BEYOND RATIONALITY

ENGINEERING DESIGN FOR SUSTAINABILITY

Leidy Klotz
Associate Professor of Civil and Environmental Engineering, Associate Professor of Architecture, University of Virginia (lk6me@virginia.edu)

Elke Weber
Gerhard R. Andlinger Professor in Energy and the Environment and Professor of Psychology and Public Policy, Princeton University

Eric Johnson
Norman Eig Professor of Business, Columbia University

Tripp Shealy
Assistant Professor of Civil and Environmental Engineering, Virginia Tech

Morela Hernandez
Associate Professor of Business Administration, University of Virginia

Bethany Gordon
(Ph.D. student) Behavioral Science for Sustainable Systems Program, University of Virginia

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 may overlook climate change implications because of nearsighted thinking, a bias which can be overcome by vividly imaging the future.

For researchers, this review illuminates needs at the convergence of decision science and engineering design. For designers (i.e., all of us), the review promises new routes to sustainability via tweaks to decision environments and via insights into our own design thinking.

Review – Beyond Rationality in Engineering Design for Sustainability

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 may overlook climate change implications because of nearsighted thinking, a bias which can be overcome by vividly imaging the future. For researchers, this review illuminates needs at the convergence of decision science and engineering design. For designers (i.e., all of us), the review promises new routes to sustainability via tweaks to decision environments and via insights into our own design thinking.

Co-Authors and affiliations

- Leidy Klotz, Associate Professor of Civil and Environmental Engineering, Associate Professor of Architecture, University of Virginia (corresponding, lk6me@virginia.edu)
- Elke Weber, Gerhard R. Andlinger Professor in Energy and the Environment and Professor of Psychology and Public Policy, Princeton University
- Eric Johnson, Norman Eig Professor of Business, Columbia University
- Tripp Shealy, Assistant Professor of Civil and Environmental Engineering, Virginia Tech
- Morela Hernandez, Associate Professor of Business Administration, University of Virginia
- Bethany Gordon, Ph.D. student, Behavioral Science for Sustainable Systems Program, University of Virginia

“Everyone designs who devises courses of action aimed at changing existing situations into preferred ones.” - Herbert Simon[1]

Design for sustainability means attempting transformations from the status-quo in order to improve the well-being of present-day humans without compromising that of future generations and the environments we all rely on. Engineering, broadly defined, is the creative application of science. So, regardless of what your diploma says, you likely practice engineering design for sustainability. In your personal life, you may do so by insulating your attic, or by creating a diet with less meat to reduce your carbon footprint. In your professional and public lives, your designs may seek a more sustainable world through changes in policies, education, business practices, and the human-built environment.

Engineering design for sustainability typically includes an array of stakeholders, including professionals and amateurs. To illustrate this crucial point, suppose the design objective is to create more sustainable mobility within a city. (We use examples from buildings, roads, and other physical infrastructure throughout this review because these examples are relatable and transferrable and because this built environment influences the majority of energy consumption and climate emissions worldwide[25] and is central to Sustainable Development Goals[26]). Not only do designers in this example need to account for the movement of people, they also must consider the fuel use and pollution from various types of transportation, as well as quality of life implications for those who will use the system, and for those who will not use it, but will live nearby. Interdependencies must be considered and can lead to multifunctional design responses, such as automated toll systems, that both reduce delays for drivers and also reduce emissions and therefore improve infant mortality rates in nearby neighborhoods[24]. Designing for sustainable mobility involves contributions from builders, architects, and engineers of all types, and also from groups ranging from planners to understand demographic trends, to ecologists to understand land-use impacts, to residents and users to understand perceived and actual needs, and so on. Each of these stakeholders is practicing engineering design must be able to communicate across disciplines and juggle new environmental and social goals over long time frames.

As designers, we are humans, meaning we 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 computational ability, and utility that is self-centered, reference independent, and exponentially discounted over time.

