., Hara, K., Uwasu, M. & Umeda, Y. Research needs and challenges faced in supporting scenario design in sustainability science: a literature review. *Sustain. Sci.* **11**, 331–347 (2016).
This review collates an array of sustainability scenarios and extracts common features for reference in designing future scenarios.
58. Rumore, D., Schenk, T. & Susskind, L. Role-play simulations for climate change adaptation education and engagement. *Nat. Clim. Change* **6**, 745–750 (2016).
59. Wu, J. S. & Lee, J. J. Climate change games as tools for education and engagement. *Nat. Clim. Change* **5**, 413–418 (2015).
60. Rai, V. & Beck, A. L. Play and learn: serious games in breaking informational barriers in residential solar energy adoption in the United States. *Energy Res. Soc. Sci.* **27**, 70–77 (2017).
The application of serious games can surmount misgivings about the cost of residential solar energy.
61. Aronson, E. The theory of cognitive dissonance: a current perspective. *Adv. Exp. Soc. Psychol.* **4**, 1–34 (1969).
62. Bem, D. J. Self-perception theory. *Adv. Exp. Soc. Psychol.* **6**, 1–62 (1972).
63. Weber, E. U. Climate change demands behavioral change: what are the challenges? *Soc. Res. Int. Q.* **82**, 561–580 (2015).
64. Pellegrini-Masini, G. & Leishman, C. The role of corporate reputation and employees' values in the uptake of energy efficiency in office buildings. *Energy Policy* **39**, 5409–5419 (2011).
65. Corbett, C. J. & Muthulingam, S. Adoption of voluntary environmental standards: the role of signaling and intrinsic benefits in the diffusion of the LEED green building standards. Preprint at http://dx.doi.org/10.2139/ssrn.1009294 (2007).
66. Evans, L. et al. Self-interest and pro-environmental behaviour. *Nat. Clim. Change* **3**, 122–125 (2013).
67. Wade-Benzoni, K. A., Tost, L. P., Hernandez, M. & Larrick, R. P. It's only a matter of time: death, legacies, and intergenerational decisions. *Psychol. Sci.* **23**, 704–709 (2012).
68. Truelove, H. B., Carrico, A. R., Weber, E. U., Raimi, K. T. & Vandenbergh, M. P. Positive and negative spillover of pro-environmental behavior: an integrative review and theoretical framework. *Glob. Environ. Change* **29**, 127–138 (2014).
69. Slovic, P. The construction of preference. *Am. Psychol.* **50**, 364–371 (1995).
70. Tversky, A. & Kahneman, D. Judgment under uncertainty: heuristics and biases. *Science* **185**, 1124–1131 (1974).
71. Jansson, D. G. & Smith, S. M. Design fixation. *Des. Stud.* **12**, 3–11 (1991).
72. Linsey, J. S. et al. A study of design fixation, its mitigation and perception in engineering design faculty. *J. Mech. Des.* **132**, 041003 (2010).
73. Viswanathan, V. K. & Linsey, J. S. Design fixation and its mitigation: a study on the role of expertise. *J. Mech. Des.* **135**, 051008 (2013).
74. Viswanathan, V. K. & Linsey, J. S. Physical models and design thinking: a study of functionality, novelty and variety of ideas. *J. Mech. Des.* **134**, 091004 (2012).
75. Chrysikou, E. G. & Weisberg, R. W. Following the wrong footsteps: fixation effects of pictorial examples in a design problem-solving task. *J. Exp. Psychol. Learn. Mem. Cogn.* **31**, 1134–1148 (2005).
76. Beamish, T. D. & Biggart, N. W. The role of social heuristics in project-centred production networks: insights from the commercial construction industry. *Eng. Proj. Organ. J.* **2**, 57–70 (2012).
In the commercial building industry, social heuristics aid communication but limit innovation by solidifying design norms.
77. Sio, U. N., Kotovsky, K. & Cagan, J. Fixation or inspiration? A meta-analytic review of the role of examples on design processes. *Des. Stud.* **39**, 70–99 (2015).
Presenting a single uncommon example in design promotes high-quality, novel ideas and decreases the likelihood of design fixation.
78. Klotz, L., Mack, D., Klapthor, B., Tunstall, C. & Harrison, J. Unintended anchors: building rating systems and energy performance goals for US buildings. *Energy Policy* **38**, 3557–3566 (2010).
79. Harris, N., Shealy, T. & Klotz, L. How exposure to "role model" projects can lead to decisions for more sustainable infrastructure. *Sustainability* **8**, 130–138 (2016).
80. Bhattacharyya, A., Jin, W., Le Floch, C., Chatman, D. G. & Walker, J. L. Nudging people towards more sustainable residential choice decisions: an intervention based on focalism and visualization. In *14th International Conference on Travel Behavior and Research* (IATBR, 2015).
81. Christensen, B. T. & Schunn, C. D. The relationship of analogical distance to analogical function and preinventive structure: the case of engineering design. *Mem. Cogn.* **35**, 29–38 (2007).
82. Casakin, H. P. & Goldschmidt, G. Reasoning by visual analogy in design problem-solving: the role of guidance. *Environ. Plann. B Plann. Des.* **27**, 105–119 (2000).
83. She, J. & MacDonald, E. Priming designers to communicate sustainability. *J. Mech. Des.* **136**, 011001 (2014).
84. Cash, D. W. et al. Knowledge systems for sustainable development. *Proc. Natl. Acad. Sci. USA* **100**, 8086–8091 (2003).
85. Kahneman, D. & Tversky, A. *Intuitive Prediction: Biases and Corrective Procedures* (Decisions and Designs, Eugene, OR, 1977).
86. Flyvbjerg, B., Holm, M. S. & Buhl, S. Underestimating costs in public works projects: error or lie? *J. Am. Plann. Assoc.* **68**, 279–295 (2002).
Budget estimates for public works projects systematically underestimate actual costs.
87. Pickrell, D. H. A desire named streetcar: fantasy and fact in rail transit planning. *J. Am. Plann. Assoc.* **58**, 158–176 (1992).
88. Kahneman, D. & Lovallo, D. Timid choices and bold forecasts: a cognitive perspective on risk taking. *Manag. Sci.* **39**, 17–31 (1993).
89. Cha, E. J. & Ellingwood, B. R. Risk-averse decision-making for civil infrastructure exposed to low-probability, high-consequence events. *Reliab. Eng. Syst. Saf.* **104**, 27–35 (2012).
90. Kiparsky, M. et al. Barriers to innovation in urban wastewater utilities: attitudes of managers in California. *Environ. Manag.* **57**, 1204–1216 (2016).
91. Flyvbjerg, B., Garbuio, M. & Lovallo, D. Delusion and deception in large infrastructure projects: two models for explaining and preventing executive disaster. *Calif. Manag. Rev.* **51**, 170–193 (2009).
92. Kunreuther, H. et al. Risk management andclimate change. *Nat. Clim. Change* **3**, 447–450 (2013).
93. Loewenstein, G. & Elster, J. *Choice over Time* (Russell Sage Foundation, New York, NY, 1992).
94. Costanza, R. et al. The value of the world's ecosystem services and natural capital. *Nature* **387**, 253–260 (1997).
95. Jacquet, J. et al. Intra-and intergenerational discounting in the climate game. *Nat. Clim. Change* **3**, 1025–1028 (2013).
96. Lee, J. Y. & Ellingwood, B. R. Ethical discounting for civil infrastructure decisions extending over multiple generations. *Struct. Saf.* **57**, 43–52 (2015).
97. Cantarelli, C. C., Flyvbjerg, B., van Wee, B. & Molin, E. J. Lock-in and its influence on the project performance of large-scale transportation infrastructure projects: investigating the way in which lock-in can emerge and affect cost overruns. *Environ. Plann. B Plann. Des.* **37**, 792–807 (2010).
98. Viswanathan, V. K. & Linsey, J. S. Role of sunk cost in engineering idea generation: an experimental investigation. *J. Mech. Des.* **135**, 121002 (2013).
Design fixation is linked to feelings of sunk costs due to the time, cost and effort spent creating a model.
99. Evins, R. A review of computational optimisation methods applied to sustainable building design. *Renew. Sustain. Energy Rev.* **22**, 230–245 (2013).