As in economics and political science[2], assumptions of perfect rationality have guided design to varying degrees. Formal models of engineering design are based on assumptions of perfect rationality[3]. Actual approaches used in engineering design, and more broadly across professional disciplines[4,5], include varying consideration of how designers[6,7] and users[8] actually think and behave. This review organizes research-based evidence to enhance both formal models and existing approaches.

Much of the evidence in this review extends from a series of Nobel Prize-winning advances, which describe ways that classical assumptions of perfect rationality 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[9,10]. 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 users' thermal comfort. The system therefore 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 ignores thermal comfort provided through other means such as increased ventilation and more 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, or only, calculating machines[11–13]. Our thoughts and actions extend beyond the narrowly defined notion of perfect rationality and are influenced by factors such as contextual cues, social norms, decision anchors, and selectively recalled feelings and experiences.

Such previously overlooked "cognitive biases" (i.e., systematic patterns of deviation from classical notions of rationality) matter; they determine what we view as desirable and possible. When we are aware of them, our cognitive processes can be opportunities to advance sustainability goals. If overlooked, these processes can be obstacles to progress on core sustainability needs. For instance: insufficient perspective-taking limits our ability to prioritize human well-being over purely financial measures[14]; nearsighted thinking delays action on climate change[15]; and existing social norms and status-quo bias make it difficult for us to see ways to decouple environmental damage from economic growth[16].

A better understanding and use of the full range of judgment and choice processes can turn obstacles into opportunities. A more complete understanding of design thinking enables intentional changes in decision environments, or "choice architecture" (e.g., 17,18). Examples of choice architecture range from food menus which disclose nutritional information to retirement plans which automatically enroll employees and allow them to opt out, rather than the other way around.

Cognitive biases as obstacles and opportunities

Cities, nations, and organizations including the United Nations[19], the World Bank[20], and the Organization for Economic Co-operation and Development[21] are recognizing bounded rationality and applying choice architecture to aid end-use decision making. However, for engineering 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 design, in part because of the complex nature of design and also because individuals act differently when making decisions for others rather than themselves[22,23].

While challenging, organizing and advancing the research on engineering design for sustainability promises theoretical and social impact because decisions made during design shape the behavior of a large number of end-user decisions over extended periods of time. For example, choice architecture that encourages commuters to use more sustainable mass transit options is only possible if designers have created more sustainable transit options in the first place.

Motivated by such scenarios, this review provides greater awareness of cognitive processes related to design for sustainability, focusing specifically on the obstacles and opportunities these processes present. We used a set of generic and stylized design stages to organize existing research findings: identifying stakeholder needs; defining a problem; creating design concepts, selecting a concept, developing a detailed design, and implementing and evaluating the design (See Supplementary Information for review details). High-potential research needs are also discussed within each stylized stage of design. Obstacles, opportunities, and research needs, while relevant across design stages, are organized in the following sections (and in Table 1) by the most related stage of design.

*** Insert Table 1 Here ***

Identifying needs

An initial step common to most if not all design methods 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. 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. Designers cannot possibly identify all needs of every stakeholder, and so they need to generalize. However, stereotypes that can be tacit or intentional can lead to damaging overgeneralizations because they assume characteristics based on unfounded assumptions[28].

Research indicates that gender[29] and occupational[30] stereotypes could contribute to the limited diversity among designers of the built environment. Underrepresentation of groups such as women, racial and ethnic minorities, and those with low socio-economic 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[31]. 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[32]. Perspective-taking in design helps 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, there research suggests engineering students can be less adept than students in other disciplines at considering users' perspectives[33].

Too much emotional empathy. So far, we have considered the cognitive processes that enable designers to understand others' points of view. Beyond cognition, emotional empathy emphasizes the affective process that enables perspective-taking[34]. A version of this empathy has been described as the first of five steps in the design thinking process, which is frequently used to explain and guide design for sustainability[5,8,35]. 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.

However, 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[36]. It may also mislead designers through user perspectives that discount the needs of future others, underestimate possible negative future impacts[37], 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[38]. Stakeholder engagement encompasses various approaches (e.g., interviews, workshops, surveys) to identify the social and environmental issues which matter most to users in order to improve design decision-making[39]. Research confirms the value of stakeholder engagement to align sustainable building design with stakeholder priorities[40] and also to gather the community input needed to develop urban spaces that support social connections[41].

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, and even may 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 above-ground 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[36]. In particular, it is more difficult to feel emotional empathy for out-group victims, such as future generations or people in far-away areas who will be negatively impacted by climate change[42]. Existing models of how empathy is contextualized in design[43–45] 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[31].

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, i.e., rules of behavior that are either prevalent or considered acceptable in a given social environment[46]. Social norms may limit innovation in some cases. In the built environment, existing social norms about weatherization[47] and heating and cooling systems may well inhibit diffusion of residential energy efficiency design options[48]. Similarly, existing diffusion of energy efficient designs in commercial buildings is probably based less on intentional consideration and more on status-quo routines[49,50]. Social emulation can even help explain diffusion of city-level sustainable building policies[51].

Defaults. The power of social norms can also be used by designers to encourage more sustainable choices[52]. For example, defaults are the choices that get made if no action is taken[53]. 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[54]. One of the reasons defaults have this strong effect on choice is that people think of the default option as an implicit recommendation, i.e., 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[55], or as a loss versus as a gain relative to a different reference point, to take advantage of loss aversion[11]. 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[56]. Similar experimental research on framing effects shows that modifying the defaults choices in the Envision® rating system leads to more ambitious (43% in this case) goals for sustainability[57].

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 this barrier to more sustainable futures by creating plausible descriptions of what could happen[58]. 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[59].

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 (e.g., planning for climate change adaptation[60,61]) and small (e.g., designing individual residential solar energy systems[62]).

Cognitive dissonance and self-perception. Future research is needed to better understand designers' desire to reduce cognitive dissonance[63] and enhance self-perception[64]. In other words, we do not just act in ways to maximize utility, we act in ways to make ourselves feel better[65], 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[66,67].

Emotional associations and spillover effects. It would be especially beneficial to design for sustainability to learn how behaviors 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[68]. 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' behaviors 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[69]. 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[70]. For example, designers who advocate for walkable neighborhoods 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 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[71].

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 (e.g., recency effect, anchoring bias[72]) 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[73]. Fixation can limit the breadth of sustainable design options that are generated by faculty members, and expert designers[74–76]. Pictures meant to inspire designers can unintentionally introduce fixation on ideas related to the examples presented in the pictures[77].

Default design. Fixation and premature selection contribute to the default design bias, which is a tendency toward previously used designs, and limits innovation for sustainability in the building industry[78]. 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[79].

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[80]. 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[81]. 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[82].

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[83]. For instance, 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[84]. 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[85].

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[86].

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[87]. 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[88]. However, the planning fallacy can also stem from designers' self-deluded thinking that the selected project is best[89]. 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 favorable as possible. While the planning fallacy research focuses on self-delusion about cost and schedule, this same delusion likely 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[90]. Alternatively, designers reactions to new approaches may be overly cautious and risk-averse, which can constrain innovation for sustainability in civil infrastructure[91], including in urban water systems[92].

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[93]. For instance, if the proposed response were a bus rapid transit system, 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[94], 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[95]. 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[96], in cooperative efforts to mitigate climate change[97], and in risk forecasts for infrastructure design[98]. 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 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 cheaper alternatives in favor of more costly ones[99]. 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[100].

Heuristics in design software. Designers can receive support during detailed design from software that allows for rapid simulation of multiple alternatives. For example, transportation modeling 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 modeled 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 (i.e., comparing new solutions with the best found so far) and evolutionary heuristics (i.e., maintaining a population of solutions and eliminating the poorest in each iteration)[101].