100. Payne, J. W., Bettman, J. R. & Johnson, E. J. *The Adaptive Decision Maker* (Cambridge Univ. Press, Cambridge, 1993).
101. Zaval, L., Keenan, E. A., Johnson, E. J. & Weber, E. U. How warm days increase belief in global warming. *Nat. Clim. Change* **4**, 143–147 (2014).
102. Daly, S. R., Yilmaz, S., Christian, J. L., Seifert, C. M. & Gonzalez, R. Design heuristics in engineering concept generation. *J. Eng. Educ.* **101**, 601–629 (2012).
Over 60 rules of thumb used in engineering design are assembled and described.
103. Baddeley, A. Working memory: theories, models, and controversies. *Annu. Rev. Psychol.* **63**, 1–29 (2012).
104. Arroyo, P., Tommelein, I. D., Ballard, G. & Rumsey, P. Choosing by advantages: a case study for selecting an HVAC system for a net zero energy museum. *Energy Build.* **111**, 26–36 (2016).
105. Arroyo, P., Fuenzalida, C., Albert, A. & Hallowell, M. R. Collaborating in decision making of sustainable building design: an experimental study comparing CBA and WRC methods. *Energy Build.* **128**, 132–142 (2016).
106. Gifford, R. *Environmental Psychology: Principles and Practice*. (Optimal Books, Colville, WA, 2007).
107. Deuble, M. P. & de Dear, R. J. Green occupants for green buildings: the missing link? *Build. Environ.* **56**, 21–27 (2012).
108. Hewitt, E. L. et al. Distinguishing between green building occupants' reasoned and unplanned behaviours. *Build. Res. Inf.* **44**, 119–134 (2016).
109. National Research Council *Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond* (National Academies Press, 2014).
110. Wang, M., Rieger, M. O. & Hens, T. The impact of culture on loss aversion. *J. Behav. Decis. Mak.* **30**, 270–281 (2017).
111. Benartzi, S. et al. Should governments invest more in nudging? *Psychol. Sci.* **28**, 1041–1055 (2017).
112. National Academies of Sciences and Engineering *The Value of Social, Behavioral, and Economic Sciences to National Priorities: A Report for the National Science Foundation* (National Academies Press, 2017).
113. Stern, P. C., Sovacool, B. K. & Dietz, T. Towards a science of climate and energy choices. *Nat. Clim. Change* **6**, 547–555 (2016).
114. Hellström, T. Dimensions of environmentally sustainable innovation: the structure of eco-innovation concepts. *Sustain. Dev.* **15**, 148–159 (2007).

Acknowledgements
This material is based on work supported by the US National Science Foundation through grant number 153104.

Author contributions
L.K., E.W., E.J., T.S. and M.H. contributed to designing, scoping, performing, analysing and writing the review. B.G. helped perform, analyse and write the review.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information is available for this paper at https://doi.org/10.1038/s41893-018-0054-8.

Reprints and permissions information is available at www.nature.com/reprints.

Correspondence should be addressed to L.K.

Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.