Identifying root causes of heuristics. Future research should examine how decisions change when we use rules of thumb to save time and thought[102]. 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[103]. Research identifying heuristics common to design[104] 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 which 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[105]. Numerous decision making systems aim to address these cognitive limits to working memory[17]. Yet, with the exception of some preliminary research on choosing by advantages[106,107], 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 behavior during implementation and evaluation. The field of environmental psychology, for example, studies the interplay between humans and our physical environments[108]. Understanding occupant behavior is vital for more sustainable buidings[109,110]. 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 high-potential research needs that require both an applied focus as well as deep integration across multiple disciplines (e.g., decision and sustainability sciences, engineering design). This "convergent" approach to research is widely-needed and yet underused[27], in part because it requires study beyond the laboratory. One path to overcome this outstanding challenge for convergent research is through the stakeholder engagement needed in design for sustainability. Designers and researchers could work together to run natural experiments. Convergent research on decision framing, for example, could be done by asking stakeholders about needs framed either as abstract concepts (e.g., mobility) or in terms of what the abstract concepts provide (e.g., connections to family and friends). Designers would learn more about their stakeholders and researchers would learn more about how this framing shapes stakeholder input.

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[115]. Studying engineering design for sustainability in cultures where this bias 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 behaviors offers new pathways to create and test interventions that inspire the fundamental shifts in goals and actions needed for sustainability. Designers can use choice architecture to redirect potentially adverse processes into positive forces. Many of the opportunities discussed in this review are subtle changes in choice architecture (e.g., adding defaults in the Envision® rating system, introducing analogies intended to break design fixation, or requiring reference class forecasting to avoid the planning fallacy.) Choice architecture should become part of designers' toolkits not only because it works, but because it is relatively low-cost compared with new physical environments and technologies, and also compared with regulations and interventions based on self-interested incentives[111,112].

Finally, this review shows how considering just one area of behavioral science in engineering 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. Similar radical improvements require integrated consideration of the social, technological, and environmental systems where our sustainability challenges reside[113,114]. A sustainable future therefore depends on how well designers and researchers leverage behavioral sciences; in addition to the physical, formal, and biological sciences; to inform and inspire engineering design for sustainability.

Acknowledgements

This material is based on work supported by the U.S. National Science Foundation through Grant #153104. Correspondence and requests for materials should be addressed to Leidy Klotz.

References

1. Simon, H.A. *The sciences of the artificial*. (MIT press, 1996).
2. Friedman, M. *Essays in positive economics*. (University of Chicago Press, 1953).
3. Hazelrigg, G.A.A framework for decision-based engineering design. *J. Mech. Des.* **120,** 653 (1998).
4. Norman, D. *The design of everyday things: Revised and expanded edition*. (Basic Books, 2013).
5. Rowe, P.G. *Design thinking*. (MIT press, 1991).
6. Cross, N. Designerly ways of knowing. *Des. Stud.* **3,** 221–227 (1982).
7. Lawson, B. *How designers think*. (Architectural Press, 2006).
8. Brown, T. Design thinking. *Harv. Bus. Rev.* **86,** 84 (2008).
9. Simon, H.A. Models of man; social and rational. (Wiley, 1957).
10. Gigerenzer, G. Bounded and rational. *In Contemporary debates in cognitive science*, 115–133 (Blackwell, 2006).
11. Tversky, A. & Kahneman, D. The framing of decisions and the psychology of choice. *Science* **211,** 453–458 (1981).
12. Kahneman, D. & Tversky, A. Prospect theory: An analysis of decision under risk. *Econom. J. Econom. Soc.* 263–291 (1979).
13. Simon, H.A. *Models of bounded rationality: Empirically grounded economic reason*. (MIT press, 1982).
14. United Nations Environment Programme (UNEP). *Consuming differently, consuming sustainably: Behavioral insights for policymaking*. (UNEP, 2017).

15. Weber, E.U. Breaking cognitive barriers to a sustainable future. *Nat. Hum. Behav.* **1,** 0013 (2017).
16. UNEP. *Decoupling natural resource use and environmental impacts from economic growth, A report of the working group on decoupling to the international resource panel*. (UNEP, 2011).
17. Johnson, E.J. *et al.* Beyond nudges: Tools of a choice architecture. *Mark. Lett.* **23,** 487–504 (2012).
18. Thaler, R. & Sunstein, C. *Nudge: Improving decisions about health, wealth, and happiness*. (Yale University Press, 2008).
19. United Nations Development Programme (UNDP). *Behavioural insights at the United Nations – Achieving Agenda 2030*. (UNDP, 2016).
20. The World Bank. *World development report 2015: mind, society, and behavior*. (The World Bank, 2015).
21. Organisation for Economic Co-operation and Development (OECD). *Tackling environmental problems with the help of behavioural insights*. (OECD, 2017).
22. Eisenhardt, K.M. Agency theory: An assessment and review. *Acad. Manage. Rev.* **14,** 57–74 (1989).
23. Hsee, C.K. & Weber, E.U. A fundamental prediction error: Self–others discrepancies in risk preference. *J. Exp. Psychol. Gen.* **126,** 45 (1997).
24. Currie, J. & Walker, R. Traffic congestion and infant health: Evidence from E-ZPass. *Am. Econ. J. Appl. Econ.* **3,** 65–90 (2011).

25. United States Energy Information Administration (EIA). *International energy outlook 2016.* (EIA, 2016).
26. United Nations General Assembly. *Transforming our world: The 2030 agenda for sustainable development*. A/RES/70/1, 21 October, 2015.
27. National Research Council. *Convergence: facilitating transdisciplinary integration of life sciences, physical sciences, engineering, and beyond*. (National Academies Press, 2014).
28. 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).
29. 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).
30. Loosemore, M. & Tan, C.C. Occupational stereotypes in the construction industry. *Constr. Manag. Econ.* **18,** 559–566 (2000).
31. Page, S.E. *Diversity and complexity*. (Princeton University Press, 2010).
32. 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).
33. Rasoal, C., Danielsson, H. & Jungert, T. Empathy among students in engineering programmes. *Eur. J. Eng. Educ.* **37,** 427–435 (2012).
34. Davis, M.H. *Empathy: A Social Psychological Approach*. (Westview Press, 1996).
35. 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).
36. Bloom, P. *Against empathy: The case for rational compassion*. (Random House, 2017).

37. Wade-Benzoni, K.A. A golden rule over time: Reciprocity in intergenerational allocation decisions. *Acad. Manage. J.* **45,** 1011–1028 (2002).

38. 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).

39. Pidgeon, N., Demski, C., Butler, C., Parkhill, K. & Spence, A. Creating a national citizen engagement process for energy policy. *Proc. Natl. Acad. Sci.* **111,** 13606–13613 (2014).

40. Bal, M., Bryde, D., Fearon, D. & Ochieng, E. Stakeholder engagement: Achieving sustainability in the construction sector. *Sustainability* **5,** 695–710 (2013).

41. O'Hara, S.U. Community based urban development: a strategy for improving social sustainability. *Int. J. Soc. Econ.* **26,** 1327–1343 (1999).

42. Markowitz, E.M. & Shariff, A.F. Climate change and moral judgement. *Nat. Clim. Change* **2,** 243–247 (2012).

43. 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).

44. 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).

45. 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).

46. 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).

47. 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).

48. Noonan, D.S., Hsieh, C. & Matisoff, D. Spatial effects in energy-efficient residential HVAC technology adoption. *Environ. Behav.* **45,** 476–503 (2013).

49. Vermeulen, W. & Hovens, J. Competing explanations for adopting energy innovations for new office buildings. *Energy Policy* **34,** 2719–2735 (2006).

50. 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).

51. 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).

52. Nyborg, K. *et al.* Social norms as solutions. *Science* **354,** 42–43 (2016).

53. Johnson, E. & Goldstein, D. Do defaults save lives? *Science* **302,** 1338–1339 (2003).

54. Ebeling, F. & Lotz, S. Domestic uptake of green energy promoted by opt-out tariffs. *Nat. Clim. Change* **5,** 868–871 (2015).

55. 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).

56. 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).

57. Shealy, T. & Klotz, L. Well-endowed rating systems: How modified defaults can lead to more sustainable performance. *J. Constr. Eng. Manag.* **141,** 04015031 (2015).

58. Wiek, A. & Iwaniec, D. Quality criteria for visions and visioning in sustainability science. *Sustain. Sci.* **9,** 497–512 (2014).

59. 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).

60. Rumore, D., Schenk, T. & Susskind, L. Role-play simulations for climate change adaptation education and engagement. *Nat. Clim. Change* **6,** 745–750 (2016).

61. Wu, J.S. & Lee, J.J. Climate change games as tools for education and engagement. *Nat. Clim. Change* **5,** 413–418 (2015).

62. 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).

63. Aronson, E. The theory of cognitive dissonance: A current perspective. *Adv. Exp. Soc. Psychol.* **4,** 1–34 (1969).

64. Bem, D. J. Self-perception theory. *Adv. Exp. Soc. Psychol.* **6,** 1–62 (1972).

65. Weber, E.U. Climate change demands behavioral change: What are the challenges? *Soc. Res. Int. Q.* **82,** 561–580 (2015).

66. 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).

67. 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. (2007).

68. Evans, L. *et al.* Self-interest and pro-environmental behaviour. *Nat. Clim. Change* **3,** 122–125 (2013).

69. 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).

70. 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).

71. Slovic, P. The construction of preference. *Am. Psychol.* **50,** 364 (1995).

72. Tversky, A. & Kahneman, D. Judgment under uncertainty: Heuristics and biases. *Science* **185,** 1124–1131 (1974).

73. Jansson, D.G. & Smith, S.M. Design fixation. *Des. Stud.* **12,** 3–11 (1991).

74. Linsey, J.S. *et al.* A study of design fixation, its mitigation and perception in engineering design faculty. *J. Mech. Des.* **132,** 041003 (2010).

75. Viswanathan, V.K. & Linsey, J.S. Design fixation and its mitigation: a study on the role of expertise. *J. Mech. Des.* **135,** 051008 (2013).

76. 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).

77. 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 (2005).

78. 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).

79. 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).

80. 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).

81. Harris, N., Shealy, T. & Klotz, L. How exposure to "role model" projects can lead to decisions for more sustainable infrastructure. *Sustainability* **8,** 130 (2016).

82. 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. (2016).

83. Christensen, B.T. & Schunn, C.D. The relationship of analogical distance to analogical function and preinventive structure: The case of engineering design. *Mem. Cognit.* **35,** 29–38 (2007).

84. Casakin, H.P. & Goldschmidt, G. Reasoning by visual analogy in design problem-solving: the role of guidance. *Environ. Plan. B Plan. Des.* **27,** 105–119 (2000).

85. She, J. & MacDonald, E. Priming designers to communicate sustainability. *J. Mech. Des.* **136,** 011001 (2014).

86. Cash, D.W. *et al.* Knowledge systems for sustainable development. *Proc. Natl. Acad. Sci.* **100,** 8086–8091 (2003).

87. Kahneman, D. & Tversky, A. *Intuitive prediction: Biases and corrective procedures*. (Decisions and Designs Inc., 1977).

88. Flyvbjerg, B., Holm, M.S. & Buhl, S. Underestimating costs in public works projects: Error or lie? *J. Am. Plann. Assoc.* **68,** 279–295 (2002).

89. Pickrell, D.H. A desire named streetcar: Fantasy and fact in rail transit planning. *J. Am. Plann. Assoc.* **58,** 158–176 (1992).

90. Kahneman, D. & Lovallo, D. Timid choices and bold forecasts: A cognitive perspective on risk taking. *Manag. Sci.* **39,** 17–31 (1993).

91. 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).

92. Kiparsky, M. *et al.* Barriers to innovation in urban wastewater utilities: Attitudes of managers in California. *Environ. Manage.* **57,** 1204–1216 (2016).

93. Flyvbjerg, B., Garbuio, M. & Lovallo, D. Delusion and deception in large infrastructure projects: two models for explaining and preventing executive disaster. *Calif. Manage. Rev.* **51,** 170–193 (2009).

94. Kunreuther, H. *et al.* Risk management and climate change. *Nat. Clim. Change* **3,** 447–450 (2013).

95. Loewenstein, G. & Elster, J. *Choice over time*. (Russell Sage Foundation, 1992).

96. Costanza, R. *et al.* The value of the world's ecosystem services and natural capital. *Nature* **387,** 253–260 (1997).

97. Jacquet, J. *et al.* Intra-and intergenerational discounting in the climate game. *Nat. Clim. Change* **3,** 1025–1028 (2013).

98. Lee, J.Y. & Ellingwood, B.R. Ethical discounting for civil infrastructure decisions extending over multiple generations. *Struct. Saf.* **57,** 43–52 (2015).

99. 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. Plan. B Plan. Des.* **37,** 792–807 (2010).

100. Viswanathan, V.K. & Linsey, J.S. Role of sunk cost in engineering idea generation: an experimental investigation. *J. Mech. Des.* **135,** 121002 (2013).

101. Evins, R.A. review of computational optimisation methods applied to sustainable building design. *Renew. Sustain. Energy Rev.* **22,** 230–245 (2013).

102. Payne, J.W., Bettman, J.R. & Johnson, E.J. *The adaptive decision maker*. (Cambridge University Press, 1993).

103. 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).

104. Daly, S.R., Yilmaz, S., Christian, J.L., Seifert, C.M. & Gonzalez, R. Design heuristics in engineering concept generation. *J. Eng. Educ.* **101,** 601 (2012).

105. Baddeley, A. Working memory: Theories, models, and controversies. *Annu. Rev. Psychol.* **63,** 1–29 (2012).

106. 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).

107. 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).

108. Gifford, R. *Environmental psychology: Principles and practice*. (Optimal books Colville, WA, 2007).

109. Deuble, M.P. & de Dear, R.J. Green occupants for green buildings: the missing link? *Build. Environ.* **56,** 21–27 (2012).

110. Hewitt, E.L. *et al.* Distinguishing between green building occupants' reasoned and unplanned behaviours. *Build. Res. Inf.* **44,** 119–134 (2016).

111. Benartzi, S. *et al.* Should governments invest more in nudging? *Psych. 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*. (2017). doi:10.17226/24790

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).

115. Wang, M., Rieger, M.O., & Hens, T. “The Impact of Culture on Loss Aversion.” *Beh. Dec. Mking.* **30**, 270-281 (2017).

116. Grant, M. J. & Booth, A. A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Inf. Libr. J.* **26,** 91–108 (2009).

Table 1: Review Findings – Cognitive biases as obstacles, opportunities, and research needs

Obstacles	Opportunities	Research Needs
Identifying stakeholder needs		
Stereotypes		
Undervalued perspective-taking		
Too much emotional empathy		
	Stakeholder engagement	
		Functions and effects of emotional and cognitive empathy
		Ways to overcome stereotypes
Defining a design problem		
Social norms		
	Defaults	
	Framing	
Lack of perceived agency		
	Visioning and scenario generation	
	Serious games	
		Reduce cognitive dissonance and enhance self-perception
		Emotional associations and spillover effects
Creating design concepts		
Premature evaluation and selection		
Fixation		
Default design		
	Anchoring	
	Analogies	
		Salience, stories, and patterns
Selecting a design concept		
Planning fallacy		
Risk aversion to new approaches		
	Reference class forecasting	
		Perceptions of climate change risk
		Future discounting
Developing the detailed design		
Escalating commitment		
Heuristics in design software		
		Identifying root causes of heuristic thinking during design
		Effects of decision making systems and shortcuts
Implementing and evaluating designs		
		Cognitive processes of designers during evaluation